ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

Catalysis of Sorghum Stems Potash Salt in the Conversion of Bos Taurus Zebu Slaughterhouse Fat Residues into Biodiesel

Emerentien Ly- inbé[1,2,3*]; Ngoulou Abomo[1,2]; Merlin Zacharie Ayissi[1,2,3]; Fontaine Dubois Bissaï[1]; Francis Lénine Djanna Koffi[2,4]

[1]Energy Laboratory (LE), University of Douala, Douala, Cameroun
[2]National Higher Polytechnic School, University of Douala, Douala, Cameroun
[3]Research Group in Strategy, Innovation and Sustainable Development (GRESIDD)
[4]Department of Automotive Engineering and Mechatronics, (ENSPD), University of Douala, Douala, Cameroun

Corresponding Author: Emerentien Ly- Inbé*

Publication Date: 2026/03/14

Abstract: The production of biodiesel from edible oils and industrial catalysts increases its production cost and makes its price higher than fossil diesel. The fatty waste generated by slaughtering industries pollutes the environment and could be converted into bioenergy by various processes. Potash salt is extracted from sorghum and formulated to serve as a biocatalyst in the transesterification process of Bos Taurus Zebus tallow into biodiesel. The characterization of tallow, biocatalyst and biodiesel is carried out. The tallow has a viscosity, acidity index, density of 7.2 mm ^{2}/s, 5.3 mg KOH /g and 911.3 Kg/m^3 respectively. The extracted potash has a potassium content of 58.3% and a pH of 10.7, characterizing the basicity of the salt. The biodiesel production yield under the constraint of a full factorial experimental design is 96.53%. The major oleic ester in the composition of the derived biodiesel is 19.65%. The viscosity and density are 5.45 mm ^{2}/s and 874 kg/m3 at 40°C, respectively. The cetane number is 56.7, which is higher than that of regular diesel. The obtained biodiesel can be used as an additive to fossil fuels or to power compression ignition engines.

Keywords: *Biodiesel; Esterification; Full Factorial Design; Transesterification; Potash Salt.*

How to Cite: Emerentien Ly- inbé; Ngoulou Abomo; Merlin Zacharie Ayissi; Fontaine Dubois Bissaï; Francis Lénine Djanna Koffi (2026) Catalysis of Sorghum Stems Potash Salt in the Conversion of Bos Taurus Zebu Slaughterhouse Fat Residues into Biodiesel. *International Journal of Innovative Science and Research Technology,* 11(2), 3174-3187. https://doi.org/10.38124/ijisrt/26feb1487

I. INTRODUCTION

Considering the problems related to climate change, biodiesels, is becoming increasingly important. Biofuels are fuels made from biomass feedstock (Ayissi, Mohand, Sary, Obounou, & Ohandja, 2016). Biodiesel is a biofuel made from fat-rich substrates such as vegetable oils, used cooking oils and animal fats. However, the use of food as a raw material in the fight against harmful effects on the environment, and the total dependence on fossil fuels, the exploitation of biomass as an alternative energy source, especially manufacture of biofuels has created a controversy between biofuels and food substrates. Several prejudices designate the biofuel sector as the main cause of famine, anarchic occupations of agricultural land, and deforestation (Adrien, 2011; Escobar et al., 2009). Other researchers mention the problem of the high cost of producing biodiesel made from vegetable oils. These researchers estimate that the exploitation of certain reagents and vegetable oils represents between 60% and 70% of the cost of producing biodiesel. These values increase daily at the rate of the scarcity of the raw material (Sharma, Castello, Haider, Pedersen, & Rosendahl, 2021). One method to reduce the production costs of biodiesel is to valorize multiform residues by minimizing their purchase price. Used frying oils, fatty residues from slaughterhouses, and fish oils are among the raw materials to be recycled.

Biodiesel made from these materials has the advantage of being less polluting and not competing with human food or occupying agricultural land. Cattle waste from this generation has a high fat content. Among the residues, beef tallow has been identified. This is a type of residual animal fat, generally obtained during the dissection of cattle and

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

during slaughter. The amount of beef tallow varies from 5 to 12 kilograms depending on the breed and type of animal. Approximately 308,640,252 cows were slaughtered in 2022 worldwide. On average, 2,160,481,764 tonnes of beef tallow were extracted. In France, 4 million oxen were slaughtered in 2022, and nearly 24,000 tonnes of slaughter tallow residues were collected (Perrin-Guyomard et al., 2022). The dumping of slaughterhouse waste into the environment has a significant impact on the environment. To give these wastes a new life, they should be integrated into the energy value cycle. The potential of bioenergy in the energy mix is numerous. The International Energy Agency indicates that bioenergy should grow and reach 25% by 2025, without stopping to progress and reach 30%, including the statistical weight of the fuel mix in the global road transport sector by 2050 (Toldrá-Reig, Mora, & Toldrá, 2020).

The viscosity and relatively high fatty acid content make its use in diesel engines unlikely. Various methods have been proposed to align the characteristics of these animal fatty residues more closely with those of diesel fuel, including dilution, thermal treatment, emulsion, transesterification, and pyrolysis (Alloune, 2017; Mrad, Aloui, Tazerout, & Nasrallah, 2010). It has been shown that biodiesel can be advantageously obtained by a transesterification process, due to the low cost and simplicity of this process. Transesterification is a reaction in which triglycerides from oil or fats react with an alcohol in the presence of a catalyst (acid or base). The main products resulting from this process are alcoholic esters (alkyl esters) and glycerol which is the reaction by-product identified in the background (Blin, Villeneuve, Baréa, & Moussavou, 2016). Methanol or ethanol are generally used as the alcoholic reactants (Verma & Sharma, 2016). Methanol is used more frequently than ethanol due to its availability and low cost. The other argument in favor of methanol is its ability to provide a better yield when compared to ethanol under the same experimental conditions (Andreo-Martinez et al., 2022). The most effective catalysts used are alkali hydroxides, including sodium hydroxide and potassium hydroxide. These catalysts are generally imported, which significantly increases the cost of biodiesel production. In addition, they are of synthetic origin, which is not sufficiently consistent with the Sustainable Development Goals. There are biocatalysts derived from agricultural residues, trees or hulls, which are very inexpensive and environmentally friendly. These biocatalysts can play an important role in the biofuel value chain, particularly by improving the quality of biofuels. Sorghum is among the most widely cultivated cereals in the world and is a staple food for millions of people living in semi-arid and arid regions of Africa.

In terms of overall per capita consumption in Africa, this cereal is the third most important, after maize and rice (Serge, Armand, Richard, Augustin, & Albert, 2023). Globally, sorghum is the fifth cereal, after wheat, maize, rice and barley (OUEDRAOGO et al., 2023). It is a staple food in arid regions. Its global production is estimated at about 59 million tonnes, of which 27 million tonnes are specifically for Africa (OUEDRAOGO et al., 2023). (Rabo, Sadikou, & Mahamane, 2024) explain that for one hectare of crops, a yield of about 1.08 tonnes is obtained. Sorghum (millet) cultivation covers more than 21 million hectares, where nearly 500 million people depend on it for their survival. Africa accounts for 40% of global sorghum production.

Sorghum is grown for its starch yield for home consumption or small industrial flour production units. Its stalks are used for animal feed or as fuel. Some farmers use it as a soil amendment residue. Its ashes, after combustion, can be transformed into potash salt. In the village, potash salt is used as a repellent against poisons or to season food. Being a strong base, potash salt can be used as a catalyst in the process of converting fatty acids into oil esters.

Much research has been conducted on the processes of biodiesel conversion from animal fats. On this point, (Hasan & Ratnam, 2022) report in their work that the use of animal fat residues as a raw material for biodiesel synthesis improves both the supply of biodiesel and the reduction of the harmful effects of fat residue accumulation. Several authors claim that the chemical synthesis catalyst is not suitable for the conversion of this fat and suggest testing on other types of catalyst. According (Gebremariam & Marchetti, 2018), the use of acid catalysis makes the transesterification reaction very slow and requires more alcohol. Basic catalysis, on the other hand, minimizes the profitability of the transesterification process. It turns out that an alkaline catalyst accelerates the catalytic alcohol rate of fats by about 4000 times compared to an acid catalyst (Amal et al., 2024). (Zhao, Xu, Yu, Yan, & Zhang, 2013) propose the use of a solid catalyst capable of multiple reuses after washing and calcination. (Saravanan et al., 2024) explain that natural residues, such as eggshells, rice husks, coconut shells or volatile residues can be used to create a clean, less expensive and reusable natural catalyst several times.

Due to the controversy between food substrates and energy feedstock's, edible oils such as vegetable oils are no longer suitable as feedstock's for biodiesel production (Onyeka Stanislaus Okwundu, El-Shazly, & Elkady, 2019). The use of catalysts is important in the transesterification process (Bhuyan et al., 2021). The value cycle of biofuels remains confined to an open circularity model. This does not guarantee that sustainability requirements will be met. The use of fat residues in combination with a biocatalyst brings the process closer to a closed, and thus sustainable, value cycle.

In this study, potash salt is extracted and biodiesel is used and characterized according to the standards governing biofuels. An optimization model for biodiesel production from beef tallow is proposed based on an experimental design. The parametric variations of the reaction and the use of potash salt from sorghum stem as a biocatalyst are fundamental determinants underlying this production model. Sorghum-based potash salt is a local material, obtained by post-harvest calcination of sorghum stems. These sorghum stems are generally considered by farmers as crop residues. Potash salt is considered a strong base with catalytic properties similar to those of potassium hydroxide. Known for its very high solubility in alcohol, it could improve the yield of the transesterification reaction and reduce the production cost. Transesterification is carried out between beef tallow and methanol in the presence of potash salt as a biocatalyst for the formulation of a biodiesel called beef tallow methyl ester.

II. MATERIALS AND METHODS

➢ *Extraction of Beef Tallow*

The beef fat used comes from some slaughterhouses in the Douala city region of Cameroon. The extracted fat was cleaned under running water and then dried in the oven to prevent oxidation. Beef tallow is obtained by melting the fat at a temperature of 60°C to prevent carbonization of the fat. The fats were collected in a utensil as they melted. The liquid obtained was cooled to room temperature and bottled to prevent oxidation. The tallow and flour contents were evaluated. (Fig 1, a, b, c, d, e) below illustrate the steps for obtaining this beef tallow.

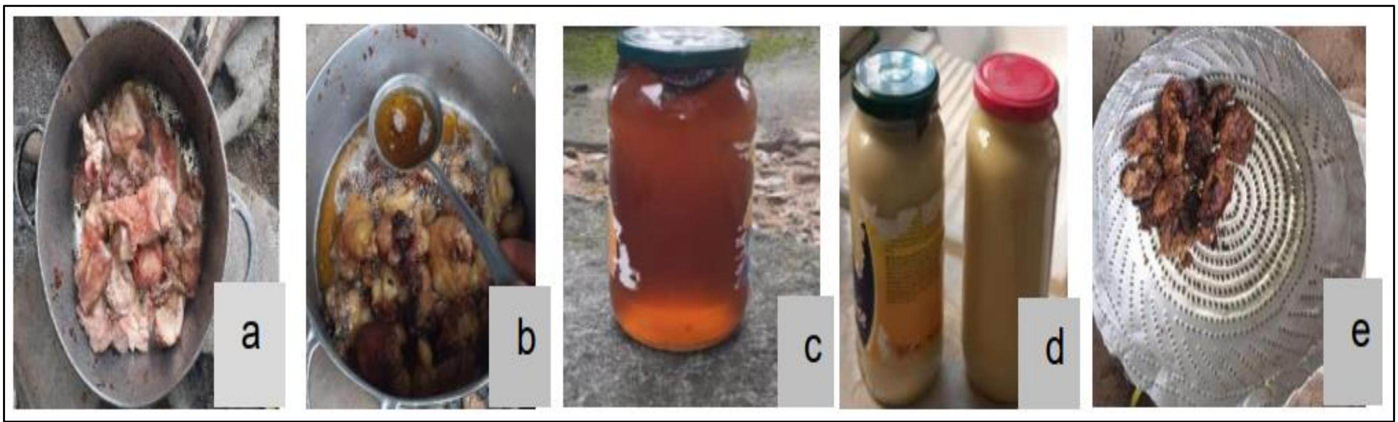

Fig 1 Block Diagram of Bos Taurus Oil Production: (a) Beef Fat, (b) Tallow Extraction, (c) Liquid State of Tallow, (d) Solid Tallow, (e) Flour

$$T_{tallow} = \frac{ms - mt}{mo} \times 100 \quad (1),$$

$$T_{flour} = 100 - T_{tallow} \quad (2)$$

With *ms* and *mo* there mass of their fat, dry and fresh, *m t* there mass flour and T_{tallow} and T_{flour} their tallow and flour content.

➢ *Methods for Extracting Potash Salts from Sorghum Stems Used as Biocatalyst*

Sorghum cultivation begins in June and ends in August in the Lake Chad region. The month of September allows the Sorghum to mature and dry. Harvesting begins in October with the process of felling the stems. All dried seeds and stems are left in the sun for one to two weeks. Once finished, the seeds are separated from the stem and collected for later use. The stems are exposed to the sun for two to three weeks until a dry matter content of more than 95% is obtained, suitable for combustion. The stems will then be burned in the open air and then crushed in a mortar until ash is obtained. A production of 4.7 kg of ash is collected after combustion for a quantity of 39.2 kg in dry matter.

The ash was dissolved in five (05) liters of distilled water. The mixture is filtered in a vacuum filtration, and 4.3 liters of filtrate are obtained, which are boiled for 6 hours until complete evaporation of the water. This gives an equivalent of 1.45 kg of potash salt crystals. The salt crystals obtained were spread on the ashes and put in the oven in order to minimize the residual humidity, and then dried as shown in (Fig2 and 3).

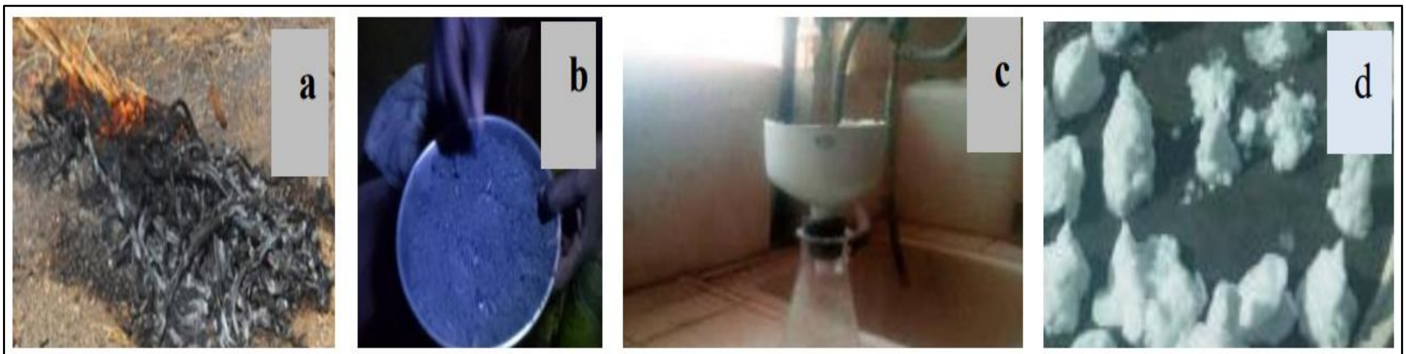

Fig2**.** Extraction of Potash Salt: Combustion of the Stem (a), Ashes (b), Vacuum Filtration (c), Potash Salt Obtained (d)

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

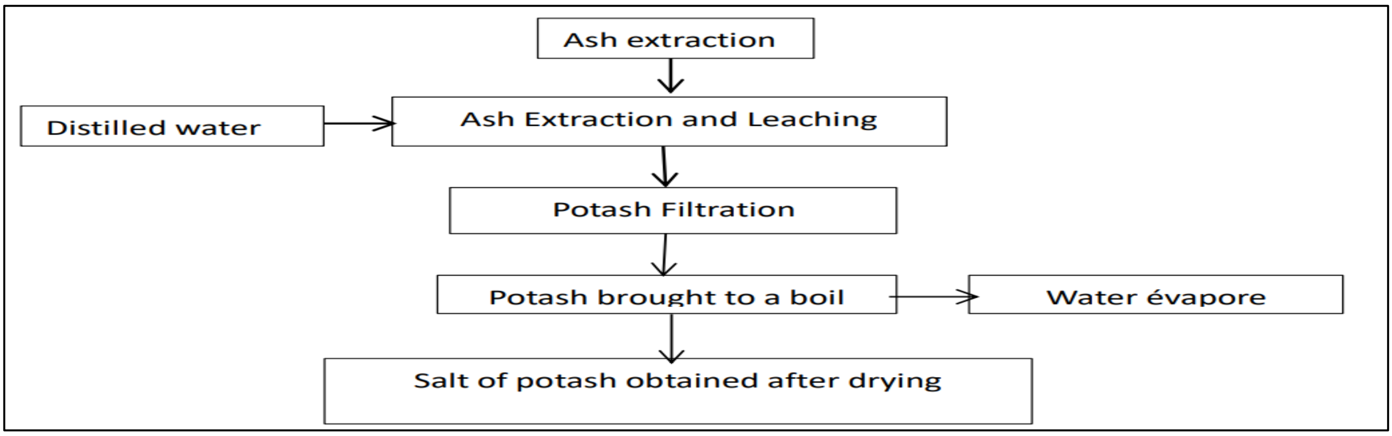

Fig 3 Flow Chart of Potash Salt Extraction

In order to assess the quality of the salt and list the different elements constituting it, a Perkin Elmer Spectrum FTIR infrared spectrometer was used to analyze the functional groups and validate the absorption band of the major elements present in the potash salt crystals. Some authors explain that the major elements found in the oil palm branch ash are potassium (K) and silicon (Si). On the other hand, minerals such as calcium (Ca), magnesium (Mg) and sodium (Na) were in low proportion. A porosity of the stem salt was also analyzed after a first transesterification, followed by its analysis of its subsequent reusability in several cycles. A STARUS brand pH meter was used to quantify the degree of basicity of this product obtained.

➢ *Modeling the Production of Methyl Esters by Transesterification on Minitab Software*

The optimization of the yield of methyl esters from beef tallow is studied using the full factorial experimental design. This model has the advantage of offering fewer trials, minimizing handling errors during the experiment, and also facilitating the approximation of the standard deviation of the different responses in methyl esters. It is based on two essential criteria: the experimental space and that of the mathematical modeling of the variables studied. The factorial design allows varying the three deterministic parameters of the reaction, namely: the alcohol/crude fatty acid (MR) mola/r ratio ε [3:1; 9:1], the catalyst/fatty acid (C) ratio (%) ε [0.5; 2] as well as the reaction time t (min) ε [30; 180]. The chosen design has two levels. Let a full factorial design of $n=2^3=8$. Using the simulation on Minitab software, which has two centered points, a total of 10 tests were performed according to the three factors of the reaction (Table 1).

Table 1 Different Configurations of the Three Parameters Involved in Their Transesterification Reaction.

Run	**Central point (*x p*)**	**RM (*x 1*)**	**C (*x 2*)**	**Time (*x 3*)**	**Yield Y (%)**
1	1	9:1	2.00	30	Y 1
2	0	6:1	1.25	105	Y 2
3	1	3:1	2.00	30	Y 3
4	1	6:1	2.00	180	Y 4
5	0	6:1	1.25	105	Y 5
6	1	9:1	0.50	30	Y 6
7	1	9:1	0.50	180	Y 7
8	1	3:1	2.00	180	Y 8
9	1	3:1	0.50	30	Y 9
10	1	3:1	0.50	180	Y 10

The variation of these parameters allows proposing a mathematical model in methyl ester of the biodiesel produced. This model determines the biodiesel yield of each test in the range delimited by the three reaction factors.

$$\mathbf{y}(\%) = a_o + a_1\mathbf{x}_1 + a_2\mathbf{x}_2 + a_3\mathbf{x}_3 + a_{12}\mathbf{x}_1\mathbf{x}_2 + a_{13}\mathbf{x}_1\mathbf{x}_3 + a_{23}\mathbf{x}_2\mathbf{x}_3 + a_{123}\mathbf{x}_1\mathbf{x}_2\mathbf{x}_3 \quad (3)$$

a_0, a_1, a_2, a_3, at $_{12}$, at $_{23}$, a_{13}, and a_{123} are the polynomial coefficients of the interactions between reactants. The value of each coefficient illustrates the impact of each reactant on the reaction, as well as on the yield of methyl ester.

$$a_0 = \frac{y_1+y_2+y_3+y_4+y_5+y_6+y_7+y_8}{8} \quad (4)$$

$$a_1 = \frac{-y_1+y_2-y_3+y_4-y_5+y_6-y_7+y_8}{8} \quad (5)$$

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

$$a_2 = \frac{-y_1-y_2+y_3+y_4-y_5-y_6+y_7+y_8}{8} \quad (6)$$

$$a_3 = \frac{-y_1-y_2-y_3-y_4+y_5+y_6+y_7+y_8}{8} \quad (7)$$

$$a_{12} = \frac{y_1-y_2-y_3+y_4+y_5-y_6-y_7+y_8}{8} \quad (8)$$

$$a_{13} = \frac{y_1-y_2+y_3-y_4-y_5+y_6-y_7+y_8}{8} \quad (9)$$

$$a_{23} = \frac{y_1+y_2-y_3-y_4-y_5-y_6+y_7+y_8}{8} \quad (10)$$

$$a_{123} = \frac{-y_1+y_2+y_3-y_4+y_5-y_6-y_7+y_8}{8} \quad (11)$$

Up of some residuals of prediction r_i of biodiesel yield.

$$r_i = \overline{y(\%)i} - y(\%)i \quad (12)$$

$\overline{y(\%)i}$ represent the prediction response.

➢ *Biodiesel Production by Transesterification of Beef Tallow*

The obtained tallow was pretreated by esterification in the presence of methanol, catalyzed by sulfuric acid, in order to remove impurities and the level of free fatty acids present in the fat. The different molecular constituents of the pretreated tallow were analyzed using a Schimadzu chromatomètre apparatus. However, beef tallow is more abundant in saturated fatty acids than other fatty acids (Ma et al., 2020; Rapport). Most of the saturated fatty acids in beef tallow are oleic acid and palmitic acid. All reagents and solvents used in this study are of analytical grade. The methanol used in the transesterification process is of commercial origin and quality, acquired on the local market. The catalyst used is potash salt extracted from sorghum stalks. Biodiesel was produced on a laboratory scale. At the beginning, the catalyst has been told us in methanol, stirred with the help of agitator magnetic and simultaneously heated by 20 to 30 °C to promote homogenization of the reaction medium. When the catalyst is completely dissolved, to obtain a blend of alcoxyde of alcohol and catalyst. The mixture obtained will be placed in a bioreactor containing tallow and reheated beef. The mixture will be agitated with a magnetic stirrer and heated at the temperature set by the thermostat. The duration of the reaction is the time between the start of agitation and the stop-here reaction. She can vary 30 minutes, 1 hour, up to 4 times according to the solubility of the reagents in tallow andthe temperature prevailing in the bioreactor. The biodiesel obtained is separated from the glycerol and then washed several times with hot water until the washing water is obtained at a pH around neutral. The washed biodiesel is subsequently dried in an oven and filtered, after which it will be prepared for characterization tests. The biodiesel production yield is derived from (equation 13).

$$r(\%) = \frac{m_{biodiesel}}{m_{suif\ de\ boeuf}} \times 100 \quad (13)$$

(Fig 4) illustrates the different stages of biodiesel production in this study.

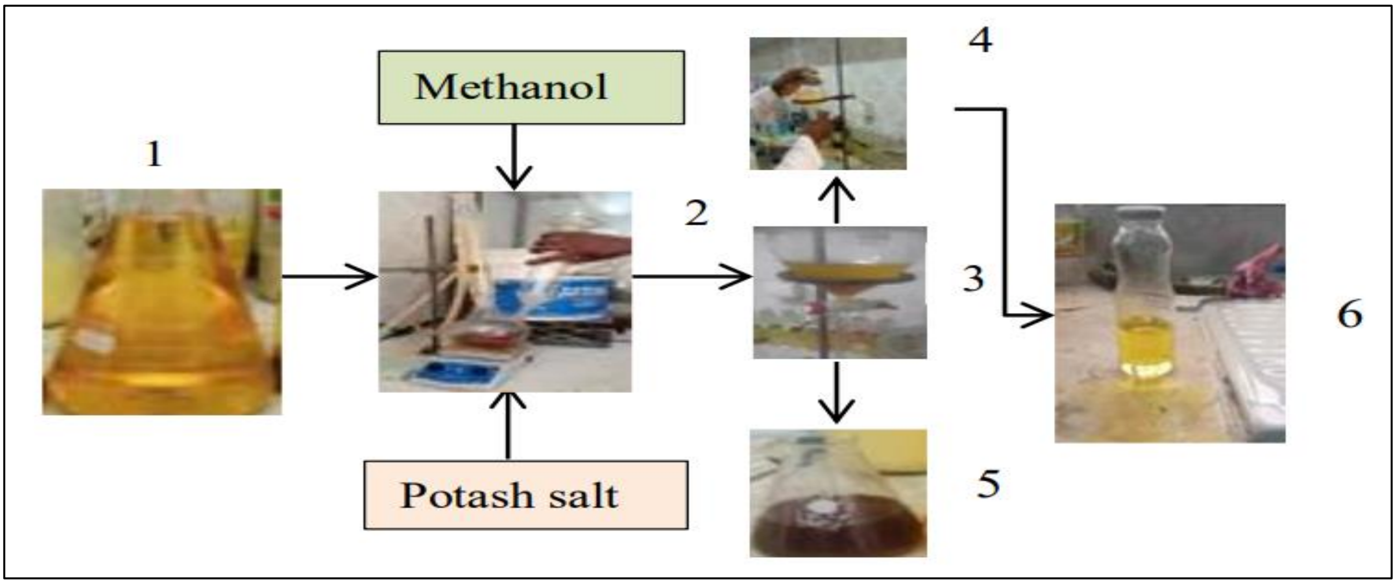

Fig 4 Biodiesel Production Protocol

1. Pretreated fat; 2. Transesterification; 3. Decantation and post-transesterification; 4. Biodiesel washing; 5. Glycerin; 6. Obtained methyl ester

The physicochemical properties of the produced biodiesel were evaluated. A fraction of the obtained biodiesel was used for gas chromatographic analysis to determine the molecular chains of the dominant esters.

➢ *Characterization of Beef Tallow and Biodiesel Produced*

Physicochemical analyses such as density, kinematic viscosity, saponification index, cetane number, acid number

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

and iodine number were performed according to ASTM D, EN and GB/T standards to determine the quality of the produced tallow and biodiesel. The densities of the produced tallow and biodiesel were analyzed according to EN14214 using a 25-mL pycnometer and a regulated thermo-capsule. The kinematic viscosities and saponification indexes of the tallow and biodiesel were analyzed according to ASTMD6751, using a UBBELOH type glass capillary viscometer and by titration. The acidity index and cetane values being characteristic of the fuels were carried out according to the method described in GB/T25199, corresponding to the titration. The iodine number was determined by the titration method, using the EN 14214 standard. The different atomic and molecular constituents of tallow, potash salt and biodiesel were evaluated.

III. RESULTS AND DISCUSSIONS

Analysis of the various inputs to the reaction provides results that determine the quality of the tallow and biodiesel produced.

➢ *Beef Tallow Extraction and Pretreatment Yield*

From 2.6 kg of fat, 2.1736 kg of beef tallow were extracted, giving a yield of 83.6% of tallow and a flour content of 16.4%. This high flour content can be attributed to the uncontrolled temperature during the extraction of fatty acids, as each fatty acid has a distinct melting point. In addition, tallow losses may occur during the filtration process of the extracted beef tallow. Application of the esterification method resulted in an estimated purity of 93% of beef tallow. It is advisable to perform the esterification of free fatty acids of fats before transesterification using acid catalysis (Awad, 2011).

➢ *Analysis of the Contents and Characterization of the Different Constituents of Potash Salts*

For 200 g of extracted ash, the amount of vegetable salt obtained from the controlled preparation is of the order of 5.3%, therefore sufficient to transform 800 g of beef tallow. The results of the vacuum filtration test of 1000 mg of concentrated ash show the concentration level of the different minerals obtained in (Table 2).

Table 2 Characterization of Sorghum Stalk Ash After Filtration

Ash constituents	Concentration (mg/l)	Rate (%)
Silicon (Si)	194	19.4
Potassium (K)	583	58.3
Calcium (Ca)	116	11.6
Sodium (Na)	92	9.2
Other traces	15	1.5

In this table, we see that the major elements are potassium, silicon and sodium. This allows us to say that the sorghum stalk ash appears to be potassium. However, its hydrolysis by simple vacuum filtration allows these minerals to be completely dissolved and ions to be released into solution. A pH value of approximately 10.7 suggests the basic nature of the various components present in the filtrate. And the boiling of the filtrate and the absorption of part of the water molecule allowed the formation of salt crystals consisting mainly of potassium hydroxide (KOH), calcium hydroxide Ca $(OH)_2$, calcium oxide (CaO) and sodium hydroxide (NaOH). It is thought that the potash salt could play a role in the alkalization of triglycerides in the process of converting tallow into biodiesel. This FTIR present in the (Fig 5) below will show the basic characteristics of the potash salt.

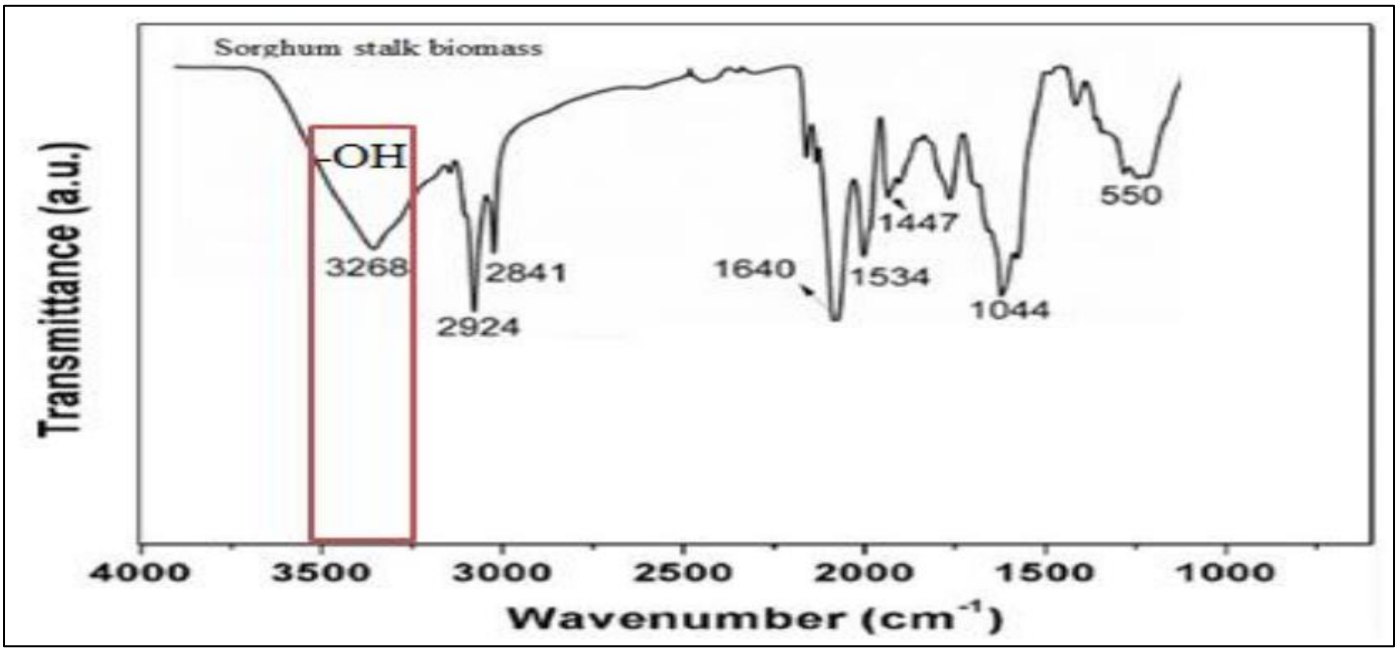

Fig 5 FTIR Analysis of Sorghum Stem Potash Salt

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

This (Fig 5) depicts the FTIR analysis result of potash salt. It shows many peaks, which indicates that the products from potash salt are complex organic compounds. Indeed, in the single bond region (2500-4000 cm-1), a broad absorption band between 3500 and 3250 cm^{-1} was observed in each case, indicating hydrogen bonds in the products. This confirms the presence of hydroxide groups (-OH), which can be bonded to calcium and potassium, forming very strong bases. However, the potash salt of sorghum stem as a whole can play the role of a basic catalyst that can act in the transesterification process.

- *Biodiesel Synthesis from Pretreated Beef Tallow: Biodiesel Optimization*

Experimental analysis of the experimental design gave different yields depending on the proportions of reagents used, as shown in (Table 3).

Table 3 Results of the Different Tests of the Experimental Design

Test	Center point	RM (x_1)	RC (x_2)	Time (x_3)	Yields y (%)
1	1	9 :1	2.00	30	93.71
2	0	6 :1	1.25	105	96.53
3	1	3 :1	2.00	30	93.30
4	1	6 :1	2.00	180	91.76
5	0	6 :1	1.25	105	96.40
6	1	9 :1	0.50	30	82.90
7	1	9 :1	0.50	180	83.47
8	1	3 :1	2.00	180	95.62
9	1	3 :1	0.50	30	76.24
10	1	3 :1	0.50	180	78.95

Other researchers have also attempted to propose operating conditions during transesterification and have obtained different yields confined in (Table 4).

Table 4 Operating Conditions During Transesterification of Fats

Fat	Catalysts	Alcohol / oil	Catalyst / Oil (%)	Time (min)	Yield (%)	References
Beef Tallow	NaOH	9:1	0.62	25	99.0	(Suwannapa & Tippayawong, 2017)
Eucalyptus oil	NaOH	61	0.2	60	95.0	(Tarabet, Hanchi, & Tazerout)
Beef Tallow	Cs_2O / Al_2O_3	10.5:1	5.3	120	95.5	(Zhao et al., 2013)
Chicken fat	CaO / $CuFe_{2-4}$	15:1	3	240	94.5	(Seffati, Honarvar, Esmaeili, & Esfandiari, 2019)
Goat tallow	H2SO4	31.88:1	59.93	150	96.7	(Chakraborty & Sahu, 2014)
Lard oil	KOH	6:1	1.25	40	96.2	(Ezekannagha, Ude, & Onukwuli, 2017)
Beef Tallow	CaO	16.39:1	5.42	202.8	95.94	(Onyeka S Okwundu, El-Shazly, Elkady, & Shaaban, 2019)
Beef Tallow	CaO	9:1	7.1	96	72	(Olubunmi, Alade, Ebhodaghe, & Oladapo, 2022)
Frying oil	NaOH	6:1	1.5	90	99.8	(Kellou & Mansour, 2016)
Zebu Bos Taurus Suet	NaOH	6:1	1.5	195	95	(Baribeau et al., 2007)

Compared with calcium oxide (CaO), a small proportion of potash salt converts more than 96% of beef tallow to biodiesel. According to (Table 3), an optimum yield of 96.53% of methyl ester was obtained for an alcohol/tallow ratio of 6:1, a biocatalyst ratio of 1.25%, and a reaction time of 105 minutes. This yield is similar to that of lard oil, which is estimated at 96.2%, as well as that of goat tallow. On the other hand, the conversion of beef tallow requires a significant amount of calcium oxide (CaO) and alcohol. The efficiency of potash salt in this process converges towards potassium and sodium hydroxide. This is because the proportions required in the reaction for these catalysts are equivalent. The different responses of biodiesel yields and the effects of the three factors in (Table 4) allow us to propose a mathematical model.

$$y(\%) = 65.471 + 1.5049x_1 + 13.367x_2 - 0.0370x_3 - 0.6471x_1x_2 - 0.001589x_1x_3 + 0.00300x_2x_3 + 0.001578x_1x_2x_3 \quad (14)$$

By analyzing the terms of (equation 14) and its linear correlations, we see that there is a positive sign in front of the amount of methanol and the catalyst. This observation shows that increasing one or the other could reduce the rate of free fatty acids and promote an increase in the yield of methyl ester. The negative sign of the reaction time shows that by

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

extending the reaction time, it would increase the yield of methyl ester but can also cause traces of water to appear during transesterification. A prolonged reaction time may facilitate the formation of soap during the transesterification process, an occurrence that is not readily noticeable during the procedure. Some authors, such as (Ghadge & Raheman, 2006) suggest eliminating water during the reaction in order to accelerate the reaction. This method seems useful to minimize the probability of saponification occurring during the reaction. The interaction effects between the reaction parameters are presented in **(**Fig 6, 7 and 8).

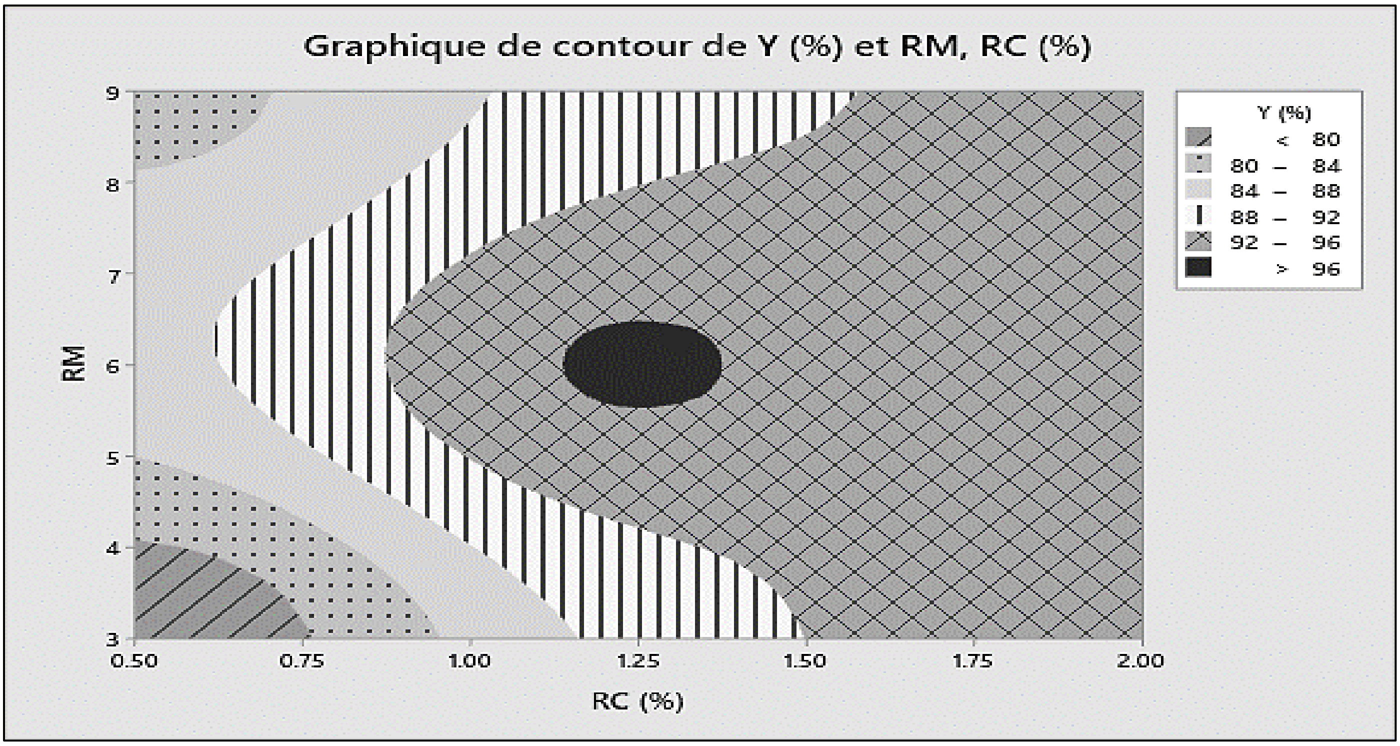

Fig 6 Contour Plot of Yield (%) as a Function of Oil/Alcohol Ratio (RM) and Catalyst Rate (CR) (%)

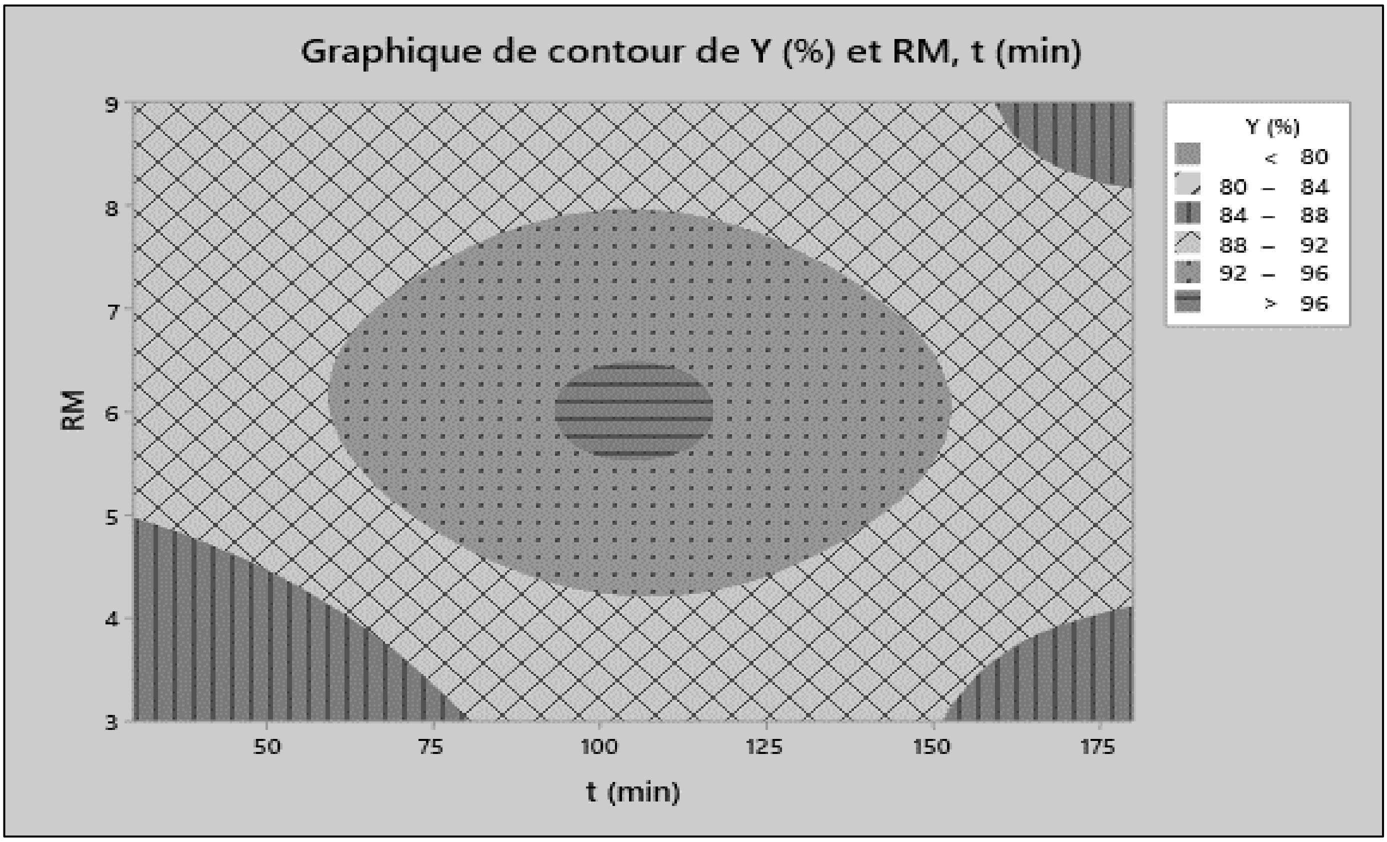

Fig 7 Contour Plot of Yield (%) as a Function of Oil/Alcohol Ratio and Time (min), RC = 1.5%

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

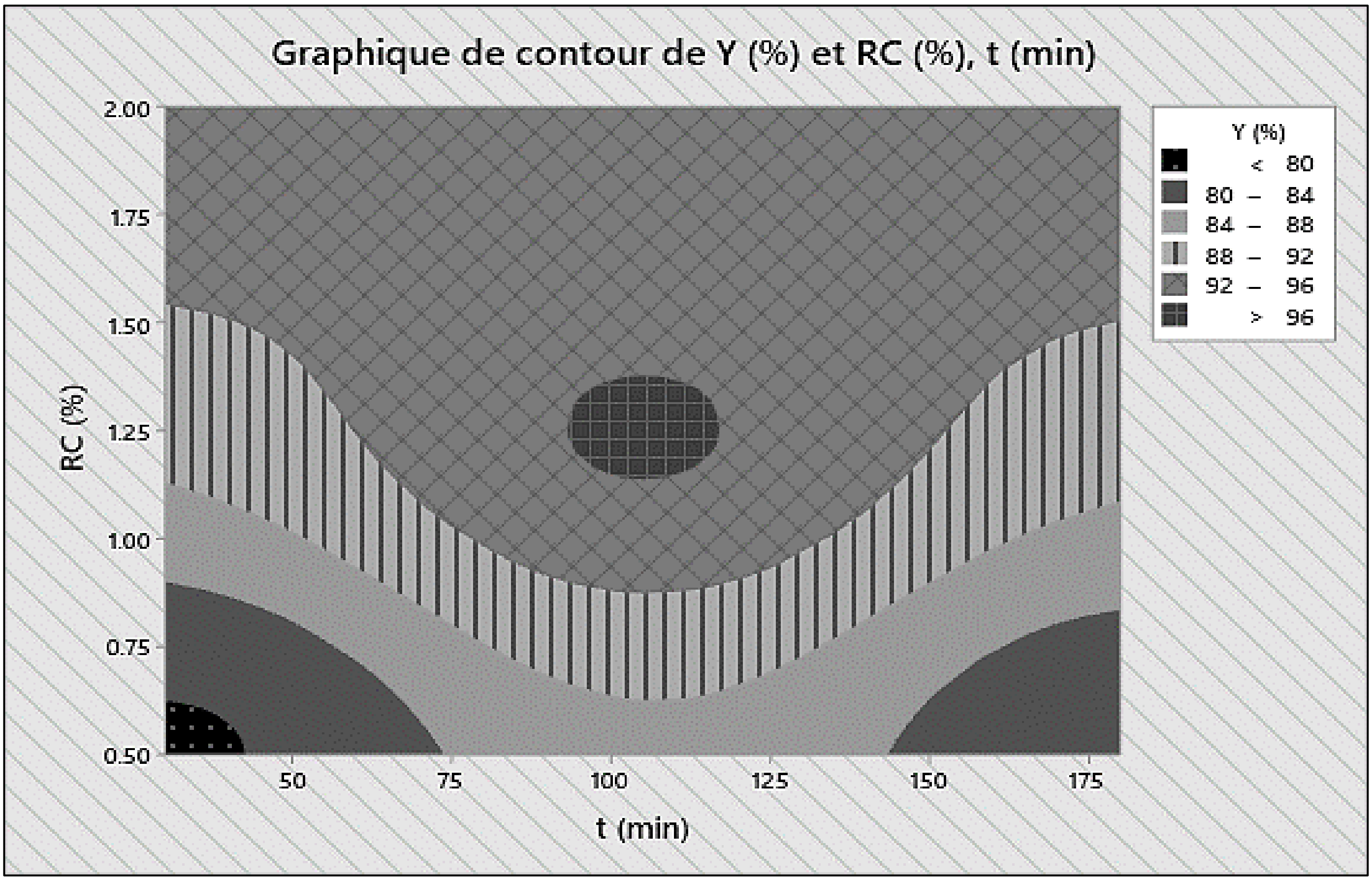

Fig 8 Contour Plot of Efficiency (%) as a Function of Catalyst Rate and Time (min), RM = 6:1

Analysis of these contours of each (Fig 6) shows that increasing one of the parameters decreases the effect of the other in the reaction. According to (Khiari, 2016; Richard, 2011), excess methanol and catalyst content makes it difficult to decant and wash biodiesel and decreases the yield of methyl ester. This effect is clearly visible in Figure 3 on small variations in the quantities of methanol. By fixing a horizontal line at the bottom of the graph, we see that the evolution of the yield of methyl ester is very rapid as a function of the increase in methanol. In (Fig7), the efficiency reaches its maximum of more than 96% for a reaction time that can vary between 93 and 117 minutes and a methanol/oil molar ratio of 5.5:1 to 6.4:1. Beyond these ranges of reagents used, a decrease in the yield of methyl ester is observed. One of the contours in (Fig 8) shows those 30 minutes are sufficient to obtain a biodiesel yield response of 92%. The produced biodiesel as well as the tallow were characterized and analyzed.

- *Characterization of the Physicochemical Parameters of Beef Tallow and Biodiesel Produced*

Several parameters of tallow and biodiesel were evaluated. (Table 5) presents a contrasting overview of the various outcomes derived from the analysis of these parameters.

Table 5 Performance Parameters of Beef Tallow and Biodiesel Produced

Physicochemical parameters	**Units**	**Beef Tallow**	**Biodiesel**	**Biodiesel Standards**
Density 40°C	Kg/m3	911.3	874	860-900 (EN14214)
Kinematic viscosity 40°C	mm2/s	7.2	5.45	1.9-6.0 (ASTMD6751)
Saponification index	mgKOH /g	191	149	180 (ASTM D6751)
Acidity index	mgKOH /g	5.3	0.15	<0.8 (GB/T25199)
Iodine index	g of iodine /100 g	73.92	58.3	117.32 max (EN 14214)
Cetane index	-	-	56.7	≥49 (GB/T25199)

It is noted that the density and viscosity of beef tallow are higher than those of regular biodiesel. They are an obstacle for the direct use of beef tallow as fuel in diesel engines (Bousbaa, Naima, & Liazid, 2014). At room temperature, beef tallow becomes denser and solidifies. At 40 °C, it is viscous and becomes less dense and less viscous. After conversion to methyl ester, the viscosity and density become compliant with biodiesel standards. These are parameters that vary depending on temperature. The (Fig 9) below allows the density of fuels to vary depending on temperature.

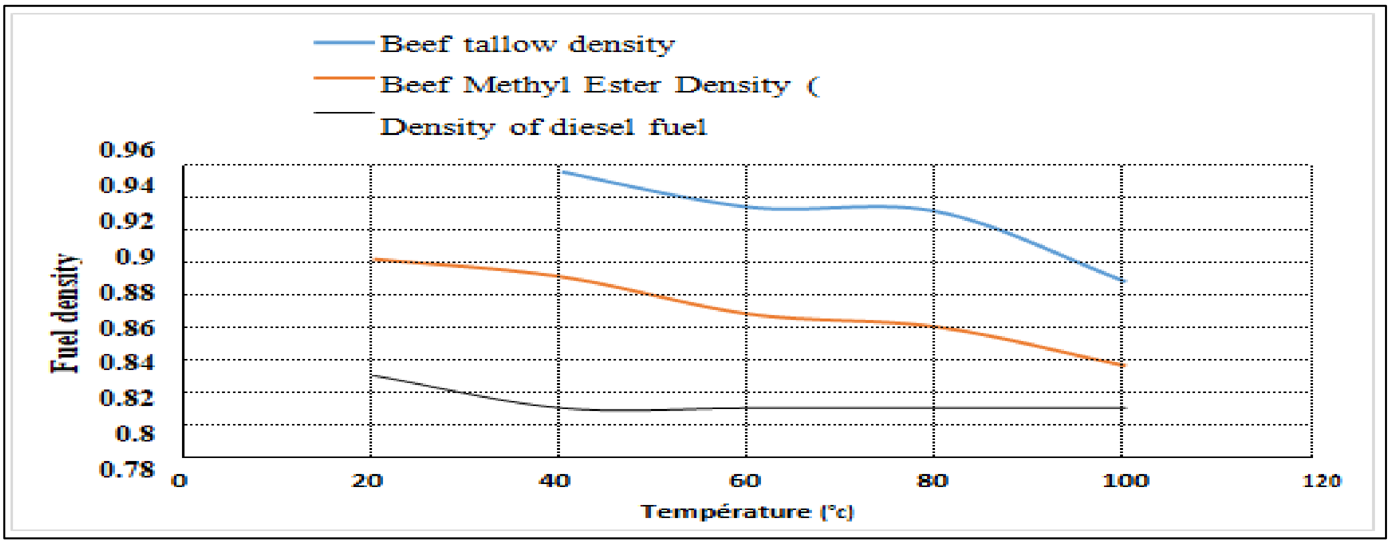

Fig 9 Evolution of the Density of the Fuel Based on the Temperature

The blue curve represents the variation in the density of tallow. This curve shows that between 20 and 30 °C, the fatty residue is indeed in a solid state. From 40°C, we observe a peak in the density of beef tallow of up to 0.946. And between 40 and 80 °C, we observe a rapid decrease in the density of tallow until reaching a value close to 0.878. On the other hand, the red curve represents the density of the methyl ester. In this curve we observe a slight variability in the density of the methyl ester, leaving from 0.892 to 0.826 for a temperature varying from 20 to 100 °C. Similarly, the black curve shows the different variations in the density of diesel. It appears that between 20 and 40 °C, the density of diesel varies slightly from 0.820 to 0.800. But from 40°C to 100°C, we notice that there is no variation in the density of diesel. Through these observations, we can say that the density of beef fat residue is higher than that of diesel, or relatively 1.15 times that of diesel for a temperature of 40 °C. It is also that of the methyl ester close to diesel, or 1.08 times that of diesel, and lower than the fat residue. According to (Normand & Treil, 1978), a density greater than 0.860 would risk engine malfunction, either from a lack of calories or from poor combustion.

This could promote the formation of smoke at full load, which results in an increase in average richness in the combustion chamber. By varying the temperature between 20 and 40 °C, a mathematical model can correct the density of the methyl ester produced.

$$d(T) = 0.89 - 0.00113(T - 40) \tag{15}$$

Viscosity, on the other hand, is a parameter that characterizes the flow of a fluid. Indeed, the less viscous the fluid, the easier it flows. It turns out that at a temperature of 40°C, the kinematic viscosity of beef tallow takes a value of 77 mm^2/s. The following (Fig 10) groups together the different results of the tests obtained.

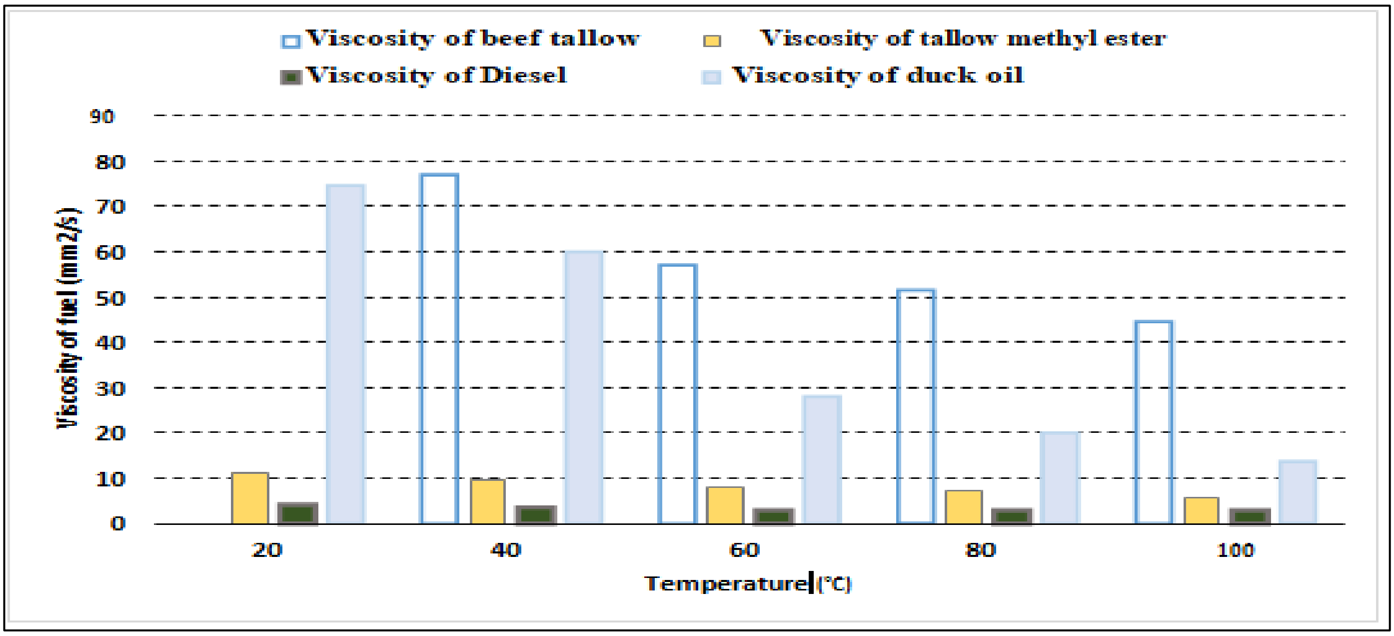

Fig 10 Variation of Fuel Viscosity in Relation to Temperature.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

In this histogram, we notice large differences between the different kinematic viscosities of tallow, methyl ester and diesel. It turns out that the difference between the viscosity of methyl ester and that of diesel is quite significant (9.7 and 3.5 mm^2/s at 40 °C), or relatively 3 times that of diesel. But as the temperature increases, the different viscosities of tallow and methyl ester gradually decrease to approach that of diesel, which beyond 40 °C its kinematic viscosity remains stable. According to (Normand & Treil, 1978), a fuel that is too viscous would increase the pressure losses in the pump and injectors, which would tend to reduce the injection pressure, deteriorate the atomization fineness, and finally affect the combustion process Conversely, insufficient viscosity could cause the injection pump to seize. So there is a middle ground to be observed, but the main thing is still to have fuel that sprays well. However, to promote the fluidity of the fuel and increase the injection rate into the engine, advanced fuel enthusiasts proceed by formulating methyl ester/diesel blend cuts and preheating the mixture.

Unlike beef tallow, the acidity number of beef tallow methyl ester is lower than the standard for biodiesel, which is expected. The high acidity could damage the copper elements in the engine (Bousbaa et al., 2014). The cetane number and iodine number of the produced methyl ester are higher than regular biodiesel, which seems logical. The high level of saturated fatty acids in beef tallow allows the methyl ester to have high cetane, iodine and cetane numbers. (Woo & Kim, 2019) reported that high levels of unsaturated fatty acids in tallow lead to significant cetane numbers of the produced ester after the conversion process. The work (Jambulingam et al., 2020) identified and quantified the specific components present in beef tallow, as shown in the (Fig 11) below.

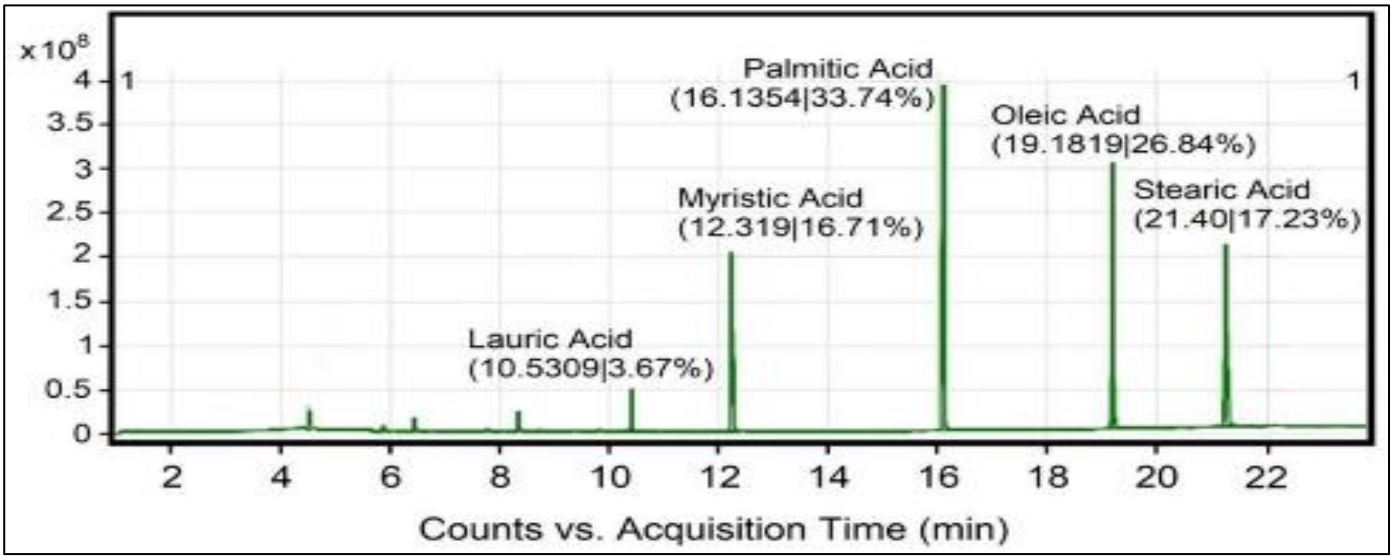

Fig 11 Structural and Typical Composition of Beef Tallow (Jambulingam et al., 2020)

According to these analyses, it appears that beef tallow fat has a predominance of saturated fatty acids consisting of 33.74% palmitic acid, 26.84% oleic acid, and 17.23% stearic acid. The profile of this result proves that palmitic, stearic and oleic acid methyl esters are also the dominant compounds. Chromatographic analysis reveals the structural composition of the beef tallow methyl ester produced.

Table 6 Structural and Typical Composition of Beef Tallow Methyl Ester

Methyl ester structures	Tallow Biodiesel (% Weight)
Methyl myristate (C15:0)	4.20
Methyl palmitate (C17:0)	18.46
Methyl stearate (C19:0)	11.37
Methyl oleate (C19:1)	19.65
Saturated acid ester	71.80

Chromatographic analysis reveals that these constituents are in the majority, with values of 18.46%, 11.37% and 19.65% respectively. The methyl ester of saturated fatty acids remains abundant. The study by (Jambulingam et al., 2020) showed that saturated fatty acid methyl ester remains above 71%. This compound can provide significant stability to the produced biodiesel. The results are consistent with those reported in (Suleiman et al., 2020). In this chromatographic analysis, this observation supports the purity of the biodiesel obtained following the washing and drying processes. (Awad, Paraschiv, Varuvel, & Tazerout, 2013) indicate that a glycerin content of 0.25% and a free fatty acid content of 0.02% in a methyl ester allow the generated biodiesel to exhibit characteristics comparable to those of petrodiesel.

➢ *Catalyst Reusability*

The extracted potash salt was soluble in methanol and throughout the reaction medium. As it is a homogeneous catalyst, it was difficult to separate it from the other

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

components of the mixture after reaction. In this study, the different phases of the mixture were separated, and the introduced potash salt was in both phases of the mixture after separation. Then, the potash salt was removed during washing of the biodiesel; therefore, it was difficult to recover the catalyst from the mixture and reuse it. It has even been demonstrated by other researchers that homogeneous catalysts make their reuse impossible after transesterification. Most of the recyclable catalysts are heterogeneous catalysts and nano catalysts. However, for the sorghum stem potash salt to have a reusability capacity, it must undergo activation into a nano catalyst before integrating it into the transesterification reaction medium. Several studies have proven that homogeneous natural catalysts activated into nanoparticles are likely to be reusable in several fatty acid transesterification cycles (Prajapati et al., 2023; Soares Dias, Ramos, Catarino, Puna, & Gomes, 2020). This is the case of (Chen et al., 2013) who activated the rice husk ash filtrate based on Li_2CO_3 into an enzymatic catalyst. The synthesized catalyst was reused several times in transesterification cycles.

IV. CONCLUSION

In this research, the focus was on exploring a method for creating an alternative biofuel derived from beef tallow, using potash salt obtained from calcined sorghum stalks as a catalyst. Experimental analysis of the biodiesel produced indicated that its chemical composition closely resembles that of conventional biodiesel, achieving an estimated production efficiency of 95.4%. The biodiesel obtained mainly comprises methyl oleate, methyl palmitate and methyl stearate, which are key components of a biodiesel-type fuel. In addition, the composition of the potash salt is comparable to that of potassium hydroxide salt. The methodology implemented has made it possible to propose a sustainable approach for converting Taurus hump residues into biodiesel. This process is possible and useful, but it is not the same. It would be useful if possible to carry out studies on its economic viability, starting with the minimization of the production cost. Although the cost of biodiesel mainly depends on the cost of raw materials used, recycling of recovered glycerol could adequately reduce the production cost. Further research could also be conducted on the technique of reusing potash salt in the transesterification process. The use of bioethanol instead of methanol would improve the sustainability of the process. Substitution of acid in the pretreatment process is highly recommended.

REFERENCES

[1]. Adrien, R. (2011). *Contexte, impacts et débats autour de la production d'agrocarburants versus le droit à l'alimentation.* Université de Sherbrooke.

[2]. Alloune, R. (2017). *Contribution à la mise au point d'un combustible innovant à base de culture locale non alimentaire pour les moteurs à combustion interne.* Université M'hamed Bougara de Boumerdès, Département de Méc.

[3]. Amal, R., Nadeem, R., Intisar, A., Rouf, H., Hussain, D., & Kousar, R. (2024). An insight into the catalytic properties and process optimization of Fe, Ni doped eggshell derived CaO for a green biodiesel synthesis from waste chicken fat. *Catalysis Communications, 187*, 106848 https://doi.org/10.1016/j.catcom.2024.106848.

[4]. Andreo-Martinez, P., Ortiz-Martinez, V. M., Salar-Garcia, M. J., Veiga-del-Bano, J. M., Chica, A., & Quesada-Medina, J. (2022). Waste animal fats as feedstock for biodiesel production using non-catalytic supercritical alcohol transesterification: A perspective by the PRISMA methodology. *Energy for Sustainable Development, 69*, 150-163. https://doi.org/10.1016/j.esd.2022.06.004.

[5]. Awad, S. (2011). *Contribution à l'étude de la valorisation énergétique des résidus graisseux et de leur combustion dans les moteurs à combustion interne| Theses. fr.* Nantes.

[6]. Awad, S., Paraschiv, M., Varuvel, E. G., & Tazerout, M. (2013). Optimization of biodiesel production from animal fat residue in wastewater using response surface methodology. *Bioresource technology, 129*, 315-320. https://doi.org/10.1016/j.biortech.2012.11.086.

[7]. Ayissi, Z., Mohand, T., Sary, A., Obounou, M., & Ohandja, L. A. (2016). Elaboration et Etude Expérimentale des Performances d'un Biocarburant Innovant à base de Deux Plantes non Comestibles Locales'. *Sciences, Technologies et Développement, Edition Spéciale*, 108-112.

[8]. Baribeau, A., Bradley, R., Brown, P., Goodwin, J., Kihm, U., Lotero, E., . . . Taylor, D. (2007). Biodiesel from specified risk material tallow: an appraisal of TSE risks and their reduction.

[9]. Bhuyan, N., Borah, M. J., Bora, N., Saikia, D., Deka, D., & Kataki, R. (2021). Heterogeneous Nanocatalytic Conversion of Waste to Biodiesel. *Nano-and Biocatalysts for Biodiesel Production*, 249-277. https://doi.org/10.1002/slct.202201671.

[10]. Blin, J., Villeneuve, P., Baréa, B., & Moussavou, R. W. (2016). Procédé écologique de production d'esters éthanoliques par transestérification éthanolique en catalyse enzymatique: OAPI. http://www.oapi.int/index.php/fr/brevets.

[11]. Bousbaa, H., Naima, K., & Liazid, A. (2014). Valorisation des déchets de poisson en biocombustible pour moteur diesel. *Le 3ème Séminaire International sur les Energies Nouvelles et Renouvelables*.

[12]. Chakraborty, R., & Sahu, H. (2014). Intensification of biodiesel production from waste goat tallow using infrared radiation: Process evaluation through response surface methodology and artificial neural network. *Applied energy, 114*, 827-836. https://doi.org/10.1016/j.apenergy.2013.04.025.

[13]. Chen, K.-T., Wang, J.-X., Dai, Y.-M., Wang, P.-H., Liou, C.-Y., Nien, C.-W., . . . Chen, C.-C. (2013). Rice husk ash as a catalyst precursor for biodiesel production. *Journal of the Taiwan Institute of Chemical Engineers, 44*(4), 622-629. https://doi.org/10.1016/j.jtice.2013.01.006.

[14]. Escobar, J. C., Lora, E. S., Venturini, O. J., Yáñez, E. E., Castillo, E. F., & Almazan, O. (2009). Biofuels: environment, technology and food security.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb1487

Renewable and sustainable energy reviews, 13(6-7), 1275-1287. https://doi.org/10.1016/j.rser.2008.08.014.

[15]. Ezekannagha, C. B., Ude, C. N., & Onukwuli, O. D. (2017). Optimization of the methanolysis of lard oil in the production of biodiesel with response surface methodology. *Egyptian Journal of Petroleum, 26*(4), 1001-1011. https://doi.org/10.1016/j.ejpe.2016.12.004.

[16]. Gebremariam, S. N., & Marchetti, J. M. (2018). Economics of biodiesel production. *Energy Conversion and Management, 168*, 74-84. https://doi.org/10.1016/j.enconman.2018.05.002.

[17]. Ghadge, S. V., & Raheman, H. (2006). Process optimization for biodiesel production from mahua (Madhuca indica) oil using response surface methodology. *Bioresource technology, 97*(3), 379-384. https://doi.org/10.1016/j.biortech.2005.03.014.

[18]. Hasan, N., & Ratnam, M. V. (2022). Biodiesel production from waste animal fat by transesterification using H2SO4 and KOH catalysts: A study of physiochemical properties. *International Journal of Chemical Engineering, 2022*(1), 6932320. https://doi.org/10.1155/2022/6932320.

[19]. Jambulingam, R., Srinivasan, G. R., Palani, S., Munir, M., Saeed, M., & Mohanam, A. (2020). Process optimization of biodiesel production from waste beef tallow using ethanol as co-solvent. *SN Applied Sciences, 2*, 1-18. https://doi.org/10.1007/s42452-020-03243-7.

[20]. Kellou, H., & Mansour, R. (2016). *Synthèse et caractérisation du biodiesel issu d'une huile de friture usagée.*

[21]. Khiari, K. (2016). *Contribution à l'étude des propriétés thermo-physiques des biocarburants de seconde génération et leur influence sur le comportement des moteurs.* Ecole des Mines de Nantes.

[22]. Ma, Y., Bi, Q., Li, G., Liu, X., Fu, G., Zhao, Y., & Wang, L. (2020). Provenance variations in kernel oil content, fatty acid profile and biodiesel properties of Xanthoceras sorbifolium Bunge in northern China. *Industrial crops and products, 151*, 112487. https://doi.org/10.1016/j.indcrop.2020.112487.

[23]. MRAD, N., ALOUI, F., TAZEROUT, M., & NASRALLAH, S. B. (2010). *Valorisation des graisses animales comme biocombustibles pour moteurs diesel.* Paper presented at the Proceedings Congress Société Française de Thermique.

[24]. Normand, X., & Treil, A. (1978). *L'Industrie du raffinage du pétrole: leçons sommaires* (Vol. 2): Editions Technip.

[25]. Okwundu, O. S., El-Shazly, A. H., & Elkady, M. (2019). Comparative effect of reaction time on biodiesel production from low free fatty acid beef tallow: a definition of product yield. *SN Applied Sciences, 1*, 1-12. https://doi.org/10.1007/s42452-018-0145-1.

[26]. Okwundu, O. S., El-Shazly, A. H., Elkady, M. F., & Shaaban, W. M. (2019). *Response surface modeling and optimization of heterogeneous methanolysis of beef tallow.* Paper presented at the AIP Conference Proceedings. https://doi.org/10.1063/1.5116930.

[27]. Olubunmi, B. E., Alade, A. F., Ebhodaghe, S. O., & Oladapo, O. T. (2022). Optimization and kinetic study of biodiesel production from beef tallow using calcium oxide as a heterogeneous and recyclable catalyst. *Energy Conversion and Management: X, 14*, 100221. https://doi.org/10.1016/j.ecmx.2022.100221.

[28]. OUEDRAOGO, N., SAWADOGO, N., NIKIEMA, M. P., KOURAOGO, I., SAWADOGO, A. P., & NEBIE, B. (2023). Performance agronomique et mise en évidence de la distinction inter-variétale, de l'homogénéité et de la stabilité intra-variétale de sept variétés de sorgho au Burkina Faso. *Sciences Naturelles et Appliquées, 42*(2 (1)), 89-106.

[29]. Perrin-Guyomard, A., Bruneau, M., Mourand, G., Kempf, I., Cuzzucoli, D., & Granier, S. (2022). Dispositif français de surveillance de la résistance aux antibiotiques des bactéries zoonotiques et commensales isolées chez les animaux d'élevage et dans les denrées alimentaires d'origine animale. *Bulletin épidémiologique, 96*(3), 1-12.

[30]. Prajapati, P., Shrivastava, S., Sharma, V., Srivastava, P., Shankhwar, V., Sharma, A., . . . Agarwal, D. (2023). Karanja seed shell ash: A sustainable green heterogeneous catalyst for biodiesel production. *Results in Engineering, 18*, 101063. https://doi.org/10.1016/j.rineng.2023.101063.

[31]. Rabo, Y., Sadikou, I. B. M., & Mahamane, A. (2024). Effets de Faidherbia albida (Delile) sur des Paramètres de Croissance et de Rendement du Mil (Pennisetum glaucum (L.) R. Br) en Milieu Paysan dans la Commune de Tibiri (Niger). *ESI Preprints, 20*(6).

[32]. Rapport, I. Les biocarburants et la faim dans le monde. www.i-sis.org.uk/biofuelsAndWorldHunger.php.

[33]. Richard, R. (2011). *Transestérification éthanolique d'huile végétale dans des microréacteurs: transposition du batch au continu.*

[34]. Saravanan, R., Sathish, T., Ağbulut, Ü., Sathyamurthy, R., Sharma, P., Linul, E., & Asif, M. (2024). Waste bull bone based reusable and biodegradable heterogeneous catalyst for alternate fuel production from WCO, and investigation of its usability as fuel substitute. *Fuel, 355*, 129436. https://doi.org/10.1016/j.fuel.2023.129436.

[35]. Seffati, K., Honarvar, B., Esmaeili, H., & Esfandiari, N. (2019). Enhanced biodiesel production from chicken fat using CaO/CuFe2O4 nanocatalyst and its combination with diesel to improve fuel properties. *Fuel, 235*, 1238-1244. https://doi.org/10.1016/j.fuel.2018.08.118.

[36]. Serge, R. K., Armand, A. B., Richard, T., Augustin, G., & Albert, N. (2023). Physicochemical Properties and Fertility Level of the Vertisols Surface Horizons for muskuwaari [Sorghum bicolor (L.) Moench] Cultivation in the Sudano-Sahelian zone of Cameroon. *Journal of Agriculture and Ecology Research International, 24*(5), 142-161.

[37]. Sharma, K., Castello, D., Haider, M. S., Pedersen, T. H., & Rosendahl, L. A. (2021). Continuous co-processing of HTL bio-oil with renewable feed for

drop-in biofuels production for sustainable refinery processes. *Fuel, 306*, 121579. https://doi.org/10.1016/j.fuel.2021.121579.

[38]. Soares Dias, A. P., Ramos, M., Catarino, M., Puna, J., & Gomes, J. (2020). Solvent assisted biodiesel production by co-processing beef tallow and soybean oil over calcium catalysts. *Waste and Biomass Valorization, 11*, 6249-6259. https://doi.org/10.1007/s12649-019-00903-7.

[39]. Suleiman, I. A., Abubakar, S., Kaisan, M. U., Magaji, S., Abubakar, A. S., Shitu, S., . . . Umaru, S. (2020). Production and performance appraisal of biodiesel derived from used cooking oil on compression ignition engine. *FUDMA Journal of Sciences, 4*(2), 658-672. https://doi.org/10.33003/fjs-2020-0402-240.

[40]. Suwannapa, P., & Tippayawong, N. (2017). Optimization of two-step biodiesel production from beef tallow with microwave heating. *Chemical Engineering Communications, 204*(5), 618-624. https://doi.org/10.1080/00986445.2017.1294585.

[41]. Tarabet, L., Hanchi, S., & Tazerout, M. Conversion d'une l'Huile Végétale en Carburant pour le Moteur Diesel.

[42]. Toldrá-Reig, F., Mora, L., & Toldrá, F. (2020). Trends in biodiesel production from animal fat waste. *Applied Sciences, 10*(10), 3644. https://doi.org/10.3390/app10103644.

[43]. Verma, P., & Sharma, M. (2016). Comparative analysis of effect of methanol and ethanol on Karanja biodiesel production and its optimisation. *Fuel, 180*, 164-174. https://doi.org/10.1016/j.fuel.2016.04.035.

[44]. Woo, D. G., & Kim, T. H. (2019). Fuel properties of biodiesel produced from beef-tallow and corn oil blends based on the variation in the fatty acid methyl ester composition. *Korean Journal of Agricultural Science, 46*(4), 941-953. https://doi.org/10.7744/kjoas.20190076.

[45]. Zhao, X., Xu, G., Yu, Y., Yan, X., & Zhang, B. (2013). Optimization of transesterification of beef tallow for biodiesel production catalyzed by solid catalysts. *Transactions of the Chinese Society of Agricultural Engineering, 29*(17), 196-203.