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Assessment of Waste Animal Fats (WAFS) Biodiesel Production Potential as an Alternative Fuel for Zambia: A Case Study of Southern Province

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ABSTRACT: The volatility in global fuel prices and the desire to reduce energy dependency on fossil fuels has necessitated the speeding up of alternative energy supply sources. Further, the global urgent need to reduce the accumulation of CO_2 and green house gas (GHG) emissions as a result of fossil fuels use and the mandate by united nations to move towards sustainably produced energy for the transport sector, industry and power generation demands that we seek energy solutions that meet reduced negative impact on the environmental.

It is in this regard that this study seeks alternatives in waste animal fats (WAFs) biodiesel as an option could meet the demand for fuel in the transport sector, industry and communities and where practical for power generation. For the transport sector and power generation , the biodiesel maybe blended with the fossil diesel in the approved ratios as stipulated by the Energy Regulation Board and the Zambia Bureau of Standards.

This study focuses on the biodiesel production potential based on the modified two-step process. The two step process involve passing the feedstock through **esterification** with sulphuric acid as catalyst in the presence of methanol and there after base catalysed using sodium hydroxide in methanol in a process referred to as **transesterification.** The resulting products in the **esterification** process are the **esters and water** whilst in the **transesterification** are the **biodiesel and glycerol**.

The feedstock used are those of waste animal fats (WAFs) of cattle, pig and chicken that has been discarded from meat processing and animal slaughter houses. The feedstocks have been carefully selected based on the animals raised in the country with a bigger slaughtered population as well as reared. The population of animals reared and slaughtered annually are obtained from the Zambia Ministry of Agriculture animal population census records. Based on these records, the preferred feedstock sources where obtained.

The study further ;

1. explores the economic potential of the biodiesel production for the Zambian government and beyond.
2. compares some of the characteristics of WAF biodiesel to that of imported fossil diesel
3. affirms that WAF biodiesel has a very good impact in reducing environmental pollution as it is non-toxic and bio-degradable.

This study will help the country move closer to an effective sustainable development as required by the united nations sustainability goals should the full scale production get implemented in Zambia.

KEY WORDS: biodiesel, waste animal fats, sustainability, esterification, transesterification

1.0 INTRODUCTION

Zambia largely imports fossil fuels to meet its energy needs for its industry, transport and communities. This dependency has seen its forex demand increase year in and year out. In the process, putting a huge strain on its economic performance as a direct result of the ever increasing global fossil diesel prices. In the transport sector, an increase in the global fuel prices translates into increased transportation costs for food and commodities. This in turn leads to a spike in food prices. To help mitigate this trend, Zambia, needs to look for alternatives in its national energy sources in the likes of waste animal fats - (WAFs) biodiesel. This WAFs biodiesel will not only address the huge forex demand for the purchase of fossil diesel, it will also add jobs into the economy and most importantly contribute positively to the environment, sustainability and governance which the imported fossil diesel negates to a large extent. Further, the WAF biodiesel has better emission characteristics during combustion, non toxic and does not pollute the environment. The WAFs feedstock used does not compete with food for human consumption. These characteristics make WAFs biodiesel attractive for consideration as an alternative energy source.

1.1 What is biodiesel

Biodiesel is a fatty acid alkyl ester which is produced by transesterifying triglycerides in oil or fat with organic solvent such as methanol, ethanol, butanol and even pentanol in the presence of homogeneous or heterogeneous catalyst under optimum temperature and time. The sources for triglycerides are plant oils and saturated animal fats,

having different compositions of fatty acids, either bonded with other glyceride molecules as triglycerides or as independent Free Fatty Acids (FFA). This bio-degradable fuel is non-toxic with zero effect on environment and has very low level of CO, SO, hydrocarbon emissions. It has unique characteristics like high oxygen content, high cetane number and zero sulphur content. These properties make this WAFs biodiesel sustainable and renewable, thus enabling it to be used for combustion and energy based applications.

1.2 Chemistry of animal fat

The fat primarily consists of (i) Triglycerides, (ii) Phospholipids and (iii) Sterols. The triglyceride molecule compromises of three fatty acids molecules connected with a common glyceride spine having substantial amount of oxygen infused in its structure and these fatty acids reacts with alcohol during transesterification reaction to produce Fatty Acid Alkyl Ester (biodiesel). The difference between fat and oil is based upon the saturation and its degree in the carbon chain. Oil exists in liquid phase because of unsaturated fatty acids (mono-unsaturated, polyunsaturated) whereas animal fats like suet, tallow and lard exist in solid state because of saturated fatty acids. The variation in fatty acids is based upon the number of carbon in the chain, degree and number of saturation in it. The phospholipids can be removed by degumming the fats using orthophosphoric acid (in case of acid degumming) or with water (in case of water degumming) . Most commonly used waste animal fats for biodiesel production are pork lard, beef tallow, chicken fat and animal fat mix. (Gokul Raghavendra Srinivasan et al 2018 - Comprehensive Study on Biodiesel Produced from Waste Animal Fats - A Review)

2.0 BIODIESEL SYNTHESIS METHODOLOGY

These are the widely four known techniques for the biodiesel synthesis .

a) **Enzymatic methods**: Requires use of enzymes in the biodiesel production and seems to be less affected by water. This method is not used on large commercial scale due to inhibiting cost of the enzymes.

b) **Glycerolysis**: In this technique, glycerol is added to the feedstock and heated to high temperature (200^{o} C), usually with a catalyst such as zinc chloride. The glycerol reacts with the Free Fat Acids (FFAs) to form mono- and diglycerides. This produces a low FFA feedstock that can be processed using traditional alkali-catalyzed means.
The disadvantage of glycerolysis is the high temperature and that the reaction is relatively slow. An advantage though, is that no methanol is added during the pre-treatment so that as water is formed by the reaction FFA + glycerol monoglyceride + water, the water immediately vaporizes and can be vented from the mixture.

c) **Acid catalysis**: This technique uses a strong acid, such as sulphuric acid, to catalyze the esterification of the FFAs and the transesterification of the tri-glycerides. The reaction does not produce soaps because no alkali metals are present. The esterification reaction of the FFAs to alcohol esters is relatively fast, proceeding substantially to completion in 1 h at 60 ^{o} C. However, the transesterification of the triglycerides is very slow, taking several days to complete. Heating to 130 ^{o} C can greatly accelerate the reaction, but reaction times will still be 30 - 45 min. Another problem with acid catalysis is that the water production from the following reaction FFA + methanol methyl ester + water stays in the reaction mixture and ultimately stops the reaction, usually well before reaching completion.

d) **Acid catalysis followed by alkali catalysis**: This approach solves the reaction rate problem by using each technique to accomplish the process for which it is best suited. Since acid catalysis is relatively fast for converting the FFAs to methyl esters, it is used as a pretreatment for the high FFA feedstocks. Then, when the FFA level has been reduced to 0.5% or lower, an alkali catalyst is added to convert the triglycerides to methyl esters. This process can convert high FFA feedstocks quickly and effectively. Water formation is still a problem during the pretreatment phase. One approach is to simply add so much excess methanol during the pretreatment that the water produced is diluted to the level where it does not limit the reaction. Then the acid-catalyzed reaction mixture is allowed to settle.. After a few hours, a methanol-water mixture will rise to the top and can be removed. This way, the process becomes less energy-intensive.

2.1 The modified two step process

In this study, the modified two step process, **option 4** for the synthesis of the biodiesel was adopted. The waste animal-derived fats are first cleaned of the excess protein and bone remnants and then sliced into fine pieces. These pieces are loaded into the 1000 ml beaker and measured. The loaded beaker of WAFs is transferred onto a magnetic hot plate stirrer and heated until the fats are melted to liquid oil. The resulting oil is decanted into a flask, weighed first without contents and weighed again with oil. Hereafter, transferred into an oven at 105 degrees to avoid the oil going back into solid state and at the same time rid the oil of any excess moisture. **Note**: The weights of the empty beaker and flask are measured to help determine the amount of the fats used and later the amount of the oil used in the **esterification**

and transesterification part of the production process. These measured weights will later be used to determine the percentage yield of the oil and biodiesel.

The products of the **esterification** are decanted by gravity, fig 2a - step 5 and taken into the **transesterification** to produce the biodiesel fig 2a - step 6.

2.2 Biodiesel synthesis using the modified two step process set up

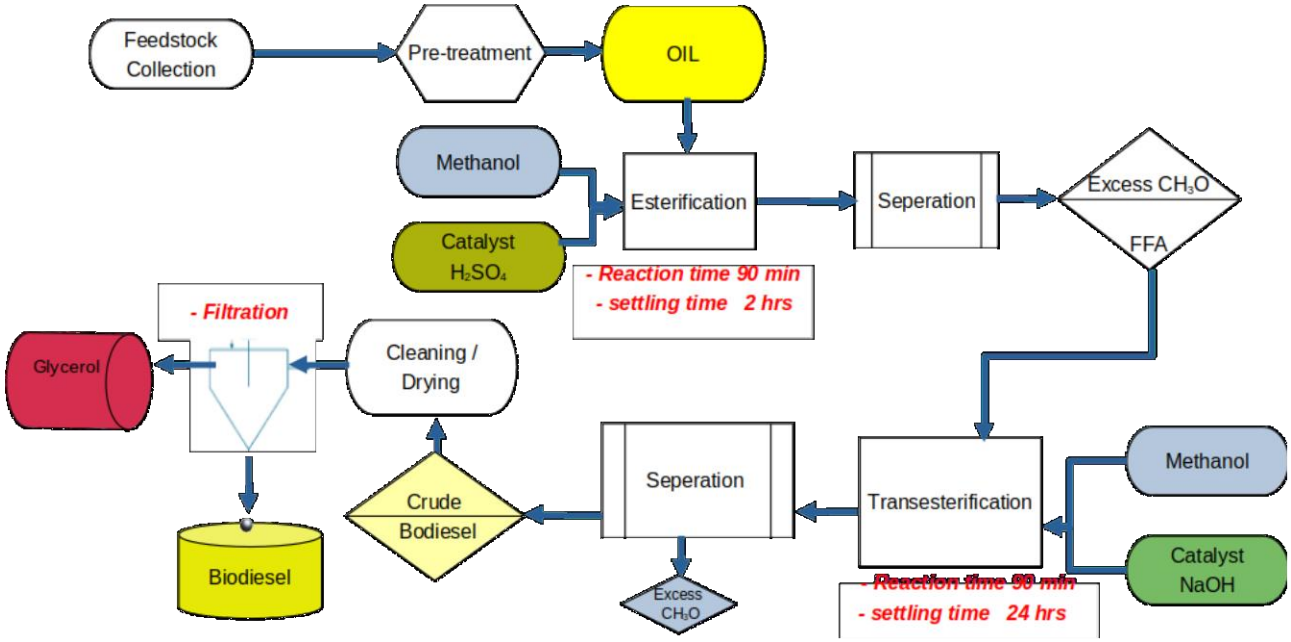


Fig 2.2 The **modified two- step production of biodiesel** in which free fat acids (FFA) are taken through **transesterification**

2.3 Biodiesel synthesis using the modified two step process pictorial set up

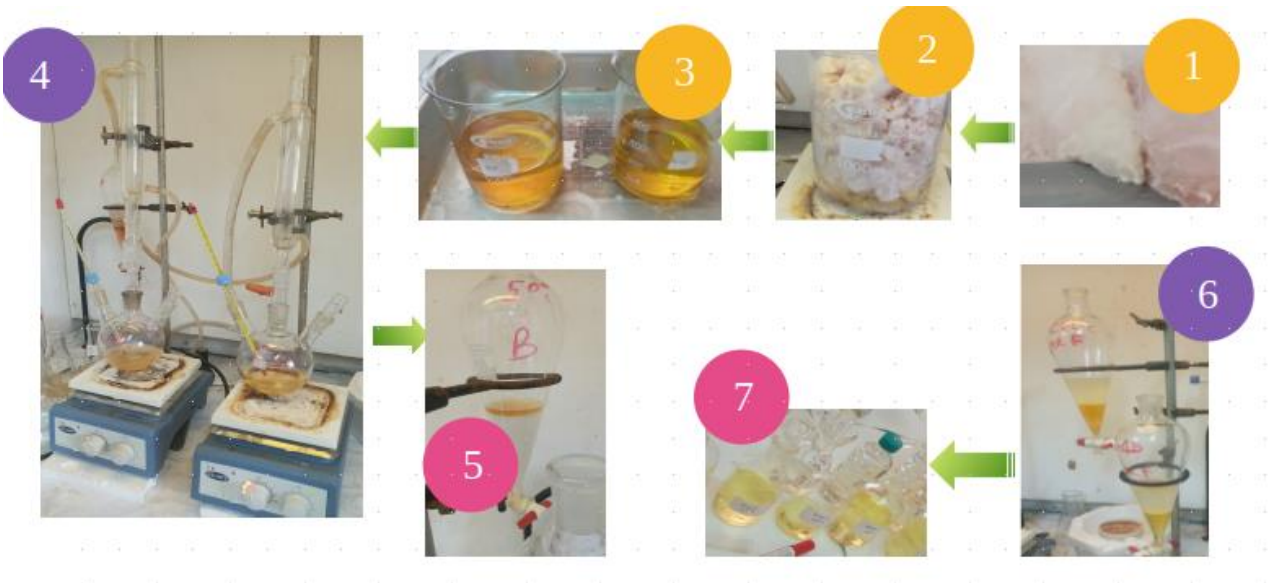


Fig 2.3 The modified two - step biodiesel production in pictures

The oil derived from the melted animal fats is taken through **esterification** in **step 4** using H_2SO_4 as a catalyst in methanol-mixture to produce the free fat acids (FFA). This procedure is repeated using NaOH as catalysts in methanol

mixture with the obtained FFA to produce biodiesel and glycerol in a process called **transesterification**

Step 5, Free Fat acids (FFA) – bottom layer and excess methanol in top layer

Step 6, Biodiesel & glycerol - top layer and excess methanol in bottom layer

2.4 Materials and sequencing in biodiesel synthesis using the modified two step process

Below are the materials used in the synthesis of biodiesel

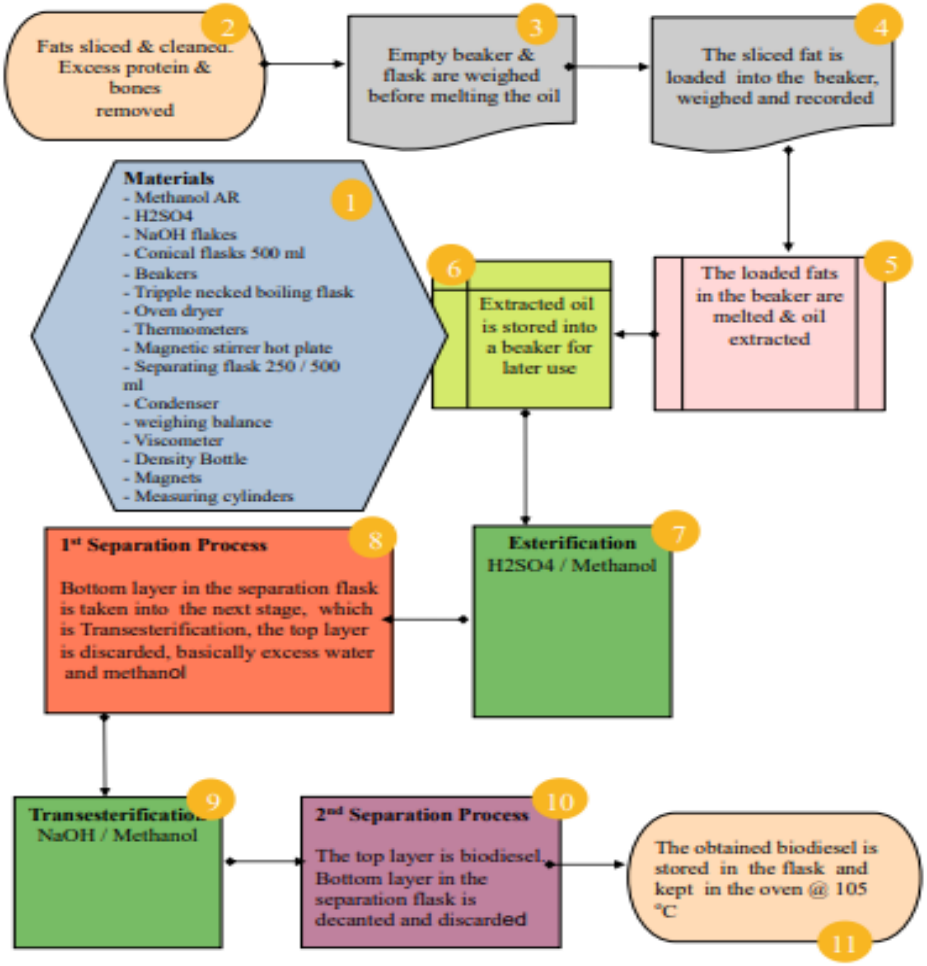


Fig 2.4 Biodiesel synthesis sequence using the two step process

2.4 The modified two step -process detailed description

2.4.1 **Esterification**

The **first step,** being the **esterification**, which is the reduction of high saturated free fat acids to less than 1% free fat acid (FFA) . This reduction is required for a better biodiesel yield and to avoid catalyst consumption in soap formation (Bouaid, Boulifi, Martinez & Aracil - 2012) . In this step, A quantity of extracted oil is measured and poured into the reaction vessel. The oil had been pre-heated to 105 ^{0}C to remove moisture and volatile impurities. Then set temperatures from 45, 50, 55, 60 ^{0}C are chosen and 1.0 % vol/vol H_2SO_4 catalyst will be mixed with methanol (mole ratio of oil to methanol of 1:5) and stirred for 5 minutes and then the mixture will be added to the heated oil maintained at the desired temperature from the ranges given above, and the reaction will be continued for **90 minutes** by continuously stirring, using magnetic stirrer hot plate (Bouaid et al., 2012; Sabarish et al., 2016). Finally,the esterified oil will be transferred into a separating funnel for separating the excess methanol and allowed to settle for 2 hours, which is step 5 in fig.2a.

The acid **esterification** (H_2SO_4) as catalyst

$$RCOOH + CH_3OH \longrightarrow RCOOCH_3 + H_2O$$

2.4.2 **Transesterification**

The second step, **transesterification-** a most commercially used method for biodiesel synthesis was adopted. The process takes place by first mixing the alcohol with catalyst (NaOH). The alcohol/catalyst mixture, sodium methoxide is then mixed with the FFA obtained during the esterification

process. The the FFA are poured into the reaction vessel with the magnetic stirrer activated and reacted for 90 minutes in the presence of the alcohol/catalyst mixture at varying temperature ranges for each batch starting from 45, 50 , 55 and 60 degrees. The reaction takes place at atmospheric pressure and stirred continuously at suitable speed on the Stuart magnetic hot plate stirrer. At the end of the 90 minutes, the contents in the reaction vessel are poured into the separation flask and allowed to settle for 24 hours, step 7 in Fig 2a.

In this process, triglycerides (TG) and/or free fatty acids (FFAs) are converted into esters using an organic solvent, generally short-chain alcohols. The sources for these lipids include both edible and non-edible oils, discarded and recycled greases, **animal fats**, and edible oil wastes, presenting different fatty acid composition profiles (Ait Belale et al., 2021; Ishak & Kamari, 2019; Rezania et al., 2021; Sharma et al., 2021; Singh et al., 2020).

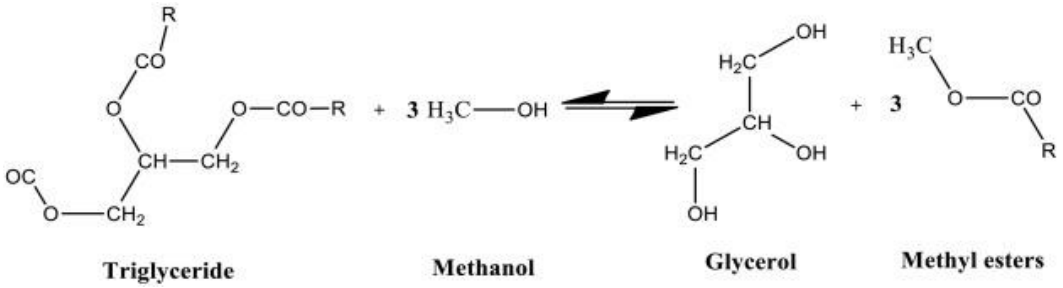


Fig 2.4.2 Transesterification of triglycerides (TG) in methanol into biodiesel.

Methanol or ethanol are usually used as alcohol reactants to produce biodiesel from vegetable oils and animal fats (Verma & Sharma, 2016). Methanol is more frequently used in comparison to ethanol because of its availability and lower cost. Other short-chain alcohols such as isopropanol can be employed as an alternative (Huang et al., 2015; Redel-Macías et al., 2021)

The **transesterification** reaction is influenced by **several variables** which include reaction temperature, reaction time, alcohol-to-oil ratio, type and amount of catalyst, and feedstock composition (Banerjee et al., 2018; Vinoth Arul Raj et al., 2021).

The produced biodiesel from the transesterification process is further cleaned by removing excess soaps as much as practical. The removal of these soaps is by adding warm distilled water. The obtained biodiesel, top layer in a separating funnel, step 7 in fig. 2 is separated from the excess methanol and water then decanted into a beaker. The obtained biodiesel is placed in an oven for one hour at 105 degrees to help remove as much moisture as practical. Once the biodiesel has been ridden of the water, a filter paper is used to remove the glycerol remnants. This way, the quality of the produced biodiesel is enhanced and the shelf life is improved.

3.0 POST - SYNTHESIS OF BIODIESEL

The biodiesel once produced is further purified by doing the following;

a) If a mixture of glycerol is observed in the decanted biodiesel from the separation flask, it is recommended to use a filter paper to clean it up. This is achieved by first putting the biodiesel in an oven for desirable period at 105 ^{o} C to ensure the excess water is removed and whilst hot enough, poured onto a filter paper to trap any glycerol.
If the biodiesel obtained shows signs of clouding, especially that produced from cow fat, it could imply presence of the soaps in the product. In this case it is recommended that one uses warm distilled water to wash it off. The process of washing is repeated several times until a clean and clear biodiesel is observed. After which the obtaining biodiesel is taken into an oven at 105 ^{0} C to rid it of excess water.

b) The biodiesel once cleaned should be stored in a cool dry well secured packaging away from direct sunlight to avoid photo degradation.

c) If the biodiesel is in mass production, any accumulation of moisture in the storage vessel should be monitored and frequently removed to help maintain a reasonable shelf life of the biodiesel.

4.0 EXPERIMENTAL METHODOLOGY IN PICTURES

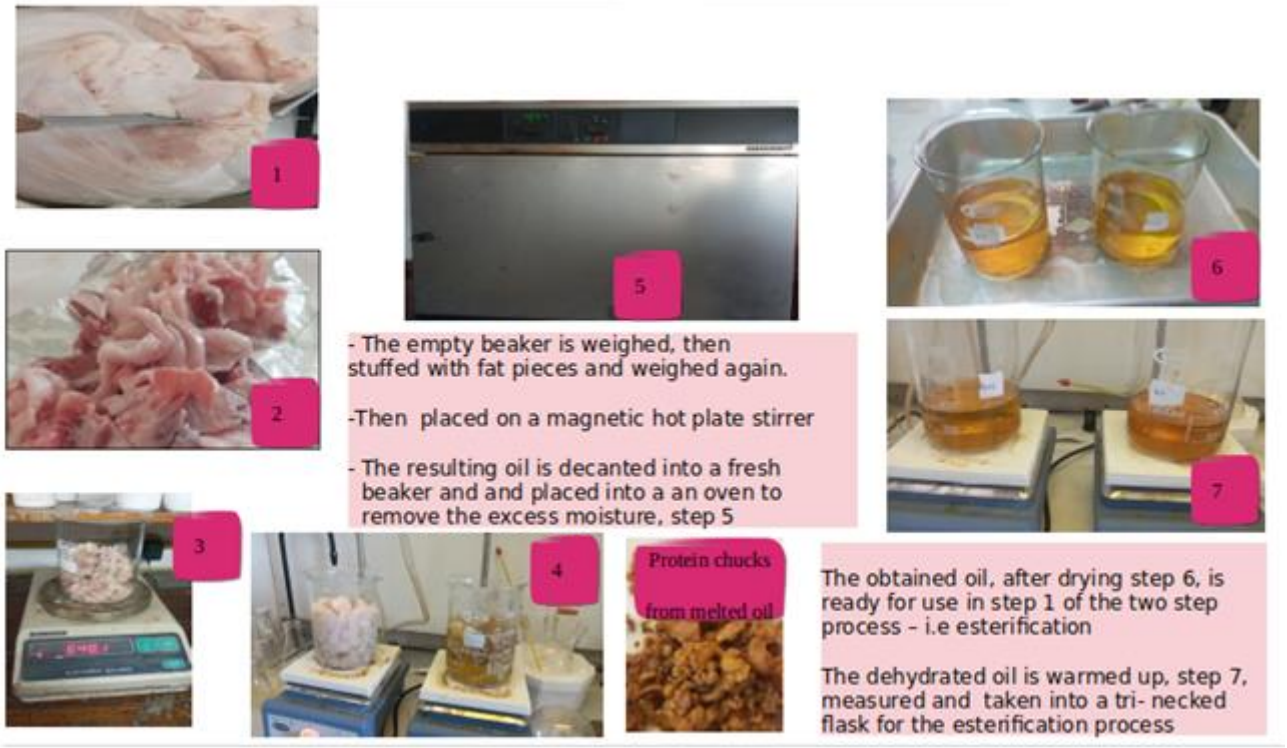


Fig 4a Feedstock and oil generation

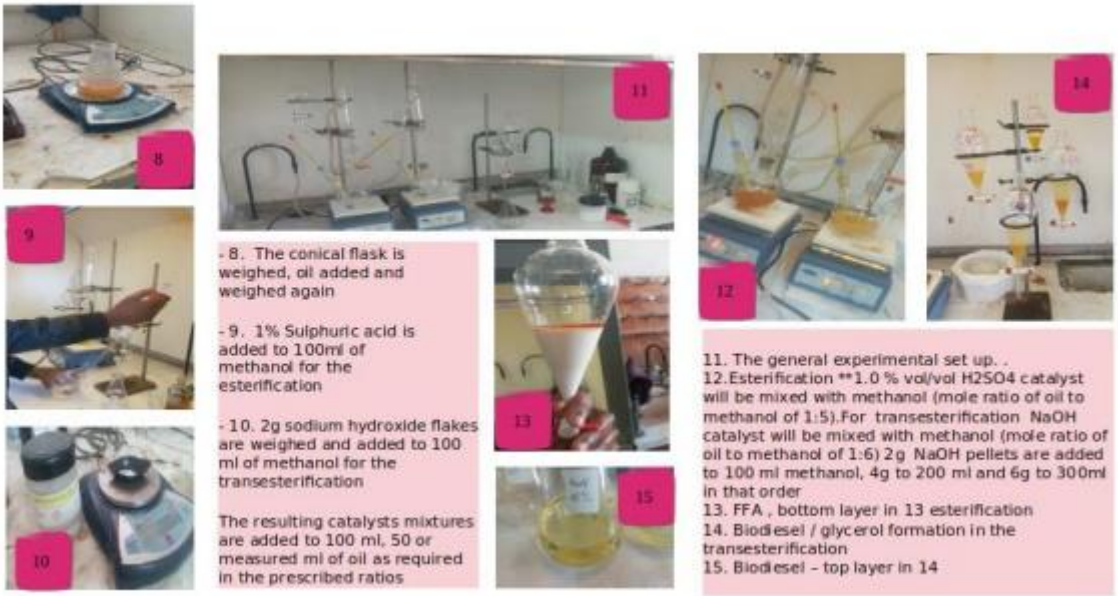


Fig 4 b Experimental layout

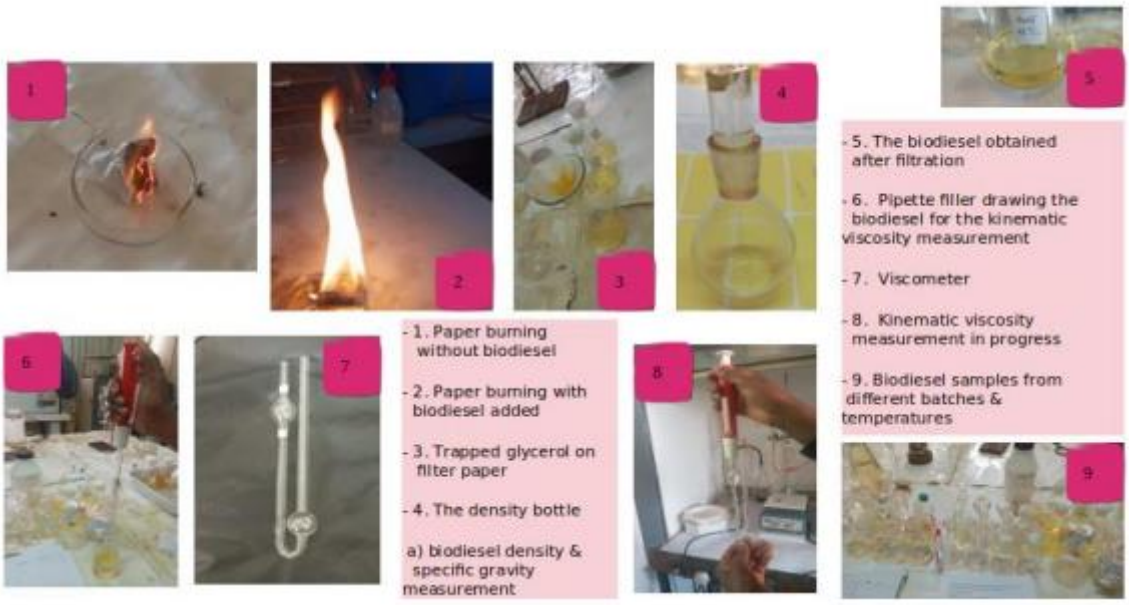


Fig 4c Characterisation of the produced biodiesel in pictures

5.0 OIL GENERATION FROM WAFs

Fig 4a Oil extraction from fat

The fat is sliced, with bone remnants taken out. The resulting fine pieces of fat are then stuffed into a beaker of 1000ml. The weights of the beaker before and after loading the fats in, is taken and recorded for use in the calculation of percentage oil and biodiesel yields.

The beaker loaded with the fat is then placed onto the Stuart magnetic hot plate stirrer and heated until the solid mass of fat breaks down into liquid and all available oil is let free. The remaining chunks of protein, which are brown fried pieces are allowed to be separated from the oil by decanting into a fresh beaker or conical flask. The obtained oil is weighed and the result is recorded. Its critical that the vessel used to measure the obtained oil is weight before and after the oil is poured into it. These entries will form part of the data required to be used later for consolidation of the yield percentages of oil and the subsequent biodiesel generated from the oil.

5.2 Biodiesel yield obtained from processed WAFs oils at respective temperatures

	Sample I.D	Weight of flask (g)	Weight of flask +Oil	Weight of processed Oil	weight of biodiesel flask	Weight of + Biodiesel produced	% Biodiesel yield
1	Beef 60 º C	161.29	229.91	68.62	222.29	61.00	88.90%
2	Beef 55 º C	117.00	197.08	80.08	135.68	55.60	69.43%
3	Beef 50 º C	111.36	191.46	80.10	169.47	58.11	72.55%
4	Beef 45 º C	84.07	175.29	91.22	145.08	61.01	66.88%
5	Beef 60 º C 1	109.18	158.22	49.04	143.70	34.52	70.39%
6	Beef 55 º C 1	148.90	248.80	99.90	227.87	78.97	79.05%
7	Beef 50 º C1	112.01	162.55	50.54	142.81	30.80	60.94%
8	Beef 45 º C 1	102.30	201.90	99.60	181.27	78.97	79.29%
9	Beef 60 º C 2	153.11	198.47	45.36	179.76	26.65	58.75%
10	Beef 55 º C2	102.30	201.90	99.60	181.27	78.97	79.29%
11	Beef 50 º C 2	109.05	160.35	51.30	146.85	37.80	73.68%
12	Beef 45 º C2	148.90	248.80	99.90	238.07	89.17	89.26%
13	Pork 60 º C	144.58	195.28	50.70	178.24	33.66	66.39%
14	Pork 55 º C	116.83	164.24	47.41	146.47	29.64	62.52%
15	Pork 50 º C	109.17	158.56	49.39	143.77	34.60	70.05%
16	Pork 45 º C	108.73	160.79	52.06	146.68	37.95	72.90%
17	Pork 60 º C 1	133.95	182.77	48.82	165.23	31.28	64.07%
18	Pork 55 º C 1	116.83	164.24	47.41	146.47	29.64	62.52%
19	Pork 50 º C 1	101.76	150.71	48.95	133.71	31.95	65.27%
20	Pork 45 º C 1	101.35	139.52	38.17	135.01	33.66	88.18%
21	Pork 60 º C 2	153.80	253.80	100.00	241.16	87.36	87.36%
22	Pork 55 º C2	116.12	161.12	45.00	180.87	27.69	61.53%
23	Pork 50 º C 2	101.45	151.45	50.00	133.40	31.95	63.90%
24	Pork 45 º C2	101.35	139.52	38.17	133.27	31.92	83.63%
25	Chicken 60 º C	135.25	161.29	26.04	154.48	19.23	73.85%
26	Chicken 55 º C	117.55	167.55	50.00	163.03	45.48	90.96%
27	Chicken 50 º C	91.58	141.58	50.00	137.44	45.86	91.72%
28	Chicken 45 º C	98.30	148.30	50.00	141.34	43.04	86.08%
29	Chicken 60 º C 1	152.22	192.22	40.00	192.68	40.46	101.15%
30	Chicken 55 º C 1	151.17	191.52	40.35	191.52	40.35	100.00%
31	Chicken 50 º C 1	156.58	186.73	30.15	186.12	29.54	97.98%
32	Chicken 45 º C 1	155.96	191.60	35.64	190.68	34.72	97.42%

33	Chicken 60 º C 2	148.31	219.10	70.79	213.5	65.19	92.09%
34	Chicken 55 º C 2	132.96	193.10	60.14	177.9	44.94	74.73%
35	Chicken 50 º C 2	113.27	173.38	60.11	166.9	53.63	89.22%
36	Chicken 45 º C 2	118.18	180.70	62.52	166.7	48.52	77.61%

Table 5.2 – Biodiesel yield for each feedstock at respective temperatures

A combined weight of 2107.08 g of oil was used to produce 1643.83 g of biodiesel for the three feedstocks translating into 1889.46 ml of biodiesel corresponding to approximately 1.89 litres of biodiesel.

The formula density = Mass / volume used to obtain the volume of biodiesel generated.

Mass = 1643.83 g of biodiesel
density = 0.87 g/cm3 for biodiesel
Hence, the volume of the biodiesel produced

$$= \frac{\text{Mass}}{\text{Density}}$$

$$= \frac{1643.83}{0.87}$$

= 1889.45 ml

= 1.89 litres of biodiesel

Therefore 2.1kg of oil gives 1.89 litres of biodiesel from the combined 3 feedstocks .

To quantify the amount of biodiesel that could be produced from X amount of fat processed from each feedstock, we revisit the batch quantities of fat used to produce the oil. Then the percentage yield of biodiesel is worked from the oil processed. Then based on the yield , we conduct ratios to estimate the biodiesel that can realistically be obtained from each type of fat melted for that particular feedstock.

5.3 Quantification of oil & biodiesel production potential

5.3.1 Oil Yield

Feed stock type	Fat Used(g)	Oil generated (g)	% Yield
Beef	1128.11	915.26	81.13%
Pork	1350.20	1005.34	74.46%
Chicken	664.07	575.74	86.70%

5.3.1 Biodiesel Yield

Feed stock type	Oil processed	Biodiesel produced	% Yield
Beef	915.26	691.57	75.56%
Pork	616.08	441.30	71.63%
Chicken	575.74	510.96	88.75%

5.3.2 Biodiesel production potential

Using the national animal census data from the Ministry of Agriculture in Zambia based on the 2022 livestock survey report of 04-01-2023, with focus on the southern province, the following where the estimates of biodiesel that could be produced.

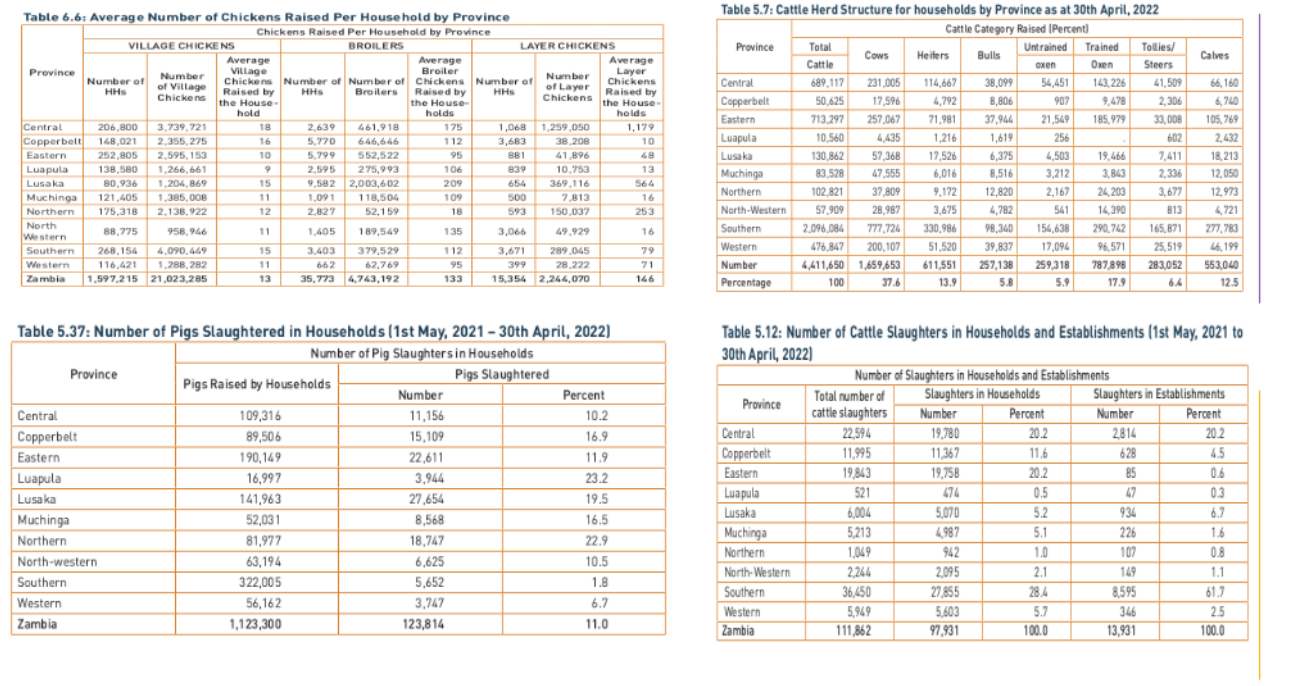


Table 6.6: Average Number of Chickens Raised Per Household by Province

Province	Chickens Raised Per Household by Province								
	VILLAGE CHICKENS			BROILERS			LAYER CHICKENS		
	Number of HHs	Number of Village Chickens	Average Village Chickens Raised by the House-hold	Number of HHs	Number of Broilers	Average Broiler Chickens Raised by the House-holds	Number of HHs	Number of Layer Chickens	Average Layer Chickens Raised by the House-holds
Central	206,800	3,739,721	18	2,639	461,918	175	1,068	1,259,050	1,179
Copperbelt	148,021	2,355,275	16	5,770	646,646	112	3,683	38,208	10
Eastern	252,805	2,595,153	10	5,799	552,522	95	881	41,896	48
Luapula	138,580	1,266,661	9	2,595	275,993	106	839	10,753	13
Lusaka	80,936	1,204,869	15	9,582	2,003,602	209	654	369,116	564
Muchinga	121,405	1,385,008	11	1,091	118,504	109	500	7,813	16
Northern	175,318	2,138,922	12	2,827	52,159	18	593	150,037	253
North Western	88,775	958,946	11	1,405	189,549	135	3,066	49,929	16
Southern	268,154	4,090,449	15	3,403	379,529	112	3,671	289,045	79
Western	116,421	1,288,282	11	662	62,769	95	399	28,222	71
Zambia	1,597,215	21,023,285	13	35,773	4,743,192	133	15,354	2,244,070	146

Table 5.7: Cattle Herd Structure for households by Province as at 30th April, 2022

Province	Cattle Category Raised (Percent)							
	Total Cattle	Cows	Heifers	Bulls	Untrained oxen	Trained Oxen	Tollies/ Steers	Calves
Central	689,117	231,005	114,667	38,099	54,451	143,226	41,509	66,160
Copperbelt	50,625	17,596	4,792	8,806	907	9,478	2,306	6,740
Eastern	713,297	257,067	71,981	37,944	21,549	185,979	33,008	105,769
Luapula	10,560	4,435	1,216	1,619	256	.	602	2,432
Lusaka	130,862	57,368	17,526	6,375	4,503	19,466	7,411	18,213
Muchinga	83,528	47,555	6,016	8,516	3,212	3,843	2,336	12,050
Northern	102,821	37,809	9,172	12,820	2,167	24,203	3,677	12,973
North-Western	57,909	28,987	3,675	4,782	541	14,390	813	4,721
Southern	2,096,084	777,724	330,986	98,340	154,638	290,742	165,871	277,783
Western	476,847	200,107	51,520	39,837	17,094	96,571	25,519	46,199
Number	4,411,650	1,659,653	611,551	257,138	259,318	787,898	283,052	553,040
Percentage	100	37.6	13.9	5.8	5.9	17.9	6.4	12.5

Table 5.37: Number of Pigs Slaughtered in Households (1st May, 2021 – 30th April, 2022)

Province	Number of Pig Slaughters in Households		
	Pigs Raised by Households	Pigs Slaughtered	
		Number	Percent
Central	109,316	11,156	10.2
Copperbelt	89,506	15,109	16.9
Eastern	190,149	22,611	11.9
Luapula	16,997	3,944	23.2
Lusaka	141,963	27,654	19.5
Muchinga	52,031	8,568	16.5
Northern	81,977	18,747	22.9
North-western	63,194	6,625	10.5
Southern	322,005	5,652	1.8
Western	56,162	3,747	6.7
Zambia	1,123,300	123,814	11.0

Table 5.12: Number of Cattle Slaughters in Households and Establishments (1st May, 2021 to 30th April, 2022)

Province	Number of Slaughters in Households and Establishments				
	Total number of cattle slaughters	Slaughters in Households		Slaughters in Establishments	
		Number	Percent	Number	Percent
Central	22,594	19,780	20.2	2,814	20.2
Copperbelt	11,995	11,367	11.6	628	4.5
Eastern	19,843	19,758	20.2	85	0.6
Luapula	521	474	0.5	47	0.3
Lusaka	6,004	5,070	5.2	934	6.7
Muchinga	5,213	4,987	5.1	226	1.6
Northern	1,049	942	1.0	107	0.8
North-Western	2,244	2,095	2.1	149	1.1
Southern	36,450	27,855	28.4	8,595	61.7
Western	5,949	5,603	5.7	346	2.5
Zambia	111,862	97,931	100.0	13,931	100.0

Fig 5.3.2 The 2022 livestock survey extract – Courtesy of Ministry of Agriculture, Zambia

Based on this, the study and that of ZAMBEEF chicken, beef and pork processing data , herewith the production potential of the biodiesel.

5.3.2.1 Chicken fat biodiesel production potential
33,000 chickens per day slaughtered

1.85 kg average live weight

Average dressed weight 1.68 kg

2.5% of 1.68 kg is chicken skins

Thus, 0.042 kg is skins - of these 40 % will be fat

Thus, fat = 0.0168 i.e 0.0168 kg of fat

Hence, 554.4 kg of fat generated per day when 33,000 chickens are slaughtered

2024 Leap year
366 days in total
104 weekends
15 public holidays
247 working days

136,937 kg. This is the fat generated in a year (2024)

118,724 kg. Oil generated based on the yield rate of 86.7% from fat

105,368 kg of biodiesel at the yield rate of 88.75% of oil used

Hence, the volume generated of biodiesel will be 121,112 litres of biodiesel per year from 33,000 chickens /year. Which is 4 truck loads of 30 m^3

5.3.2.2 Beef fat biodiesel production potential

17.78 kg of beef fat
Rate 0.8113 of fat processed gives 14.42 kg of oil generated
Rate 0.7556 of oil processed gives 13.43 kg of biodiesel

using d=m/v and density of 0.87 kg/m^3 ; gives
15.44 litres of diesel per slaughtered animal
36450 Animal slaughtered annually in southern province
Hence,15.44 * 36450 =562,788 litres of biodiesel to be produced

5.3.2.3 Pork fat biodiesel production potential
63 Kg Average carcass weight
8954 Carcasses
142 animals represented

379.67 total fat for 8954 carcasses
2.67 kg of fat per animal
1.99 kg of oil generated
1.43 kg of diesel

Using the national data on the pigs slaughtered per year, we get

5652*1.43 8,082 litres of biodiesel per year from 5652 slaughtered pigs /year.

With this information, and the overall national animal data from the Ministry of Agriculture, we should be in a position to make informed decision on the potential that exists on an national scale to produce biodiesel from these feedstocks

5.3 Combined batch individual temperature % biodiesel yield for each feedstock

Feedstock 1		Feedstock 2		Feedstock 3	
Beef 60 ° C	72.68%	Pork 60 ° C	72.61%	Chicken 60 ° C	89.03%
Beef 55 ° C	75.92%	Pork 55 ° C	62.19%	Chicken 55 ° C	88.56%
Beef 50 ° C	69.06%	Pork 50 ° C	66.41%	Chicken 50 ° C	**92.97%**
Beef 45 ° C	**78.48%**	Pork 45 ° C	**81.57%**	Chicken 45 ° C	87.04%

Table 5.3 – Combined batch best temperature in terms of % biodiesel yield for each feedstock

More biodiesel was produced at 45 ºC for feedstocks of beef and Chicken whilst that of chicken was high enough but had more at 50 ºC. However the overall best temperature to produce the biodiesel remained at 45 ºC as the temperature was considered optimal based on the prevailing experimental results and that the overall quantities and volumes of biodiesel produced at combined average yields of 82.36 % at respective temperatures confirmed this compared to 78.11 % at 60oC which was not desirable due to loss of methanol in evaporation even when the condenser was hooked up.

5.4 Average biodiesel % yield for the 3 feedstocks at respective temperatures

60 ° C	78.11%	✗
55 ° C	75.56%	
50 ° C	76.15%	
45 ° C	82.36%	✓

Temperatures close to the boiling point of methanol (65ºC) are not desirable even if the condenser is hooked up. Rapid evaporation was observed at 60 ºC reducing the available methanol for complete reaction in the biodiesel formation. Thus, to avoid soap formation , lower temperatures are desirable based on these experimental experiences and further, its desirable to reduce the speed of the magnetic stirrer to lower the heat generated as a direct result of the agitation caused during mixing

Fig 5.4 Average biodiesel % yield for the 3 feedstocks at respective temperatures

5.5 Density and specific gravity

	Sample I.D	Wt.of Bottle + Sample (g)	Wt. of Bottle + Water	Wt. of Bottle Only	Wt. of Sample	Wt. of Water	Density of Biodiesel	Density of Water	Specific Gravity of Biodiesel
1	Beef 60 ° C	43.9466	46.9558	22.1320	21.8146	24.8238	0.8726	0.992952	0.8788
2	Beef 55 ° C	44.1281	46.9558	22.1320	21.9961	24.8238	0.8798	0.992952	0.8861
3	Beef 50 ° C	44.4085	46.9558	22.1320	22.2765	24.8238	0.8911	0.992952	0.8974
4	Beef 45 ° C	43.8620	46.9558	22.1320	21.7300	24.8238	0.8692	0.992952	0.8754
5	Beef 60 ° C 1	44.2935	46.9558	22.1320	22.1615	24.8238	0.8865	0.992952	0.8928
6	Beef 55 ° C 1	44.1214	46.9558	22.1320	21.9894	24.8238	0.8796	0.992952	0.8858
7	Beef 50 ° C 1	43.9320	46.9558	22.1320	21.8000	24.8238	0.8720	0.992952	0.8782
8	Beef 45 ° C 1	44.0020	46.9558	22.1320	21.8700	24.8238	0.8748	0.992952	0.8810
9	Beef 60 ° C 2	44.4087	46.9558	22.1320	22.2767	24.8238	0.8911	0.992952	0.8974

10	Beef 55 º C 2	44.2828	46.9558	22.1320	22.1508	24.8238	0.8860	0.992952	0.8923
11	Beef 50 º C 2	43.8707	46.9558	22.1320	21.7387	24.8238	0.8695	0.992952	0.8757
12	Beef 45 º C 2	43.9932	46.9558	22.1320	21.8612	24.8238	0.8744	0.992952	0.8807
13	Pork 60 º C	43.9358	46.9558	22.1320	21.8038	24.8238	0.8722	0.992952	0.8783
14	Pork 55 º C	44.0295	46.9558	22.1320	21.8975	24.8238	0.8759	0.992952	0.8821
15	Pork 50 º C	44.0260	46.9558	22.1320	21.8940	24.8238	0.8758	0.992952	0.8820
16	Pork 45 º C	43.9734	46.9558	22.1320	21.8414	24.8238	0.8737	0.992952	0.8799
17	Pork 60 º C 1	43.8490	46.9558	22.1320	21.7170	24.8238	0.8687	0.992952	0.8748
18	Pork 55 º C 1	43.7604	46.9558	22.1320	21.6284	24.8238	0.8651	0.992952	0.8713
19	Pork 50 º C 1	43.8603	46.9558	22.1320	21.7283	24.8238	0.8691	0.992952	0.8753
20	Pork 45 º C 1	43.8295	46.9558	22.1320	21.6975	24.8238	0.8679	0.992952	0.8741
21	Pork 60 º C 2	43.8542	46.9558	22.1320	21.7222	24.8238	0.8689	0.992952	0.8751
22	Pork 55 º C 2	43.8258	46.9558	22.1320	21.6938	24.8238	0.8678	0.992952	0.8739
23	Pork 50 º C 2	43.8853	46.9558	22.1320	21.7533	24.8238	0.8701	0.992952	0.8763
24	Pork 45 º C 2	43.0798	46.9558	22.1320	20.9478	24.8238	0.8379	0.992952	0.8439
25	Chicken 60 º C	44.2964	46.9558	22.1320	22.1644	24.8238	0.8866	0.992952	0.8929
26	Chicken 55 º C	44.6406	46.9558	22.1320	22.5086	24.8238	0.9003	0.992952	0.9067
27	Chicken 50 º C	44.7058	46.9558	22.1320	22.5738	24.8238	0.9030	0.992952	0.9094
28	Chicken 45 º C	44.6535	46.9558	22.1320	22.5215	24.8238	0.9009	0.992952	0.9073
29	Chicken 60 º C 1	44.0291	46.9558	22.1320	21.8971	24.8238	0.8759	0.992952	0.8821
30	Chicken 55 º C 1	43.8326	46.9558	22.1320	21.7006	24.8238	0.8680	0.992952	0.8742
31	Chicken 50 º C 1	43.9955	46.9558	22.1320	21.8635	24.8238	0.8745	0.992952	0.8807
32	Chicken 45 º C 1	43.798	46.9558	22.1320	21.6660	24.8238	0.8666	0.992952	0.8728
33	Chicken 60 º C 2	44.5636	46.9558	22.1320	22.4316	24.8238	0.8973	0.992952	0.9036
34	Chicken 55 º C 2	44.5256	46.9558	22.1320	22.3936	24.8238	0.8957	0.992952	0.9021
35	Chicken 50 º C 2	44.6914	46.9558	22.1320	22.5594	24.8238	0.9024	0.992952	0.9088
36	Chicken 45 º C 2	44.5788	46.9558	22.1320	22.4468	24.8238	0.8979	0.992952	0.9042

Fig.5.5 Density and specific gravity measurement

5.5.1 Density measurements

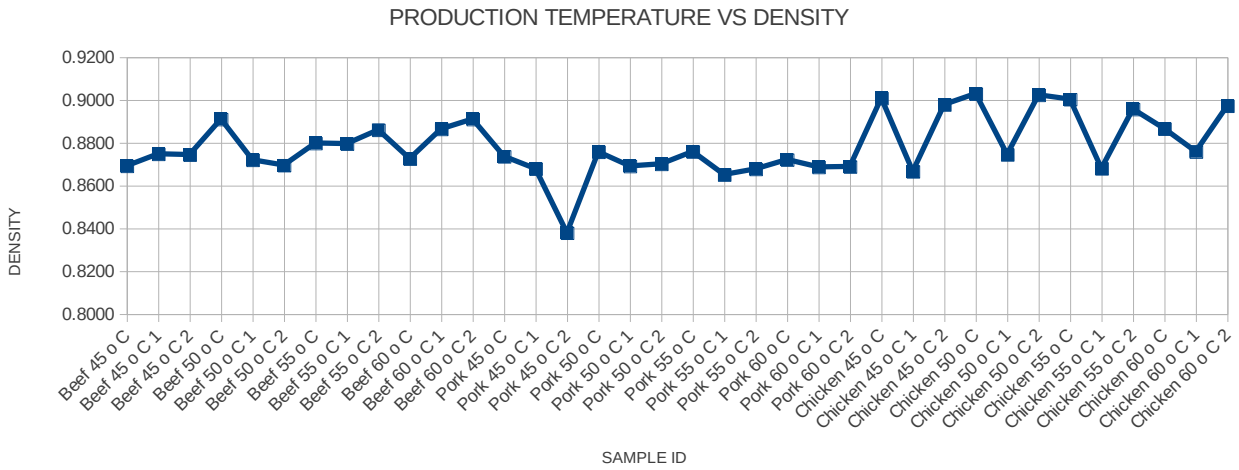


Fig. 5.5.1 Density measurement

The density of all the tested samples was within the range of the ASTM standards of biodiesel that is around 0.860 and 0.900 g/cm^3 except for one outlier with 0.8379 g/cm^3, but still falls within fossil diesel density.

5.6 Viscosity measurements

	Sample I.D	Wt.of Bottle + Sample (g)	Wt. of Bottle + Water	Wt. of Bottle Only	Wt. of Sample	Wt. of Water	Density of Biodiesel	Density of Water	Specific Gravity of Biodiesel	Viscosity constant	Time (s)	Viscosity
1	Beef 60 o C	43.9466	46.9558	22.1320	21.8146	24.8238	0.8726	0.992952	0.8788	0.238	18.00	3.74
2	Beef 55 o C	44.1281	46.9558	22.1320	21.9961	24.8238	0.8798	0.992952	0.8861	0.238	23.00	4.82
3	Beef 50 o C	44.4085	46.9558	22.1320	22.2765	24.8238	0.8911	0.992952	0.8974	0.238	26.00	5.51
4	Beef 45 o C	43.8620	46.9558	22.1320	21.7300	24.8238	0.8692	0.992952	0.8754	0.238	12.67	2.62
5	Beef 60 o C 1	44.2935	46.9558	22.1320	22.1615	24.8238	0.8865	0.992952	0.8928	0.238	24.00	5.06
6	Beef 55 o C 1	44.1214	46.9558	22.1320	21.9894	24.8238	0.8796	0.992952	0.8858	0.238	18.00	3.77
7	Beef 50 o C 1	43.9320	46.9558	22.1320	21.8000	24.8238	0.8720	0.992952	0.8782	0.238	18.33	3.80
8	Beef 45 o C 1	44.0020	46.9558	22.1320	21.8700	24.8238	0.8748	0.992952	0.8810	0.238	17.67	3.68
9	Beef 60 o C 2	44.4087	46.9558	22.1320	22.2767	24.8238	0.8911	0.992952	0.8974	0.238	23.00	4.88
10	Beef 55 o C 2	44.2828	46.9558	22.1320	22.1508	24.8238	0.8860	0.992952	0.8923	0.238	23.00	4.85
11	Beef 50 o C 2	43.8707	46.9558	22.1320	21.7387	24.8238	0.8695	0.992952	0.8757	0.238	18.00	3.73
12	Beef 45 o C 2	43.9932	46.9558	22.1320	21.8612	24.8238	0.8744	0.992952	0.8807	0.238	19.00	3.95
13	Pork 60 o C	43.9358	46.9558	22.1320	21.8038	24.8238	0.8722	0.992952	0.8783	0.238	17.00	3.53
14	Pork 55 o C	44.0295	46.9558	22.1320	21.8975	24.8238	0.8759	0.992952	0.8821	0.238	17.00	3.54
15	Pork 50 o C	44.0260	46.9558	22.1320	21.8940	24.8238	0.8758	0.992952	0.8820	0.238	14.29	2.98
16	Pork 45 o C	43.9734	46.9558	22.1320	21.8414	24.8238	0.8737	0.992952	0.8799	0.238	14.00	2.91
17	Pork 60 o C 1	43.8490	46.9558	22.1320	21.7170	24.8238	0.8687	0.992952	0.8748	0.238	12.33	2.55

18	Pork 55 o C 1	43.7604	46.9558	22.1320	21.6284	24.8238	0.8651	0.992952	0.8713	0.238	12.75	2.63
19	Pork 50 o C 1	43.8603	46.9558	22.1320	21.7283	24.8238	0.8691	0.992952	0.8753	0.238	13.00	2.69
20	Pork 45 o C 1	43.8295	46.9558	22.1320	21.6975	24.8238	0.8679	0.992952	0.8741	0.238	14.00	2.89
21	Pork 60 o C 2	43.8542	46.9558	22.1320	21.7222	24.8238	0.8689	0.992952	0.8751	0.238	15.00	3.10
22	Pork 55 o C 2	43.8258	46.9558	22.1320	21.6938	24.8238	0.8678	0.992952	0.8739	0.238	15.00	3.10
23	Pork 50 o C 2	43.8853	46.9558	22.1320	21.7533	24.8238	0.8701	0.992952	0.8763	0.238	14.00	2.90
24	Pork 45 o C 2	43.0798	46.9558	22.1320	20.9478	24.8238	0.8379	0.992952	0.8439	0.238	18.00	3.59
25	Chicken 60 o C	44.2964	46.9558	22.1320	22.1644	24.8238	0.8866	0.992952	0.8929	0.238	46.00	9.71
26	Chicken 55 o C	44.6406	46.9558	22.1320	22.5086	24.8238	0.9003	0.992952	0.9067	0.238	32.00	6.86
27	Chicken 50 o C	44.7058	46.9558	22.1320	22.5738	24.8238	0.9030	0.992952	0.9094	0.238	27.00	5.80
28	Chicken 45 o C	44.6535	46.9558	22.1320	22.5215	24.8238	0.9009	0.992952	0.9073	0.238	27.00	5.79
29	Chicken 60 o C 1	44.0291	46.9558	22.1320	21.8971	24.8238	0.8759	0.992952	0.8821	0.238	29.00	6.05
30	Chicken 55 o C 1	43.8326	46.9558	22.1320	21.7006	24.8238	0.8680	0.992952	0.8742	0.238	25.00	5.16
31	Chicken 50 o C 1	43.9955	46.9558	22.1320	21.8635	24.8238	0.8745	0.992952	0.8807	0.238	28.00	5.83
32	Chicken 45 o C 1	43.798	46.9558	22.1320	21.6660	24.8238	0.8666	0.992952	0.8728	0.238	28.00	5.78
33	Chicken 60 o C 2	44.5636	46.9558	22.1320	22.4316	24.8238	0.8973	0.992952	0.9036	0.238	20.00	4.27
34	Chicken 55 o C 2	44.5256	46.9558	22.1320	22.3936	24.8238	0.8957	0.992952	0.9021	0.238	13.00	2.77
35	Chicken 50 o C 2	44.6914	46.9558	22.1320	22.5594	24.8238	0.9024	0.992952	0.9088	0.238	17.00	3.65
36	Chicken 45 o C 2	44.5788	46.9558	22.1320	22.4468	24.8238	0.8979	0.992952	0.9042	0.238	13.00	2.78

Table 5.6 viscosity measurements

The combined average viscosity of 4.20 cent poise was obtained for the 36 experiments conducted..

In the data obtained we had two out-layers of data which where for the chicken first batch at 60 ^{o}C and 55 ^{o}C corresponding to 9.71 mm^2/s and 6.86 mm^2/s respectively. The values obtained,other than the two outliers are comparable to the acceptable range of 1.9 – 6.0 mm^2/s to that of the ASTM D445 test method. Cold Flow Properties and Kinematic Viscosity of Biodiesel - Nwadike Isioma, Yahaya Muhammad et al, 2013

Biodiesel fuels with high viscosity tend to form larger droplets in the injection which leads to a poor fuel atomization that increases the spray tip penetration and decreases the spray angle, deriving into a poor combustion. Thus, to ensure that the viscosity falls within the acceptable range, a composite sample of all three feedstocks can be used. Literature has it that use of sodium methoxide in the transesterification process helps to resolve this compared to use of ethanol.

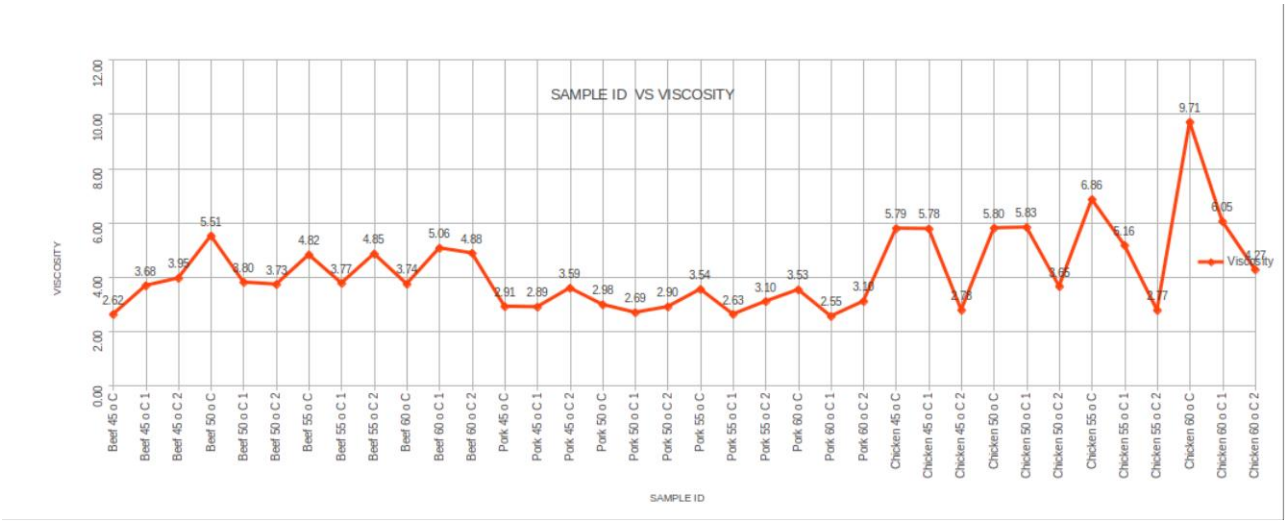


Fig 5.6 a Viscosity Vs Sample ID

The observation from the graph is that the biodiesel produced from pork had lower viscosity compared to that of biodiesel from beef. That produced from chicken gave mixed results with one outlier but generally within acceptable range for viscosity values of biodiesel from animal fats i.e 1.6 – 6.0 mm^2/s

6.0 DISCUSSION

The interest in biodiesel as a sustainable source of energy continues to increase due to its advantages over fossil fuels (Deshmukh et al., 2019; Fazal et al., 2019; Jayakumar et al., 2021; Li et al., 2019; Naveenkumar & Baskar, 2021; Srivastava et al., 2020). In terms of chemical composition, biodiesel typically consists of a blend of fatty acid methyl esters (FAMEs) or fatty acid ethyl esters (FAEEs) with virtually sulfur-free content (Adewale et al., 2015; Hoekman et al., 2012; Quayson et al., 2020). Compared to conventional diesel, biodiesel exhibits a superior flashpoint, higher cetane number, and its combustion produces lower carbon monoxide emissions and decreased levels of nitrated compounds, less particulate matter, and lower emissions of both unburned hydrocarbons (UHC), and aromatic hydrocarbons (Kaya et al., 2018). Moreover, biodiesel offers safer handling and non-toxicity. This translates into a lower harmful impact on human health versus the exhaust produced from conventional diesel due to lower amounts of carcinogenic compounds. Furthermore, biodiesel has almost the same energy efficiency as petroleum diesel with additional lubricity benefits for engine performance (Ayetor et al., 2015; Dahiya et al., 2018; Giakoumis & Sarakatsanis, 2019; Liu et al., 2019).

In recent times, the the biodiesel has been used as a solvent for bio-degrading the spilled fossil diesel on land and ship wreckages.

From the observed oil and biodiesel yields percentages, potential exists to exploit the biodiesel production for the benefit of the communities and the environment. Further, the above added benefits that biodiesel brings to humanity and the environment is enough justification to support biodiesel investments opportunities.

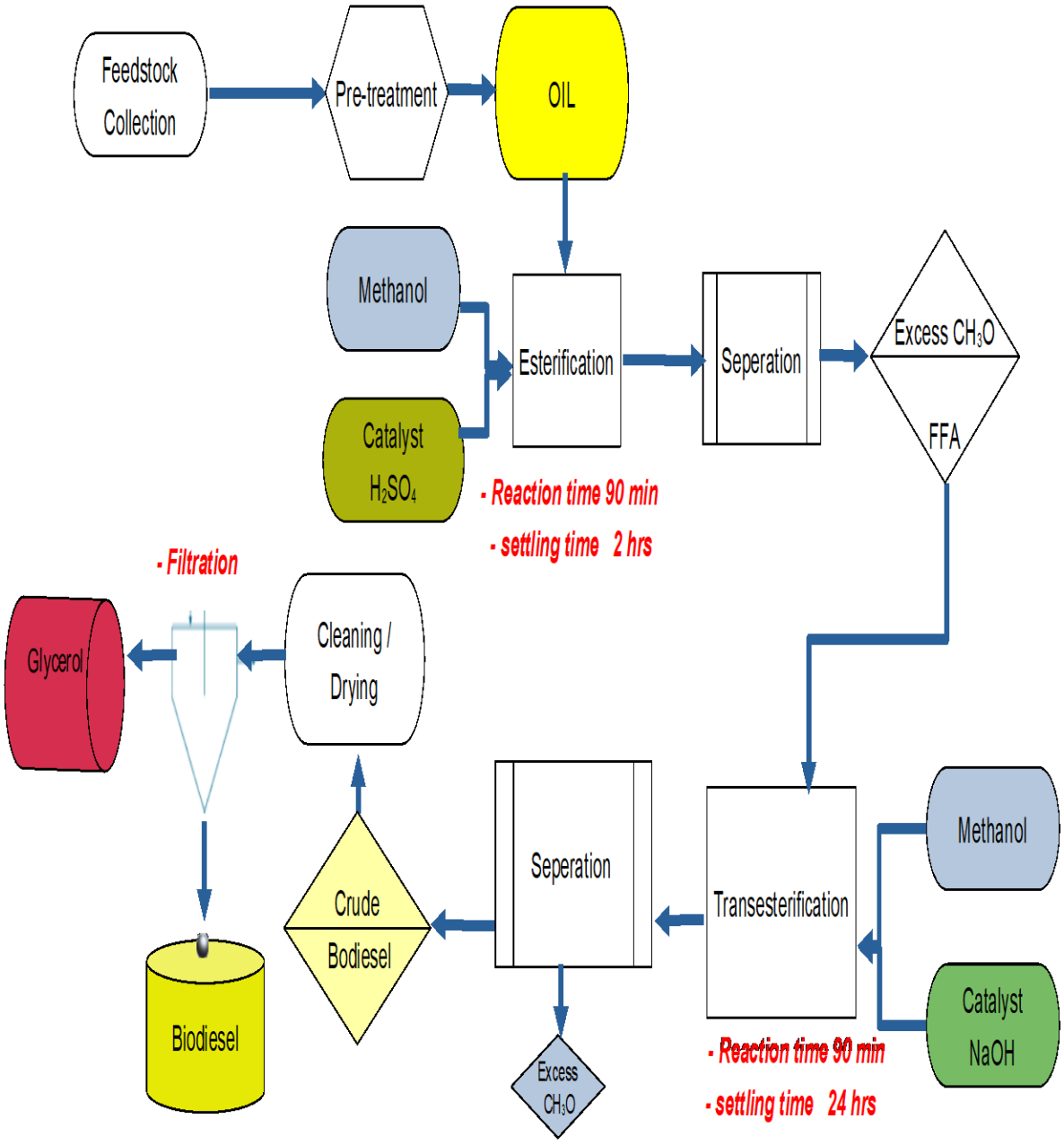
7.0 CONCLUSION

There are not enough quantities of feedstock to produce the biodiesel from animal fats of chicken, pig and cattle to make meaningful impact on the economy on a large scale. However,there exist great potential to produce the biodiesel using the chicken, pig and cattle fats at a lower scale in Zambia as the feedstock is readily available and the fact that we have the technical working knowledge on how to produce it. This provides opportunity to help reduce on the carbon foot print and as well as the GHG emissions, particularly if the biodiesel is added to the transportation and power generation sectors.

Further, this, will no doubt help created and generate economic value chains that will go on to improve the livelihood of the informal sector by creating opportunities for the most vulnerable people in our communities. It is in this light the the public, stake holders and the government of the Republic of Zambia, should consider biodiesel production.

Further, there exists an enormous tax revenue collection potential if the production structures are crafted in a way to support the biodiesel industry. Finally, to ensure adequate feedstock availability, a multi-feedstock approach of process lines to include used engine oil, used vegetable oils, grease and fats must be considered.

Enlarged fig. 2.2 Biodiesel synthesis using the modified two step process



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