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Innovative Processing Techniques for Boosting Light End Fractions in Crude Oil Distillation

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Abstract
Processing heavy Antan crude oil in conventional refineries is constrained by its high viscosity, low API gravity, and elevated sulphur content, which result in poor light distillate recovery and excessive residue formation, limiting its economic viability. This study investigates the upgrading of Antan crude through blending with Oso condensate using a newly assembled, innovative distillation column. Various blend ratios were experimentally evaluated, with a 40:60% (Antan crude oil + Oso condensate) composition selected for detailed analysis. In parallel, a MATLAB-based design and optimization framework was developed to enhance yield prediction and process efficiency. Atmospheric distillation of pure Antan crude produced negligible light fractions. In contrast, the 40:60 blend significantly improved product recovery, yielding 25.60% naphtha, 15.37% kerosene, 12.49% diesel, and 45.50% residue, demonstrating the effectiveness of condensate-assisted upgrading. Computational optimization further enhanced performance, increasing yields to 34.11% naphtha, 24.26% kerosene, and 18.87% diesel, while reducing residue to 22.38%. This represents gains of 8.51%, 8.89%, and 6.38% in naphtha, kerosene, and diesel, respectively, alongside a substantial reduction in residuum. The model accurately captured process behaviour and outperformed conventional experimental approaches. Economic analysis shows that the optimized blend improves Gross Product Worth (97.2 $/bbl) and Net Refinery Margin (7.7 $/bbl) relative to Antan crude alone (89.9 $/bbl GPW; 1.9 $/bbl NRM). Profitability indicators confirm strong economic viability, with annual profit reaching 254.1 M$, positive NPV (+962.4 M$), and IRR of 18 – 20%, compared to negative returns for unblended Antan crude. The integration of blending strategies with computational optimization provides a robust pathway for upgrading heavy Nigerian crude oils. This approach enhances light product recovery, reduces processing risk, and improves refinery profitability, offering a practical and scalable solution for maximizing the value of challenging feedstocks.

Keywords: *Oso condensate, Antan crude oil, blending, characterization, integrated distillation Unit.*

1.0 Introduction

Nigeria's energy demand is rising due to population growth, urbanization, economic diversification, and improved living standards, while declining conventional crude reserves continue to challenge global supply and Organization of Petroleum Exporting Countries (OPEC) operations. Heavy crude oils, such as Nigeria's Antan crude, are increasingly important but present significant processing challenges due to high viscosity, low API gravity, and elevated sulphur and impurity content [1, 2]. Several upgrading technologies, including carbon rejection, hydrogen addition, thermal conversion, solvent deasphalting, and crude oil blending, have been developed to improve crude quality. Among these, blending offers greater economic and operational flexibility. Prior to distillation, crude oil is preheated in a fractionation furnace to promote separation based on true boiling points (TBP), followed by processing in the crude distillation unit (CDU) and vacuum distillation unit (VDU), where lighter fractions are recovered and heavier residues are further processed [3].

Recent studies have explored optimization opportunities in atmospheric and vacuum distillation using computational design tools. For instance, Aspen HYSYS-based optimization studies reported light fraction (gasoline/naphtha) yield improvements of approximately 3–6% through adjustment of operating conditions such as temperature and pressure [4,5]. Similarly, MATLAB-based optimization and artificial intelligence models, including artificial neural networks (ANN) and genetic algorithms (GA), have demonstrated prediction and yield improvements in the range of 5–8%, primarily by optimizing process variables rather than feedstock composition [5]. While these approaches improve separation efficiency, they generally treat crude oil composition as fixed and rely on simplified thermodynamic assumptions, which may not adequately capture the complex, non-linear behaviour of heavy crude systems.

To address these limitations and reduce refinery operating costs while maintaining desirable distillate yields, blending heavy Antan crude with lighter Oso condensate presents a cost-effective alternative for

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improving feedstock quality and refining performance [6]. Oso condensate, characterized by high API gravity, low viscosity, and low sulphur content, effectively reduces the density and viscosity of heavy crude and modifies its distillation profile. This results in improved recovery of valuable light and middle distillates such as gasoline, kerosene, and diesel [6,7].

In contrast to previous computational studies that focus on process optimization, blending directly alters the hydrocarbon distribution and TBP characteristics of the crude, enabling potentially greater improvements in light fraction recovery and residue reduction. Furthermore, most existing computational models, including Aspen HYSYS and AI-based approaches, are limited by steady-state assumptions, simplified pseudo-component representations, and insufficient integration with experimental TBP data.

These limitations reduce their accuracy in predicting real refinery behaviour, particularly for heavy crude–condensate systems. In addition, there is a scarcity of region-specific studies focusing on Nigerian crude blends, especially Antan crude and Oso condensate. Oso gas condensate is a light hydrocarbon mixture characterized by high API gravity, low viscosity, and high volatility. It is predominantly composed of C_5–C_{10} hydrocarbons, including paraffins (n- and iso-alkanes such as pentane, hexane, and heptane), with smaller fractions of naphthene and aromatics. Although it contains a notable proportion of C_5 components (5–7 wt%), it is not exclusively rich in n-pentane; rather, its composition spans a broader light-end distribution. This wide range of light hydrocarbons contributes to its strong diluent effect, enabling effective reduction in viscosity and improvement in the distillation characteristics of heavy crude oils.

In this study, MATLAB programming was selected as the optimization tool due to its flexibility in handling non-linear systems, ability to integrate experimental data, and capability for developing customized mixture models that account for interaction effects between blend components. Unlike commercial simulators such as Aspen HYSYS, which are constrained by predefined thermodynamic packages, MATLAB enables the development of tailored optimization algorithms that directly link blend ratio, physicochemical properties, and distillation yield outcomes. Therefore, this research provides an integrated experimental–computational framework to evaluate the properties of Antan crude oil, Oso condensate, and their blends, and to optimize blend ratios using MATLAB in order to maximize light and middle distillate yields while minimizing residuum formation. This approach offers a practical and cost-effective solution for improving heavy crude processing in existing Nigerian refineries without requiring major technological upgrades.

The aim of this study is to evaluate the properties of Antan crude oil, Oso condensate, and their blends, and to optimize the blend of Antan crude–Oso condensate ratios using integrated experimental analysis and a Matlab programming model, in order to identify the optimal blend that maximizes the yield and quality of fuel fractions while minimizing residuum formation. This research is set to achieve the following objectives: To evaluate the physicochemical properties of the raw feedstock materials, to analyse the distillation characteristics of the three crude oil samples using TBP analysis in order to establish the fractional cut distribution, to optimize the Antan blend ratios (Antan crude oil + Oso condensate) through experimental testing and Matlab programming model (MPM) and finally, to obtain the optimal Antan blend ratio that maximizes the yield and quality of naphtha, kerosene, and diesel while minimizing the residuum

2.0 Materials and Methods

2.1 Materials

2.1.1 Study area

The study area is located within the offshore Niger Delta basin in the Gulf of Guinea, Nigeria, encompassing the Oso and Antan oil fields. This region lies in shallow to intermediate water depths (35–115 m), characterized by an extensive network of subsea production systems, flowlines, and export pipelines, including the 30 pipeline linking production facilities to the Escravos Terminal (Figure 1.0). The study area map showed Antan and Oso field in oil field production boundaries (production flowline). The Oso field comprises multiple production units, notably the Oso North Satellite Platform and Oso Central Complex, which serve as major gathering and processing hubs. The Antan field, situated further offshore in slightly deeper waters (55 m), operates through a dedicated wellhead platform connected through subsea flowlines to the central processing infrastructure. The spatial proximity of these fields facilitates blending and integrated production strategies [8].

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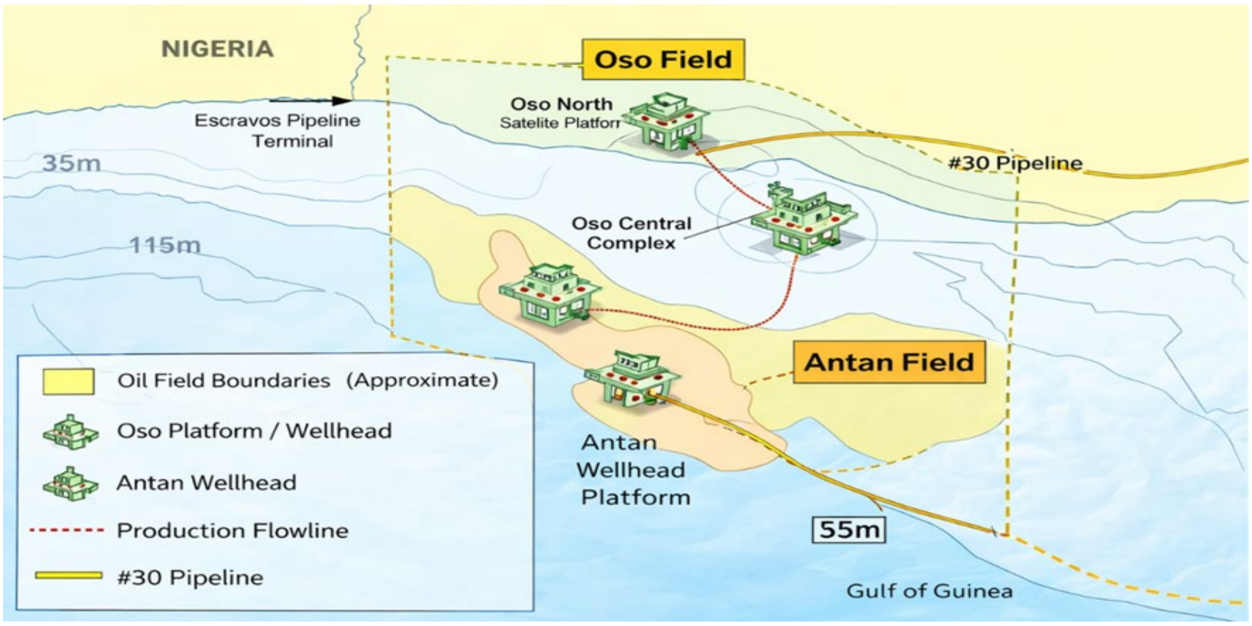

Figure 1: Study area showing Oso condensate and Antan crude oil fields and associated production facilities, flowlines and export pipeline network in Niger Delta, Nigeria

Figure 1 is a prolific area part in Niger Delta petroleum system, dominated by Tertiary deltaic sequences (Akata, Agbada, and Benin formations), which control hydrocarbon generation, migration, and trapping. Reservoirs in this region typically exhibit variations in fluid properties such as API gravity, viscosity, and sulphur content due to differences in depositional environment and thermal maturity. From an operational standpoint, the interconnected infrastructure supports efficient crude evacuation and offers opportunities for feedstock blending prior to refining. This is particularly relevant for optimizing distillation yields and improving product distribution across naphtha, kerosene, and diesel fractions.

2.1.2 Feedstock description

Crude oil samples used in this study include Antan crude oil and Oso condensate, sourced from offshore Niger Delta fields, Nigeria and Oso gas condensate obtained from Oso field jointly owned by Nigerian National Petroleum Company (NNPC) and Mobil Producing Nigeria (an ExxonMobil subsidiary) all in River State. The Oso field is known for producing gas condensate that is rich in light fractions such as nC_5 hydrocarbons (pentane), C_6H_{14}, C_7H_{16}, C_8H_{18} and hydrocarbons fractions. The samples were collected from production platforms under stabilized conditions and stored in airtight containers to prevent compositional alteration.

2.1.3 Sample preparation

Prior to analysis, all samples were homogenized and conditioned at standard laboratory temperature. Water and sediment contents were minimized using standard separation techniques (centrifugation) to ensure accuracy in physicochemical measurements.

2.1.4 Pre-refining treatment and feedstock blending strategies for heavy Antan crude oil and Oso condensate processing

After pretreatment, the crude oil samples were allowed to stabilize under controlled conditions before blending. The blending of heavy crude oil with Oso condensate prior to refining is critical for improving product quality. This is evident from the TBP characterization, which varies among crude oils depending on their physicochemical properties. Feedstock operations consist of blending, analyses and to manage the crude oil sample materials efficiently. The feedstocks are blended in precise ratios to meet specific processing requirements, optimize yields and manage quality specifications of the final products, The two crude oil samples were measured at different ratio (Antan crude + Oso condensate) at 100:0%, 90:10%, 80:20%, 70:30%, 60:40%, 50:50%, 40:60%, 30:70%, 20:80%, 10:90% and 0:100% respectively in a 1000ml cylinder each and transferred into a beaker and stirred for uniform mixing.

The two crude oil samples were poured into the measuring cylinder using their weight ratio that make up the mixture in the cylinder as the final blend crude oil. The sample mixture was transferred into the beaker and stirred for 30 minutes so as to obtain a uniform mixing. After blending, the crude oil samples in an equal volume were left over night in a refrigerator to cool so as to avoid evaporation of the light end fractions.

2.2 Crude Oil Testing and Analysis

2.2.1 Fundamental analysis of Antan crude oil, Oso condensate and the blend behaviour in refining applications

Antan crude oil, Oso condensate, and their blended sample were carefully evaluated to account for the complex and dynamic behaviour inherent in petroleum systems. Given the variability in composition and phase characteristics of crude oil and condensates, a comprehensive and detailed crude oil analysis was necessary. Such analysis provides fundamental insights into the physicochemical properties of the feedstocks, including density, volatility, viscosity, and compositional distribution. These baseline data are essential for understanding the behaviour of the Antan crude oil and Oso condensate during processing, guiding blending strategies and predicting refining performance. Consequently, the characterization serves as a critical foundation for assessing the quality, processing requirements, and economic value of both the individual samples and their blends.

2.2.2 Comprehensive characterization of Antan crude oil, Oso condensate, and their blends

The physicochemical properties of the crude oil samples and their blends were determined using standard ASTM methods: specific gravity and API gravity (ASTM D1298), viscosity at 40 °C and 100 °C (ASTM D445), pour point (ASTM D97), and sulphur content (ASTM D4294).

Specific gravity was measured using a hydrometer with a range of 0.800–0.99 in a 1000 mL graduated cylinder, alongside a 0–100 °C thermometer for temperature control. The hydrometer provides a direct reading based on its depth of immersion in the crude sample. API gravity was subsequently calculated from the measured specific gravity, with both values referenced at 60 °F (15.6 °C) [8].

Viscosity was determined using a viscometer, where a spindle rotates in the crude oil at a fixed speed, and the torque required to overcome fluid resistance is measured. This allows calculation of the kinematic viscosity at specified temperatures [8].

Sulphur content was analysed using an X-ray fluorescence (XRF) method. The crude sample was placed in a disposable cell, sealed with a cell window, and exposed to an X-ray beam. The emitted sulphur Kα radiation (5.373 Å) was measured to determine sulphur concentration in weight percent.

Pour point determination involved placing the crude sample in a pour point jar, inserting a thermometer, and cooling in a controlled bath. The temperature at which the sample ceased to flow was recorded as the pour point [7,8].

2.2.3 Thin-Layer Chromatography (TLC) for crude oil fractionation

Analytical technique for crude oils quantifications and distributions was done using thin-layer chromatography (TLC), ASTM D6560. The analysis TLC detect both saturates and aromatics in petroleum crude by fluorescence scanning using 365 nm as the excitation wavelength. Alternative detection of aromatics can be performed on either silica gel or berberine-impregnated plates by using ultraviolet (UV) densitometry at 250 nm. On the other hand, polar coal-derived products were separated into fractions, followed by dichloromethane-methanol (95 + 5, v/v), with detection by UV densitometry at 250 nm. The TLC interpret the hydrocarbons derive characteristic present in the crude oil sample [8, 9]

2.3 Experimental Procedures

Automatic distillation apparatus NDI 450 operates with a heating power of 2.0 KW and refrigeration power of 0.5 kW. The apparatus is equipped with a large 10.4-inch true-colour for effective operation. Distillation of crude oil is the main theme behind this research work that plays a vital role in petroleum industries dealing with boiling of liquid. In addition to performance, the apparatus owns all safety features that make it the most secure for distillation.

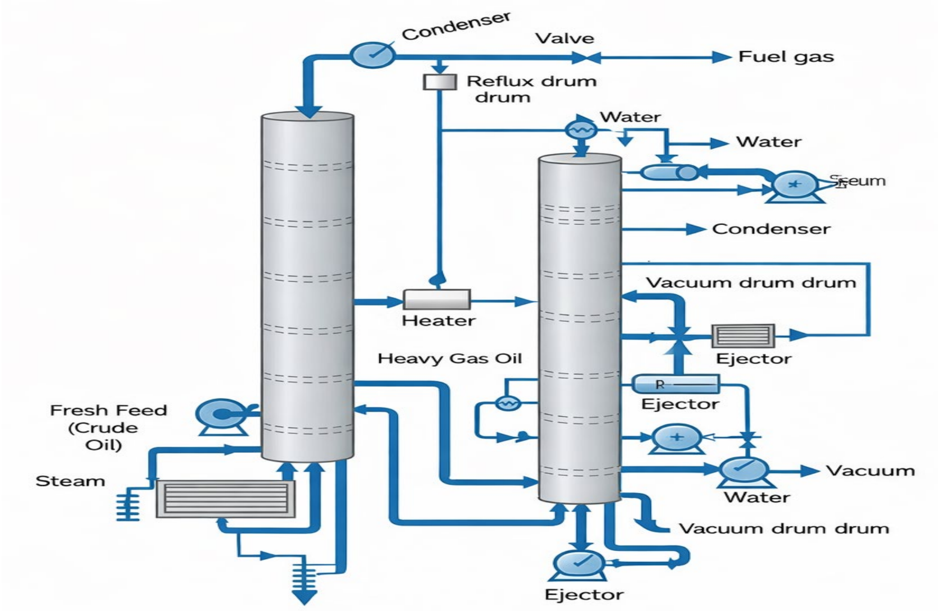

Figure 2: Schematic diagram and nomenclature of integrated distillation unit

The experimental methodology are steps in which this experiment is carried out. It includes all experimental methods as follows. After procurement of these materials and their physical properties were determined employing the appropriate ASTM methods of analysis as tabulated in Table 2. Based on the recommendation of the refinery operators, the crude blend ratio of 60:40% (Oso condensate + Antan crude oil) was considered appropriate for Kaduna refinery utilization and consumption. Atmospheric-vacuum distillation was carried out on the sample crude oil; Oso condensate, pure Antan crude and their blend applying the principle of operation using ASTM D86, ASTM D2892 and ASTM D5236 respectively. The result of crude oil blending and their properties are displayed in Tables 2, 3 and 4. The quality parameters of the obtained different fractions cuts were determine using standard methods of analyses as presented in Tables 5 and 10. Finally, a predictive model was developed that could describe the quantity of light end fractions produce on different Antan blend crude oils [9, 10]. The properties of various Antan blend crude oils in relation to the highly demanded petroleum products are used to predict the increasing product yield of the blend of Antan crude oil with Oso condensate.

2.4 Experimental Design Model for Optimizing Various Antan Blend Crude oils

The Matlab programming model (MPM) is used to optimize various crude oil blends to forecast yields of high-demand products, addressing Nigeria's shortfall in light-end fractions. By enhancing conventional refining methods, this approach predicts superior outputs of naphtha, kerosene, and diesel, reducing reliance on scarce light crudes. It aligns with research objectives by improving efficiency, marketability, and sustainability in Nigerian refineries through precise modelling of physicochemical properties and distillation processes.

2.4.1 MATLAB-based mixture design optimization

A mixture model for optimization is a statistical approach used to relate product properties or yields to the proportions of components in a blend. In crude oil systems, responses such as specific gravity and fuel yields (naphtha, kerosene, and diesel) are expressed as functions of component fractions, subject to the constraint that their sum equals unity. By incorporating interaction effects between components, mixture models (linear, quadratic, or response surface–based designs) enable accurate prediction of blend performance and identification of optimal ratios. This approach is implemented using MATLAB to maximize desirable outputs, minimize undesirable properties, and enhance refinery feedstock [10, 11].

(a) Development of mixture design equations

In crude oil blending and refinery optimization, specific gravity and product yields are key indicators of feedstock quality and processing performance. To improve prediction accuracy, quadratic mixture models incorporating interaction effects are employed.

Specific gravity

Specific gravity (SG) represents the relative density of crude oil and indicates its heaviness. Lower values correspond to lighter crudes with higher proportions of valuable light fractions. It is often minimized during optimization to enhance processing efficiency.

$$SG = b_1x_1 + b_2x_2 + b_{12}x_1x_2 \tag{1}$$

Naphtha yield

Naphtha is a light distillate fraction (30–200 °C) essential for gasoline production and petrochemical processes. Higher yields are desirable for refinery profitability.

$$Y_{\text{nap}} = c_1x_1 + c_2x_2 + c_{12}x_1x_2 \tag{2}$$

Kerosene yield

Kerosene (150–250 °C) is primarily used as aviation fuel and domestic fuel. Its yield must be optimized without compromising other fractions.

$$Y_{\text{ker}} = d_1x_1 + d_2x_2 + d_{12}x_1x_2 \tag{3}$$

Diesel yield

Diesel (200–350 °C) is a high-demand product in transportation and power generation. Maximizing diesel yield is often a primary optimization objective.

$$Y_{\text{diesel}} = e_1x_1 + e_2x_2 + e_{12}x_1x_2 \tag{4}$$

These equations describe how blend composition influences product distribution and crude quality, enabling prediction and optimization of refinery performance.

(b) Model adequacy and validation

Prior to optimization, the reliability of the developed models must be established through statistical validation: These includes coefficient of determination (R^2), Adjusted R^2, p-values (< 0.05 for significance) and graphical validation using predicted vs. experimental plots. These steps ensure that the models robust and suitable for optimization.

(c) Formulation of optimization problem

The optimization problem is formulated to determine the optimal blend ratio of Antan crude oil and Oso condensate that maximizes desirable product yields while maintaining acceptable crude quality.
Decision variables

x_1 = fraction of Antan crude, x_2 = fraction of Oso condensate

Subject to the mixture constraint:

$$x_1 + x_2 = 1$$

Objective function
To achieve a balance between product yield and crude quality, a combined objective function is define as:

Maximize $f(x) = Y_{\text{diesel}}(x) - \lambda \cdot SG(x)$

where:
$Y_{\text{diesel}}(x)$: predicted diesel yield, $SG(x)$: predicted specific gravity and λ: weighting factor
For MATLAB implementation, the problem is converted into a minimization form:

```
objective = @(x) -( (e1*x(1) + e2*x(2) + e12*x(1)*x(2)) ...
            - lambda*(b1*x(1) + b2*x(2) + b12*x(1)*x(2)) );
```

Constraints

The optimization is performed under the following constraints:
Equality constraint (mixture condition):
$x_1 + x_2 = 1$
Bound constraints:
$0 \leq x_1, x_2 \leq 1$

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MATLAB implementation:

```
Aeq = [1 1];
beq = 1;
lb = [0 0];
ub = [1 1];
```

(d) Implementation Procedure

The computational analysis was carried out using MATLAB to evaluate the effect of blending Antan crude oil and Oso condensate on specific gravity and product yields. The procedure involved defining blend ratios, assigning model coefficients obtained from regression analysis, and implementing quadratic mixture design equations.

Step 1: Blend composition

The blend fractions of the two feedstocks were defined such that their sum equals unity. A fixed ratio of 40:60 (Antan:Oso) was used:

```
x1 = 0.4;  % Fraction of Antan crude
x2 = 0.6;  % Fraction of Oso condensate
```

Step 2: Input of model coefficients

Regression coefficients derived from ANOVA and mixture design analysis were assigned for each response variable. These coefficients represent the individual and interaction effects of the blend components:

```
% Specific Gravity coefficients
b1 = 0.85; b2 = 0.75; b12 = 0.02;
% Naphtha yield coefficients (%)
c1 = 20;  c2 = 35;  c12 = 5;
% Kerosene yield coefficients (%)
d1 = 25;  d2 = 15;  d12 = 3;
% Diesel yield coefficients (%)
e1 = 30;  e2 = 20;  e12 = 4;
```

Step 3: Formulation of mixture design equations

Quadratic mixture models were implemented to predict the responses. These equations incorporate both linear and interaction effects of the blend components:

```
SG = b1*x1 + b2*x2 + b12*x1*x2;
Naphtha = c1*x1 + c2*x2 + c12*x1*x2;
Kerosene = d1*x1 + d2*x2 + d12*x1*x2;
Diesel = e1*x1 + e2*x2 + e12*x1*x2;
```

Step 4: Output and visualization

The computed values of specific gravity and product yields were displayed using formatted output statements:

```
fprintf('Specific Gravity: %.4f\n', SG);
fprintf('Naphtha Yield: %.2f%%\n', Naphtha);
fprintf('Kerosene Yield: %.2f%%\n', Kerosene);
fprintf('Diesel Yield: %.2f%%\n', Diesel);
```

2.4.2 MATLAB Implementation Approach

The problem is typically solved using linprog or intlinprog for integer constraints in the MATLAB optimization toolbox as shown in Table 1.

Table 1: Mixture design factor levels and experimental response data for crude oil blending

Run	A (%)	B (%)	Specific Gravity	Naphtha Yield (vol.%)	Kerosene Yield (vol.%)	Diesel Yield (vol.%)
1	100	0	0.9306	0.0	0.0	0.00
2	90	10	0.9240	1.5	0.6	0.35
3	80	20	0.9120	3.8	1.2	0.89
4	70	30	0.8998	5.6	3.1	1.57
5	60	40	0.8817	10.4	6.3	3.90
6	50	50	0.8697	12.0	7.5	4.80

7	40	60	0.8577	25.6	15.37	12.49
8	30	70	0.8445	28.8	17.5	14.60
9	20	80	0.8314	31.0	19.7	16.80
10	10	90	0.8184	33.2	21.9	19.00
11	0	100	0.8054	35.4	24.1	21.20

Optimization of blended crude oil and its potential distillate fractions utilizes Matlab Programming model to generate and validate the data for solving the problem for maximum yield with optimal volumetric proportions of various Antan blend crude oils. The model balances blend crude availability against product demand for naphtha, kerosene, diesel and residue fractions. The RSM analysis validate the model, ensuring that the predicted distillation yields for naphtha, kerosene, and diesel matched the experimental results, with significant improvements in reducing residue compared to conventional crude oil processed in Nigerian for an efficient refining strategy.

3.0 Results and Discussion

3.1 Preliminary Analysis and Classification of Crude Oil Samples

Preliminary analysis and classification of crude oil are essential first steps for evaluating physicochemical properties, quality, processing needs, and economic value. As composition varies by origin, early testing provides a fingerprint for classification (light/heavy, sweet/sour) and refinery compatibility decisions.

3.1.1 Analytical presentation of crude oil samples

Petroleum and its product quality are assessed by measurement of physical properties such as specific gravity, API value, viscosity and some empirical tests such as pour point or oxidation stability that are intended to relate to behavior in service. The evaluation test for the Antan crude oil, Oso condensate and the blend with Antan crude oil are shown in Tables 2.0 and 3.0, while Figure 1.0 depicted the AIP gravity contour classification.

Table 2: Physicochemical characterization of crude oil samples

Crude oil samples	Sp. Gr @ 60/60 ^{O}F	API Gravity	Sulphur Content (wt%)	Pour Point (^{O}C)	Viscosity @ 40^{O}C
Antan crude oil	0.9306	20.89	1.2	6.2	- 10.2
Oso condensate	0.8050	44.20	0.15	1.3	- 5
Antan blend crude oil	0.8577	34.60	0.45	3.3	5

The findings from Table 2.0 necessitate the upgrading of Antan crude oil with Oso condensate, this practice used to optimize feedstock quality, reduce costs, and improve refinery margins. The resulting blend, exhibits properties that shows non-linear changes in specific gravity, viscosity, and other, more complex behaviors as shown in Table 3.0. The Antan blend crude oils were classified as light, medium and heavy crude oils while sulphur content ($0.5 \leq 0 \geq 0.5$wt% as sweet or sour), viscosity and pour point of the ten crude oil samples. The physicochemical properties of Antan blend crude oils prepared at ratios of 100:0 to 0:100. The Antan blend modifies the hydrocarbon distribution by introducing lighter fractions from Oso condensate into the heavier Antan crude oil, thereby reducing undesirable components and improving overall hydrocarbon quality [12, 13].

The resulting blends exhibit characteristics comparable to Nigerian refinery feedstocks such as Bonny Medium with specific gravity (0.908), Bonny Light (0.850) and Escravos (0.845). These blends also enable classification of Antan crude oil hydrocarbon nature as heavy, medium, or light and the contaminant characteristics for Antan crude oil is sour (> 0.5 wt%) while Oso condensate is sweet (< 0.5 wt%) [13]. It can be observed from Figure 3, the 40:60 Antan crude oil–Oso condensate mixture demonstrates the most favorable performance, meeting typical Nigerian refinery specifications with specific gravity of 0.8577 (or 34.60 API^{O}). This blend is therefore recommended as a practical option for addressing shortages of lighter crude fractions in response to Nigeria's growing energy demand. Figures 4 and 5 evaluates the classification and suitability of the blends as refinery feedstocks based on their physicochemical properties. The results indicate strong potential for direct production of gasoline and transportation fuels without extensive conversion processes. The API gravity contour plot in Figure 3 support the fact that upgrading the crude oil samples result in enhancing the crude's market value prior to distillation [10, 13, 14]. This upgrading approach supports long-term economic competitiveness and operational sustainability.

Table 3: Crude oil classification-based characterization of Antan blend ratios

Blending ratio (%) Antan crude oil + Oso condensate	Specific gravity	API gravity (°API)	Crude oil Classifications
100:0	0.9306	20.89	HSOC
90:10	0.9240	22.20	HSOC
80:20	0.9120	23.65	HSOC
70:30	0.8998	25.76	MSOC
60:40	0.8817	28.98	MSOC
50:50	0.8697	31.20	MSOC
40:60	0.8577	34.60	MSWC
30:70	0.8445	36.10	MSWC
20:80	0.8314	38.69	LSWC
10:90	0.8184	41.40	LSWC
0:100	0.8054	44.20	LSWC

ACO – Antan Crude Oil, OC – Oso Condensate, HSOC - Heavy Sour Crude, MSOC - Medium Sour Crude, MSWC - Medium Sweet Crude, LSWC - Light Sweet Crude

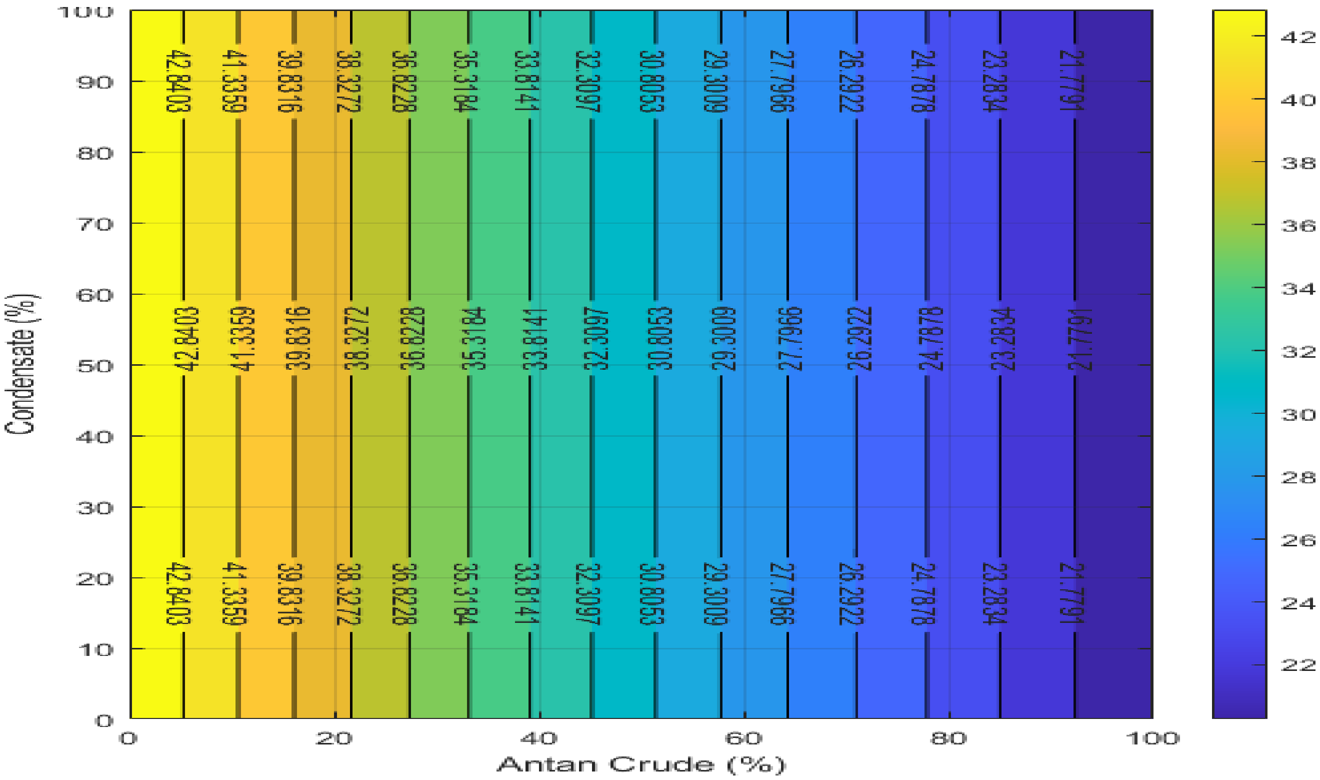

Figure 3: API gravity contour plot

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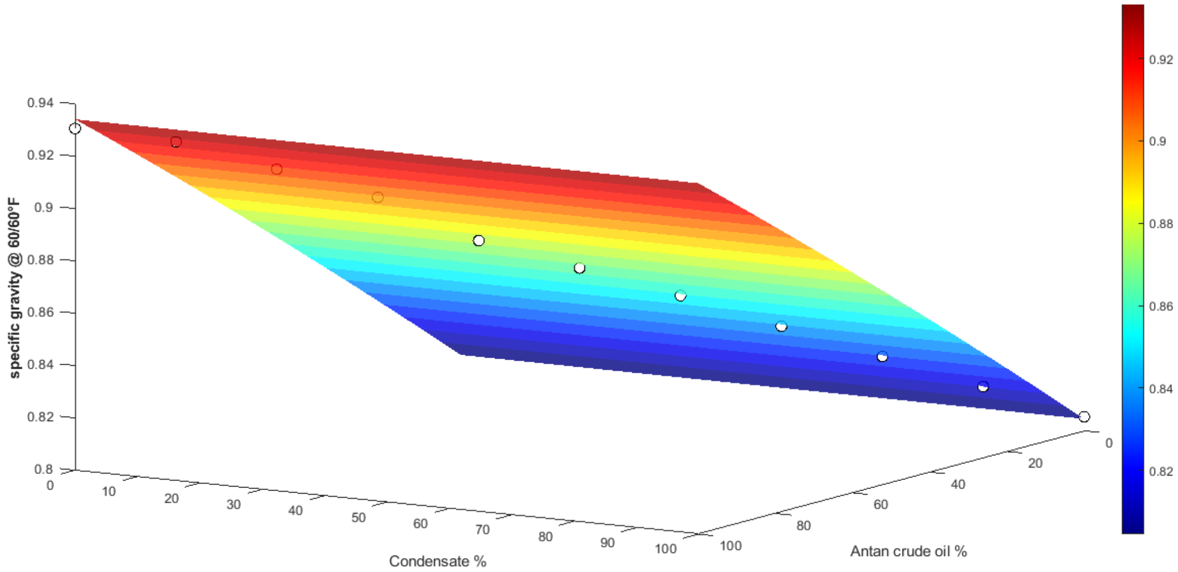

Figure 4: Raw crude oil samples and its blend analysis

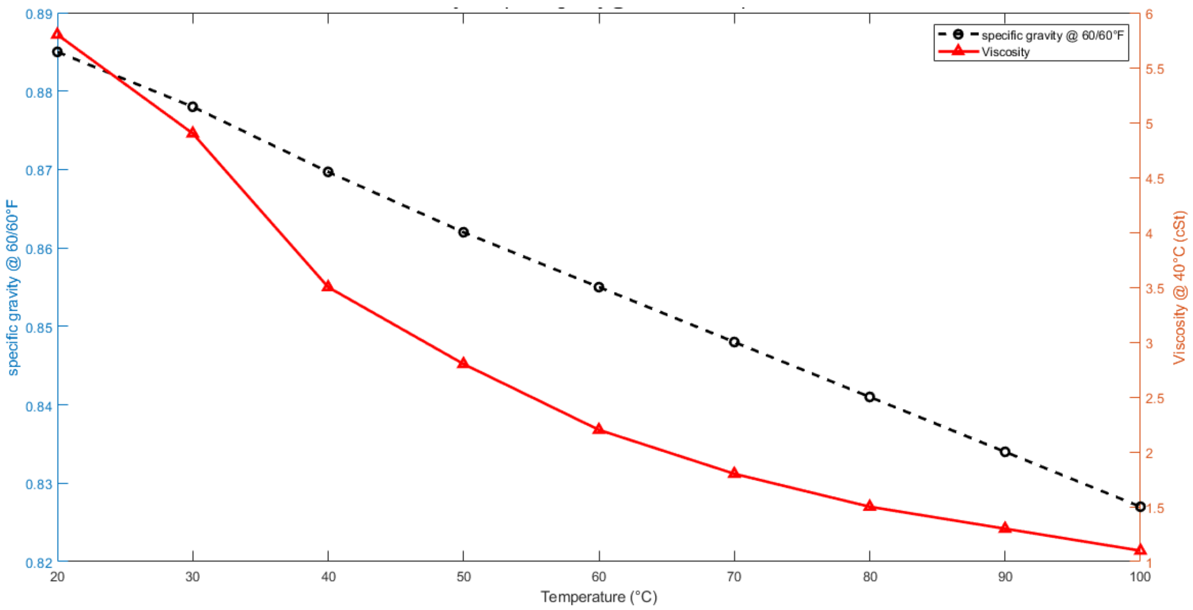

Figure 5: Crude oil physicochemical properties variation

The analysis of the crude oil composition in Figure 5 enables operators to verify the characteristics of the raw feedstocks; Antan crude, Oso condensate, and Antan blend crude oils, this determines the most efficient pathway for conversion into high-value distillate fractions. This implies that the crude oil assay provides an essential information for refining decisions. The crude oil analysis significantly impacts the performances of the feedstocks, including product yield, economic potential, heat recovery and the efficiencies of recoverable energy. This implies that, Antan crude oil and its blends have the potential to complement Nigeria's energy supply and serve as a valuable feedstock to petrochemical feedstock [15, 16].

3.2 Analysis of Crude Oil Based on Fractional Cuts Obtained from TBP Cut Distillation

The crude oil sample (Antan crude, Oso condensate and 40:60 blend crude oils) can be utilized within Nigerian refineries as a feed stock for batch distillation. The crude oil sample is separated according to their boiling points by fractional distillation. Crude oil distillation is performed under atmospheric pressure or under vacuum. Low-boiling fractions of crude oil usually vaporize below 400 °C under atmospheric pressure and thus these low-boiling fractions are separated while the high boiling by vacuum distillation.

3.2.1 Distillation profiles of the raw samples' crude oils

The varied composition in crude oil has led to the existence of a number of characterization systems. Each of these characterization systems are important for decision making at a stage of refining the crude oil sample as presented in Table 4.0.

Table 4: Physicochemical assessment of raw crude oils and their Blends distillation profiles

Crude samples/Fractions	TBP Boiling range (ᴼC)	Oso condensate	Antan crude oil	Blend crude oil
Naphtha	IBP – 170	37.62	0	25.60
Kerosene	170 – 240	16.37	0	15.37
Diesel	240 – 305	11.28	0	12.49
Residue	305+	22.74	94.45	45.50
Losses		11.99	5.50	1.04
Total		100.00	100.00	100.00

Table 4 shows Antan crude yields no light fractions due to dominant HMW components. Blending with Oso redistributes hydrocarbons, reducing HMW (94.45% to 45.50%) and yielding 25.60% naphtha, 15.37% kerosene, and 12.49% diesel. Interestingly, Figure 1 and Table 2 confirmed the result for Antan crude oil with low API gravity (20.89). API gravity of Antan blend oil revealed a high-quality crude oil with good market value and refining suitability [16]. The lighter and more valuable hydrocarbons will be obtained at ordinary distillation with high API while low API gravity indicates heavier, more viscous crude oil (Figure 2.0).

3.2.2 Integrated feasibility and quality control study of fuel distillates from crude oil feedstocks

The periodic evaluation of light petroleum fraction is to determine fuel quality, optimize refinery production and to ensure safety matching supply with high demand for transportation and feedstocks. This provides essential data for refinery design and process modeling. Quality assessment against standards relies on parameters such as API gravity, RVP, distillation range, sulphur content, and flash point, as presented in Tables 5–8.

(a) Naphtha characterization

As mentioned above, naphtha is a product obtained after distillation crude oil and it is introduced as a straight run gasoline (SRG). After leaving the distillation column, the fractions do not yet correspond to the requirements of the market so it require some form of characterization to ascertain the product quality as shown in Tables 5 and 6.

Table 5: Analytical Determination of quality parameters in different Naphtha fractions

Test parameters	Antan crude oil	Oso condensate	Blend crude oil	DPR standard specifications
Specific gravity @ 15/4 ᴼC	-	0.7482	0.7511	0.7511
API gravity	-	57.62	56.89	56.89
Total sulphur wt %	-	0.05	0.1	0.03
Octane number	-	71.02	70.00	78
Hydrocarbon type				
▪ Paraffins (vol%)	-	80.79	78.41	<2 max
▪ Olefins(vol%)	-	0.59	0.63	1 – 12
▪ Aromatics(vol%)	-	18.63	20.95	10 – 53

Table 6: Distillation cut for crude oil samples and its blend

Distillation cut ᴼC	Antan crude oil	Oso condensate	Blend crude oil
IBP	-	52	60
10	-	75	85
50	-	107	115
90	-	150	150
95	-	161	160
FBP		171	170

Tables 5 and 6 indicate that naphtha fractions from Oso condensate and the blend largely conform to Nigerian DPR specifications for specific gravity and API gravity. However, sulphur content in the blend (0.1 wt%) exceeds the DPR limit (0.03 wt%), suggesting the need for desulfurization. Octane numbers (70–71) fall below the DPR requirement (78), indicating poor anti-knock quality. Hydrocarbon composition is within acceptable paraffin and aromatic ranges. Distillation cuts (IBP 52–60 °C; FBP ~170 °C) align with typical naphtha boiling ranges, confirming suitable volatility, though quality improvement is required for refinery applications. The result showed that naphtha octane (70–73) meets the SRG limits; blend crude oil exhibits higher values due to HMW. Antan crude oil yields no products, requiring catalytic cracking; blending increases paraffins, olefins, aromatics values [10, 16]. Table 6 showed 10% point that characterizes the starting properties of the fuel (volatility), the 50% point – the rapidly of the engine warm up and the quality of air-fuel mixture formation in the warmed-up engine while the 90% point and FBP characterize the completeness of gasoline evaporation [12, 17]. The results revealed the effect of blending Antan crude oil with Oso condensate in the blend crude oil compared to the pure condensate.

(b) Kerosene characterization

Kerosene fraction is a light mixture of hydrocarbons with maximum distillation temperature of 170 °C at the 10% recovery point, a FBP of 240 °C and a minimum flash point of 37.8 °C. Table 7.0 shows the properties of the kerosene fractions at the atmospheric – vacuum distillation of the sample crude oils.

Table 7: Analytical determination of quality parameters in different Kerosene fractions

Test parameters	Antan crude oil	Oso condensate	Blend crude oil	DPR standard specifications
Specific gravity @ 15/4 °C	-	0.8225	0.8307	0.840
API gravity	-	40.54	38.84	40
Total sulphur wt%	-	0.057	0.049	0.1
Smoke point, mm	-	17	19	25
Flash point °C		55	65	38
Hydrocarbon type Paraffins Olefins Aromatic	- - -	72.89 0.810 26.80	72.16 0.800 27.01	High paraffinic. Low in straight-run. Low good burning characteristics.

Tables 7 and 8 show that kerosene fractions from Oso condensate and the blend meet key Nigerian DPR specifications for sulphur content (≤0.1 wt%), indicating good environmental performance. The blend exhibits an improved flash point (65 °C) above the DPR minimum (38 °C), enhancing handling safety, while its slightly higher smoke point (19 mm) suggests better combustion than Oso condensate, though still below the DPR-recommended 25 mm [18]. Distillation profiles (170 – 235 °C) fall within typical kerosene ranges, with the blend showing improved thermal behaviour. This indicates, the blending aligns partially with DPR standards but requires further optimization for smoke quality compliance.

Table 8: Distillation cut for crude oil samples and its blend

Distillation cut °C	Antan crude oil	Oso condensate	Blend crude oil
IBP	-	170	183
10	-	182	199
30	-	194	204
50	-	203	209
70	-	212	213
90	-	225	218
95	-	229	222
FBP	-	235	232

Furthermore, the variations in distillation cut temperatures across the crude oil samples and their blend markedly affect kerosene fraction yield, quality, and potential contamination as shown in Table 8. The Oso condensate and the blend crude oil exhibit progressive boiling ranges from IBP (170–183 °C) to FBP (232–235 °C), reflecting differences in fraction recovery and purity compared to Antan crude oil, where data gaps suggest limited kerosene yield characterization.

(c) Diesel characterization

Diesel fuel is a complex mixture derived from crude oil through fractional distillation, consisting mainly of aliphatic and aromatic hydrocarbons with a boiling point range of approximately 250–350 °C. It is classified based on the type of engine it fuels. According to the guidelines of the applicable standards, a specific volume of the products was distilled under a condition tabulated in Table 9.

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Table 9: Analytical Determination of quality parameters in different Diesel fractions

Test parameters	Antan crude oil	Oso gas condensate	Blend crude	DPR standard specifications
Specific gravity @ 60°F	-	0.8589	0.8601	0.8499
API gravity	-	33.35	33.02	37
Total sulphur wt%	-	0.171	0.169	0.2
Cetane number	-	62.97	77.71	48.5
Total ash	-	0.001	0.002	0.01
Flash point ^{O}C	-	94	100	60
Viscosity @ 40 ^{O}C	-	3.17	3.02	5.0

Table 9 shows that diesel fractions from Oso condensate and the blend generally comply with Nigerian DPR specifications. Sulphur (≤0.2 wt%), ash (≤0.01 wt%), flash point (≥60 °C), and viscosity (≤5.0 cSt) meet standards. High cetane numbers (>48.5) indicate excellent ignition quality [18]. However, API gravity values are slightly below the DPR reference, suggesting relatively heavier fuel characteristics. Experts suggest that the future petroleum supply will increasingly rely on heavier crude oils, as a substantial share of incremental demand to meet the population growth and expansion of infrastructure in countries like Nigeria [10, 13, 18].

(d) Vacuum residual characterization

Vacuum residual fractions are heavy, high-boiling petroleum components containing complex, HMW compounds and large proportion of inorganic elements. It is the final product received after distillation of crude oil as shown in Table 10

Table 10: Quality control parameter of different Vacuum residual fractions

Test parameters	Oso condensate	Antan crude	Blend crude
Specific gravity @ 15/4 ^{O}C	0.9345	0.9289	0.9500
API gravity	19.92	20.83	17.36
Total sulphur wt%	0.042	0.280	0.184
Flash point ^{O}C	136	74	145
Viscosity	16.68@ 40 ^{O}C	6.6 @ 82 ^{O}	25.41 @ 100 ^{O}C

Table 10 presents the quality control parameters of vacuum residual fractions from Oso condensate, Antan crude, and their blend, revealing clear variations in heaviness, safety, and composition. The blend crude exhibits the highest specific gravity (0.9500) and lowest API gravity (17.36), indicating a heavier and more viscous residue compared to Oso condensate and Antan crude. In contrast, Antan crude is slightly lighter (API 20.83), while Oso condensate falls in between. Sulphur content shows that Antan crude has the highest value (0.280 wt%), suggesting greater potential for corrosion and environmental concerns, whereas Oso condensate is significantly sweeter (0.042 wt%). The blend (0.184 wt%) reflects intermediate behaviour, confirming dilution effects through blending. Flash point values indicate that the blend (145°C) and Oso condensate (136°C) are safer to handle and store than Antan crude (74°C), which is relatively more volatile. Viscosity results further support these trends, with the blend showing the highest resistance to flow, consistent with its heavier nature, while Antan crude remains the least viscous. The results indicate that blending significantly alters the vacuum residue characteristics, leading to increased density and viscosity while improving handling and safety performance. In addition, sulphur content is moderated across the blended samples, enhancing their suitability for targeted refinery operations and heavy fuel applications. The yield profiles within the IBP–305 °C distillation range confirm regulatory and operational compliance, while the presence of appreciable residual hydrocarbons in Antan crude suggests strong potential as a petrochemical feedstock [12, 16, 18]. To enhance predictive accuracy and process efficiency, a computational design approach using MATLAB was suggested to be adopted to optimize feedstock blending ratios, simulate distillation yield profiles, and model the blends property behaviour. This enables robust prediction of product distributions and supports data-driven refinery decision-making for improved yield optimization and feedstock selection.

3.3 Crude Oil Characterization and Blend Optimization for Enhanced Fuel Distillate Yield in our Local Refineries in Nigeria

This study evaluates Antan crude oil, Oso condensate and 40:60% blended ratio to enhance refinery feedstock quality. Crude characterization and mixture optimization were applied to improve specific gravity and maximize fuel distillate yields, supporting efficient performance of existing Nigerian refinery systems and sustainable petroleum processing. Antan crude oil and Oso condensate were selected as representative feedstocks and their blend to enhance overall crude quality and distillate performance. Antan crude is heavy in nature, contributes higher middle and heavy fractions, while Oso condensate provides lighter hydrocarbons that improve fluidity and increase light-end recovery. The strategic blending of these two feedstocks is expected to produce a balanced crude with improved processing characteristics suitable for existing atmospheric and vacuum distillation units in local refineries.

3.3.1 Evaluation of distillation yield characteristics of three feedstocks relative to Nigerian crude

This study evaluates the distillation yield characteristics of three feedstocks using Nigerian crude oil as a benchmark. It compares fractional distribution and product recovery behaviour to assess feedstock quality and suitability for efficient refinery processing and improved fuel production performance. Bonny light (OPEC reference crude oil) is an improvement in the distillation profiles of raw crude oil samples aim to enhance the separation efficiency of volatile components, reduce energy consumption, and increase the yield of valuable light-end products while minimizing vacuum residue. Comparison with standard refinery methods provides insight for quicker characterization of crude distillate fractions, as presented in Table 11.

Table 11: Volume analysis for distillation profiles of raw crude oil samples

Crude samples/Fractions	Oso condensate yield (%)	Antan crude oil yield (%)	Blend crude oil yield (%)	Bonny light crude oil yield (%)
Naphtha	37.62	0	25.60	17.25
Kerosene	16.37	0	15.37	14.45
Diesel	11.28	0	12.49	16.15
Residue	22.74	94.45	45.50	42.50
Losses	11.99	5.50	1.04	08.50
Total	100.00	100.00	100.00	100.00

Table 11 presents the key physicochemical properties and distillation yield distribution of Oso condensate, Antan crude oil, and the Antan blend crude oil, with comparison to Bonny light as OPEC reference crude oil (benchmark) for Nigerian and global refining standard. The evaluation focuses on light distillate fractions and their corresponding yields obtained from distillation of the raw crude oil samples. Figure 4 shows Antan blend yields 25.60% naphtha, 15.37% kerosene, and 12.49% diesel. Naphtha exceeds Bonny Light (17.25%) but is lower than Oso condensate (37.62%). Vacuum residue is high (45.50%) due to HMW hydrocarbons, indicating need for upgrading (Figure 6).

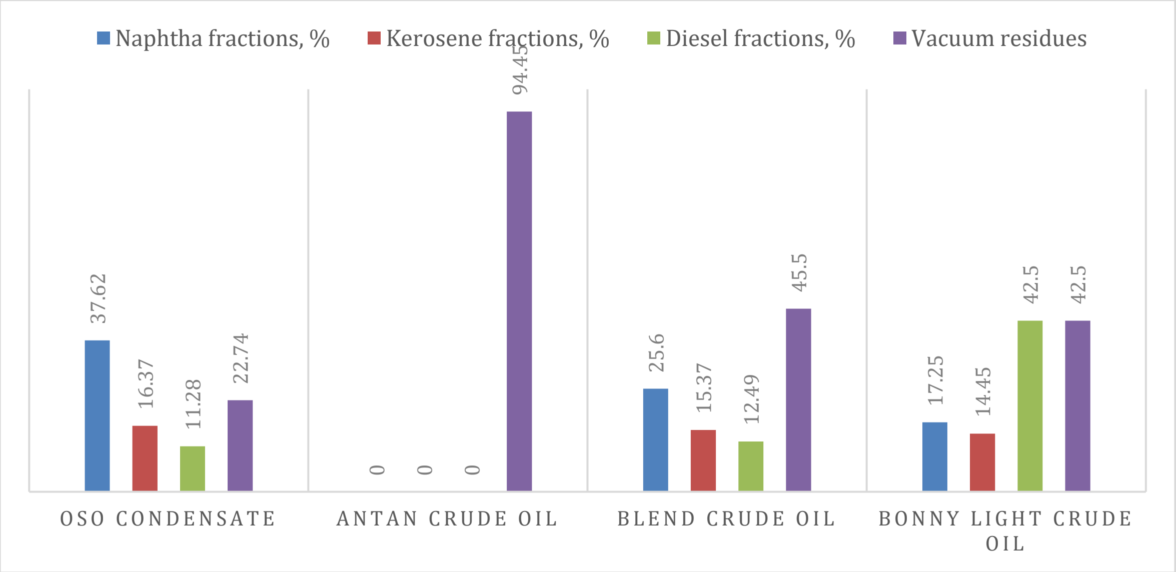

Figure 6: Evaluation of distillation yield on raw crude oil samples

Blending improves light fractions but challenges remain for residue reduction. The distillation cut distribution therefore provides an important preliminary indicator of crude oil quality and refining potential [13, 19]. In addition to the distillation profile, other critical parameters such as specific gravity, API gravity, and sulphur content were evaluated. These parameters are essential because crude oil quality and product yield correlations depend on multiple properties rather than density alone [19]. These findings provide a basis for further optimization of Antan blend crude oil ratios and processing conditions to maximize light-end recovery and reduce heavy residue formation.

Figure 6 illustrates the distribution of distillation fractions for Oso condensate, Antan crude oil, blend crude oil and Bonny light crude oil (OPEC), this highlights a clear difference in product yield patterns across the feedstocks. Bonny light crude oil, serving as a global benchmark, exhibits a favourable yield profile with significant diesel (42.5%) and balanced contributions from naphtha (17.25%), kerosene (14.45%), and residue (42.5%), reinforcing its desirability for refinery operations. The result confirms that crude blending improves distillation performance, shifting yields toward more valuable fractions while reducing heavy residue limitations.

3.3.2 Assessment of crude oil feedstock quality and spatial distribution relative global benchmarks

Assessment of crude oil feedstock quality and spatial distribution relative to global benchmarks is essential for refinery planning and crude selection. Crude oils vary significantly by origin, with properties such as API gravity, sulphur content, and yield profiles reflecting their geological formation. Globally recognized benchmarks crude oils like Basra light (Iraq), Urals oil light (Russian), and Bonny light (Nigeria), this serves as reference standards for fuel yield and quality comparison. By classifying crude types (light/heavy, sweet/sour) alongside their countries of production, this approach highlights regional variability and evaluation of local feedstocks, against international standards for optimal processing and market competitiveness (see Figure 7 to 11)

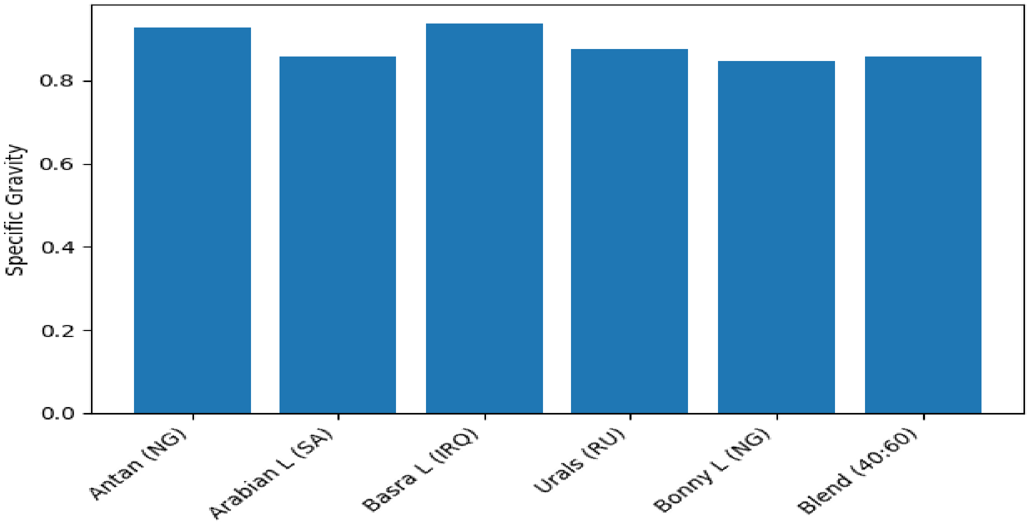

Figure 7: Plot of specific against crude oil type

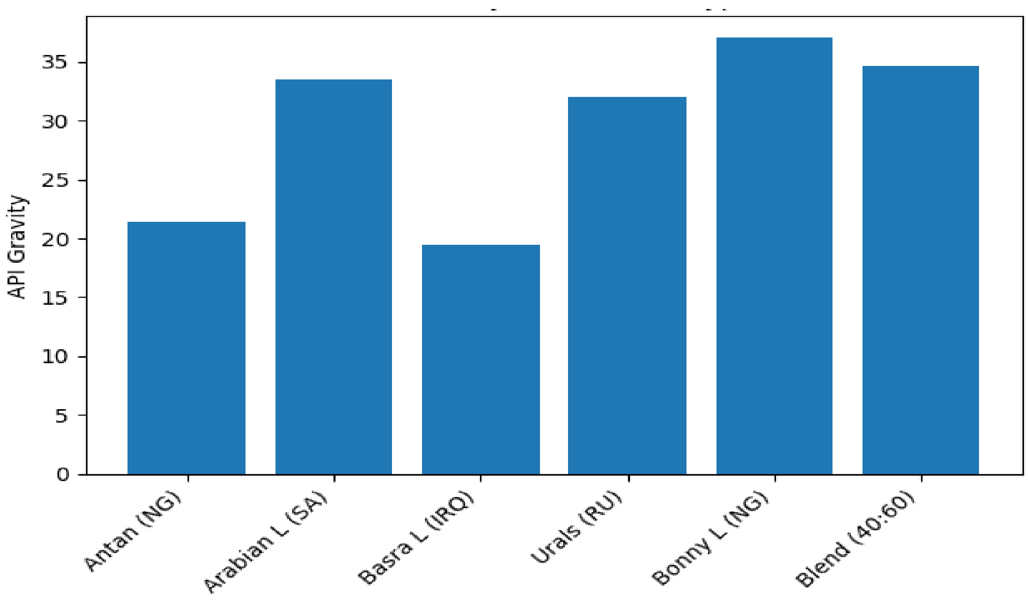

Figure 8: Plot of API gravity against crude oil type

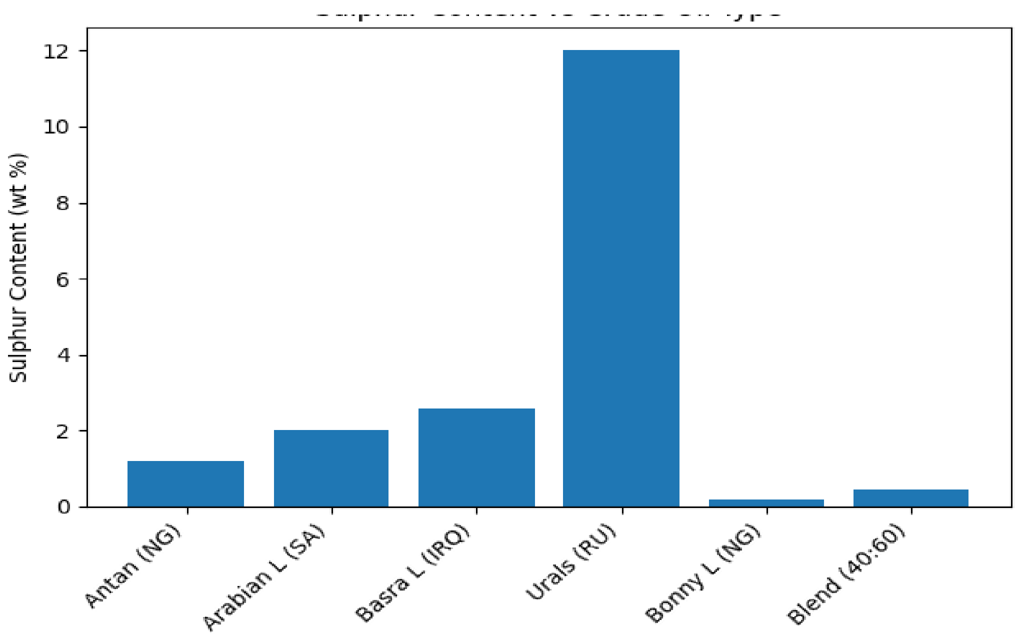

Figure 9: Plot of sulphur content against crude oil type

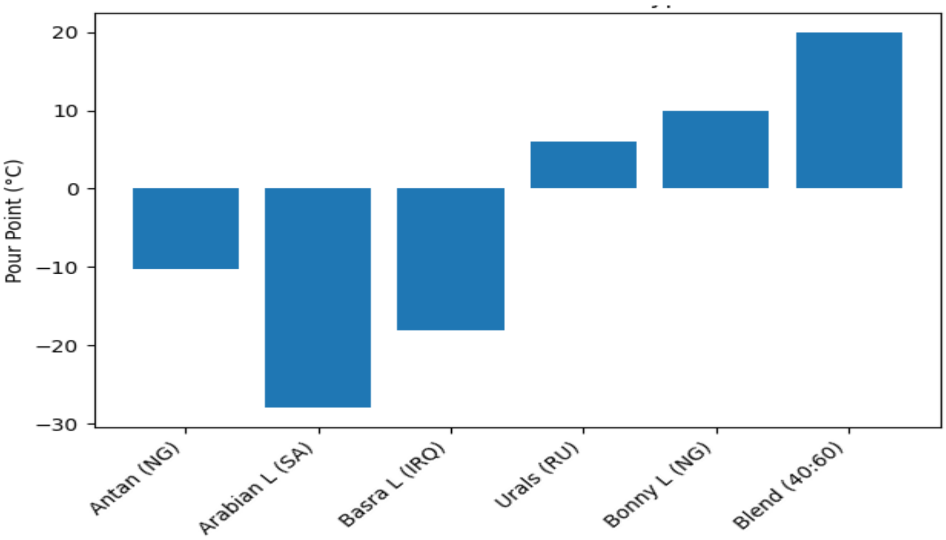

Figure 10: Plot of pour point against crude oil type

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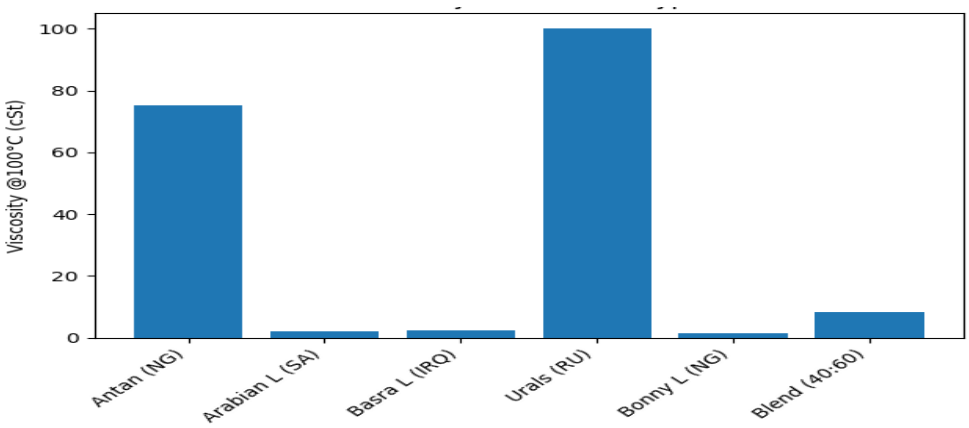

Figure 11: Plot of viscosity against crude oil type

Figures 7 to 11 are physicochemical analysis crude oil types that highlights clear compositional and quality among the crude oil samples, reflecting variations in origin, maturity, and refining suitability. The plots confirm that Bonny light and blended crude are the most refinery-friendly (light, low sulphur, low viscosity) and Urals and Basra crudes are heavier and sourer, requiring intensive processing while Blends (40:60 Antan + Oso) improves API gravity and reduces sulphur compared to heavier Nigerian crude, demonstrating strong optimization potential for refinery feedstock design. The specific gravity ranges 0.845 – 0.935 (Basra highest, the Bonny lowest). API gravity 19.44 – 37 (Bonny highest). Viscosity peaks in Urals (100 cSt) and Antan (75.10 cSt). Pour point spans −28 to 20°C. Sulphur highest in Urals (12%), lowest in Bonny (0.16%). The results reinforce a clear quality hierarchy among the crudes. Basra (0.935 SG, 19.44°API) and Antan (0.926 SG, 21.36°API) are heavy, confirming low API, high density correlation and explaining their higher viscosity (75.10 cSt for Antan crude oil). Urals stands out as the most problematic feedstock, combining extreme sulphur (12%) with very high viscosity (100 cSt), indicating severe refining and desulphurization demand. Subsequently, Bonny light (0.845 SG, 37°API) exhibits optimal properties with very low viscosity (<1.5 cSt) and sulphur (0.16%), making it highly desirable. Arabian light shows balanced performance but remains sour (2%). The blend (0.858 SG, 34.60°API) significantly improves Antan crude oil quality, reducing sulphur to 0.45% and viscosity to 8.25 cSt is demonstrating that blending effectively upgrades extra-heavy Nigerian crude into a more refinery-compatible, sweeter feedstock. These differences influence refining complexity and product yield. MATLAB design programming is essential to optimize blending ratios, accurately predict properties, and enhance feedstock quality toward desirable global benchmarks.

3.3 Optimization of Antan Blend Crude Oil Using MATLAB Programming Design

3.3.1 MATLAB design analysis for surface response plot

The application of advanced optimization and modelling to enhance the distillation yield of petroleum light fractions using software like Matlab programming design with response surface methodology (RSM) on various Antan blend crude oil samples. This procedure provides an efficient means to achieve optimal economic returns while minimizing the number of experimental runs as shown in Table 12

Table 12: MATLAB programming data for surface response plot analysis

Std	Run	Factor 1 A: Antan crude oil %	Factor 2 B: Condensate %	Factor 3 C: Specific Gravity ºF	Response 1: Naphtha	Response 2: Kerosene	Response 3: Diesel
1	1	100	0	0.9306	0	0	0
12	2	90	10	0.9240	0	0	0
9	3	80	20	0.9120	3.8	1.2	0.89
8	4	70	30	0.8998	5.6	3.1	1.57
10	5	60	40	0.8817	10.4	6.3	3.9
11	6	50	50	0.8697	12	7.5	4.8
6	7	40	60	0.8577	25.6	15.37	12.49
7	8	30	70	0.8445	28.8	17.5	14.6
4	9	20	80	0.8314	31	19.7	16.8
2	10	10	90	0.8184	33.2	21.9	19
5	11	0	100	0.8054	35.4	24.1	21.2
3	12	50	50	0.8697	18.7	11.9	8.65

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MATLAB-RSM shows increasing Oso condensate reduces specific gravity and boosts light fractions. Maximum yields for 50:50 blend: 35.40% naphtha, 24.10% kerosene, 21.20% diesel; the minimum yields: was observed 80:20 Antan blend corresponding to 3.80% naphtha, 1.20%kerosene and 0.89% diesel, respectively. Matlab analysis generates an accurate map out fraction cuts using the three keys' factors for various Antan blend crude oil samples for fraction yield estimates and efficiency by identifying optimal zones for high-value cuts for naphtha, kerosene and diesel yield (Table 12). The percentage yields of each fraction under different operating conditions, highlight increases in high-value products like 35.40% naphtha, 24.10% kerosene and 21.20% diesel fractions compared to conventional methods [10, 13, 19].

3.3.2 Optimizing process variables using ANOVA and 3D response surface plot

(a) ANOVA Linear Model for Naphtha

The Analysis of Variance (ANOVA) linear model was applied using Matlab to evaluate the influence of the independent variables such as Antan crude oil composition (A), condensate percentage (B), and specific gravity (C) on the naphtha yield response is presented in Table 13.

Table 13: MATLAB formatted ANOVA output for naphtha yield

Source	Sum of Squares	Df	Mean Square	F-Value	P-Value	Remark
Model	2136.90	3	712.30	66.68	<0.00001	Significant, S
A–Antan crude oil	9.67	1	9.67	0.9053	0.3692	Not significant, NS
B–Condensate	11.94	1	11.94	1.12	0.3212	NS
C–Specific gravity	9.84	1	9.84	0.9212	0.3652	NS
Residual	85.45	8	10.68	–	–	–
Corrected Total	2222.86	11	–	–	–	–

Statistical Parameter	**Value**
Standard Deviation	3.27
Mean Response	15.48
Coefficient of Variation, %	34.11
R^2	0.9615
Adjusted R^2	0.9471
Predicted R^2	NA
Adequate Precision	20.7764

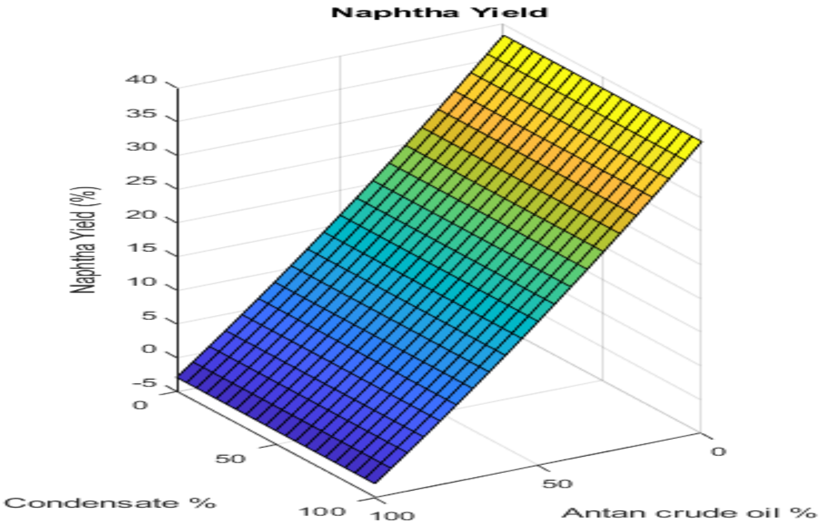

Figure 12: ANOVA analysis and 3D response surface plots for naphtha

The model shows strong prediction for naphtha yield with $R^2 = 0.9615$, adjusted $R^2 = 0.9471$, adequate precision 20.7764, and coefficient of variation 34.11%, supporting reliable process optimization.

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(b) ANOVA Linear Model for Kerosene

The Matlab ANOVA linear model evaluates Antan blend ratios, optimizing kerosene yield while meeting specifications. Blending enhances distillates, with optimized ratios producing significant kerosene yields, as summarized in Table 14.

Table 14: Matlab formatted ANOVA output for kerosene yield

Source	Sum of Squares	df	Mean Square	F-Value	P-Value	Remark
Model	936.75	3	312.25	92.80	<0.00001	S
Factor A–Antan Crude (%)	7.28	1	7.28	2.16	0.1795	NS
Factor B–Condensate (%)	8.57	1	8.57	2.55	0.1491	NS
Factor C–Specific Gravity	7.41	1	7.41	2.20	0.1762	NS
Residual Error	26.92	8	3.36	—	—	—
Corrected Total	953.66	11	—	—	—	

Statistical Parameter	Value
Model Standard Deviation	1.83
Mean Response	9.72
Coefficient of Variation (C.V %)	24.26
R^2 (Coefficient of Determination)	0.9721
Adjusted R^2	0.9616
Predicted R^2	Not Available
Adequate Precision	21.2584

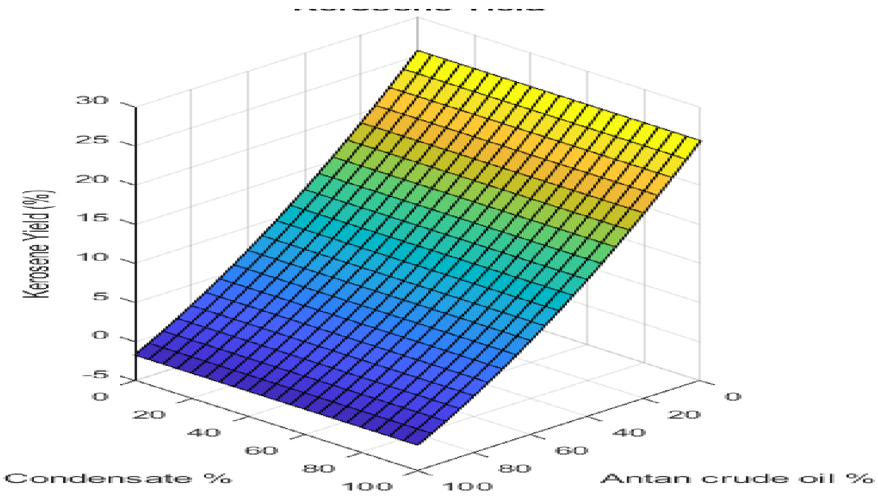

Figure 13: ANOVA analysis and 3D response surface plots for kerosene

ANOVA shows the kerosene yield model is significant ($p < 0.00001$) with $R^2 = 0.9721$ and adequate precision 24.26, confirming excellent fit and reliable prediction for optimization. Despite this, the model remains reliable for prediction and optimization as presented in Figure 13 with the adequate precision value of 24.26, which is significantly higher than the recommended minimum value of 4. This high adequate precision confirms that the model has a strong signal and can effectively be used to navigate the design space and optimize kerosene yield in Matlab-based response surface analysis.

(c) ANOVA Linear Model for Diesel

The ANOVA linear model in Matlab evaluates how Antan crude composition, condensate proportion, and specific gravity as shown in Table 15 influence diesel yield, using statistical indicators for optimization.

Table 15: MATLAB formatted ANOVA output for diesel yield

Source	Sum of Squares	Df	Mean Square	F-value	P-value	Remark
Model	709.98	3	236.66	50.73	< 0.00001	S
A–Antan crude (%)	5.70	1	5.70	1.22	0.179	NS
B–Condensate (%)	6.70	1	6.70	1.44	0.1491	NS
C–Specific gravity	5.82	1	5.82	1.25	0.1762	NS

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Residual Error	37.32	8	4.67	–	–	–
Corrected Total	747.30	1	–	–	–	–

Statistical Parameter	:Value	Additional Indicator	Value
Standard Deviation	2.16	Model factor	Linear
Mean Diesel Yield (%)	7.94	Adjusted R^2	0.9313
Coefficient of Variation (CV %)	18.87	R^2	0.9501
Predicted R^2	NA	Adequate Precision	18.0533

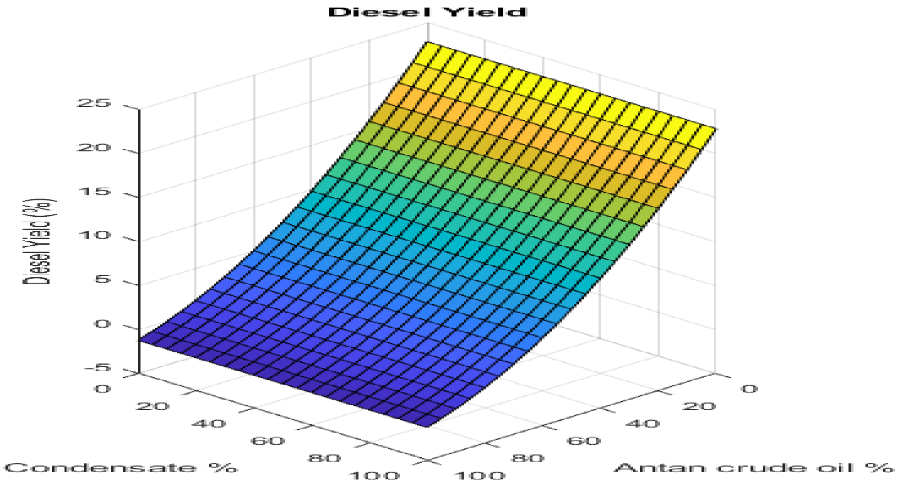

Figure 14: ANOVA analysis and 3D response surface plots for diesel

Matlab ANOVA shows the diesel yield model is statistically significant (F = 50.73, $P < 0.00001$) with $R^2 = 0.9501$, adjusted $R^2 = 0.9313$, and adequate precision 18.0533, confirming strong predictive capability despite individual variables being insignificant ($P > 0.05$). The results indicate the model reliably predicts diesel yield, explaining 95.01% of variability. High F-value and adequate precision confirm strong signal, while individual variables are insignificant, suggesting yield depends on combined factor interactions.

3.4. Comparative Evaluation of TBP Distillation Yields Using MATLAB Simulation, Laboratory Experiment, and Bonny Light Crude Benchmark

TBP distillation yield analysis plays a key role in evaluating crude oil fractionation characteristics and refinery efficiency. This study compares yields derived from Matlab-based predictive modeling, laboratory experimental measurements, and Bonny Light crude as a reference benchmark. The results reveal differences in fraction recovery, confirm the reliability of computational predictions, and demonstrate that Matlab-based design offers notable improvements over conventional laboratory methods (Figure 15).

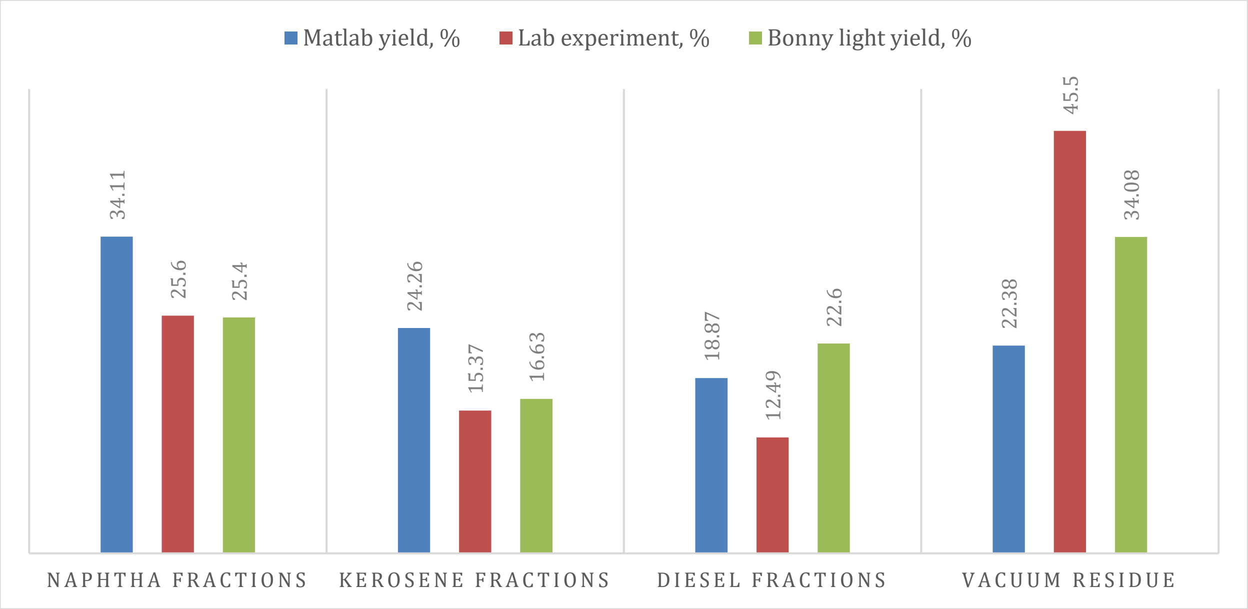

Figure 15: Characterization and optimization of product yields using MATLAB compared to other techniques

Figure 15 shows Matlab-predicted yields: 34.11% naphtha, 24.26% kerosene, 18.87% diesel, 22.38% residuum, and 0.85% losses. Laboratory distillation produced lower light fractions and higher residue (12.49% diesel, 45.50% residuum), reflecting HMW hydrocarbons retention, while naphtha and kerosene remain within Nigerian refinery standards, confirming reasonable separation efficiency. It can be observed that Matlab model predictions generally estimate higher yields of lighter fractions (34.11% naphtha) and a lower residuum fraction (22.39% residuum) compared to 25.60% naphtha and 45.50% residuum in experimental results. The small difference in loss values (0.90% predicted compared to 1.04% experimental), reducing residuum from 45.5% to 22. 38%, this further confirms that the mass balance of the distillation process is reasonably consistent [13, 20]. The model provides optimistic and reasonable predictions of distillation yields, while the experimental results reflect practical limitations of laboratory distillation systems. The findings also indicate potential for process optimization to increase diesel yield and reduce residuum formation, thereby improving the overall efficiency of crude oil fractionation.

3.5 Economic Evaluation

3.5.1 Comparative Economic Analysis of Feedstocks

Comparative economic assessment of crude oil feedstocks is fundamental to evaluating refinery performance and investment viability. In this study, Antan crude oil, Oso condensate, and a 40:60 Antan/Oso blend are analyzed relative to benchmark crudes using integrated True Boiling Point (TBP) distillation data and financial performance metrics. Key economic indicators, including Net Present Value (NPV), Internal Rate of Return (IRR), payback period, and profitability index, are employed to quantify economic attractiveness. The incorporation of these indicators provides a robust framework that links product yield distribution to long-term profitability, operational risk, and optimal crude selection strategies in refinery systems.

3.5.2 Comparative economic analysis and technical performance

Antan crude oil, a domestic heavy feedstock characterized by high viscosity and relatively low API gravity, exhibits limited direct refining value due to its high residuum yield. However, its economic potential can be significantly enhanced through strategic blending, as demonstrated by Matlab-based optimization. In contrast, Oso condensate is a light crude with high API gravity and low viscosity, making it an effective blending component for upgrading heavier crudes. Its inclusion improves flow properties, increases light-end yields, and enhances overall refinery economics. Bonny light crude serves as a premium benchmark due to its favorable properties, including high API gravity and low sulphur content. These characteristics promote higher yields of valuable light fractions such as off-gas, naphtha, and kerosene, thereby maximizing economic returns and operational efficiency [21].

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3.5.3 Performance of 40:60 Antan/Oso blend

The 40:60 Antan/Oso blend demonstrates a marked improvement in both technical and economic performance compared to Antan crude alone. The blend achieves increased recovery of high-value products like naphtha, kerosene, and diesel while a significant reduction in residue formation. This optimized yield distribution enhances gross product worth (GPW) and overall refinery margin. It is interesting to know that the blend offers a competitive alternative to benchmark crudes such as Bonny light, particularly when optimized using advanced computational approaches (Matlab design). The results highlight the effectiveness of blending strategies in transforming lower-value extra-heavy Antan crudes into economically viable refinery feedstocks, thereby supporting improved profitability and resource utilization.

3.5.4 Approaches to cost estimation

(a) Value drivers

1. API gravity and sulphur content: Light, sweet crudes (Oso condensate) produce more high-value products and require lower processing cost.
2. TBP yield structure: Higher naphtha/kerosene/diesel fractions directly increase GPW.
3. Residue content: High residue (Antan crude oil) lowers profitability unless upgrading units are available.

(b) Gross product worth

Mathematical expression

$$\text{GPW} = \sum(Y_i \times P_i)$$

GPW = Σ (Yield × Product Price)

- Y_i= Yield of product i (fraction or %)
- P_i= Market price of product i ($/bbl or $/ton)

If a crude oil produces:

- 30% Naphtha at $95/bbl
- 20% Kerosene at $105/bbl
- 25% Diesel at $115/bbl
- 25% Residue at $60/bbl

Then:

$$GPW = (0.30 \times 95) + (0.20 \times 105) + (0.25 \times 115) + (0.25 \times 60)$$
$$GPW = 28.5 + 21 + 28.75 + 15 = 93.25\ \$/bbl$$

3.5.5 Economic analysis

(a) Annual Profit (AP)

A standard refinery-based expression is:

$$\text{AP} = \text{Net Refinery Margin} \times \text{Processing Capacity} \times \text{Operating Days}$$

$$AP = NRM \times C \times D$$

Where:

- AP = Annual Profit ($/year)
- NRM = Net Refinery Margin ($/bbl)
- C = Refinery capacity (bbl/day)
- D = Operating days per year (days/year)

Annual profit is derived from refinery margin and throughput:

$$\text{Annual Profit} = \text{NRM} \times \text{Refinery Capacity} \times \text{Operating Days}$$

(b) Net present value (NPV)

$$NPV = \sum_{t=1}^{20} \frac{Annual\ Profit}{(1+0.10)^t} - Investment$$

(c) Internal rate of return (IRR)

General IRR equation

$$0 = \sum_{t=1}^{n} \frac{C_t}{(1+IRR)^t} - C_0$$

Where:

- C_t= Cash inflow (annual profit) at time t
- C_0= Initial investment (capital cost)

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- n= Project lifetime (years)
- IRR = Internal Rate of Return (unknown, solved iteratively)

(d) Simplified constant cash flow form

If annual profit is constant:

$$C_0 = AP \times \frac{1-(1+IRR)^{-n}}{IRR}$$

- **If** IRR > discount rate (hurdle rate) then project is economically viable
- **If** IRR < discount rate then project is not economically attractive

(e) Payback Period (PBP)

Time required to recover initial investment:

$$\text{PBP} = \frac{\text{Initial Investment}}{\text{Annual Profit}}$$

(f) Profitability index (PI)

Measures return per unit investment:

$$\text{PI} = \frac{\text{Present Value of Cash Flows}}{\text{Initial Investment}}$$

Table 16: Comparative refinery economics and product yield distribution of selected crude feedstocks

Parameter	Antan Crude oil	Oso Condensate	40:60 Blend	Bommy light Crude oil
Crude Cost ($/bbl)	78	82	80	85
Naphtha Yield (%)	22	35	30	28
Kerosene Yield (%)	18	20	19	21
Diesel Yield (%)	25	22	24	26
Residue Yield (%)	35	23	27	25
Naphtha Price ($/bbl)	95	95	95	95
Kerosene Price ($/bbl)	105	105	105	105
Diesel Price ($/bbl)	115	115	115	115
Residue Price ($/bbl)	60	60	60	60
Gross Product Worth ($/bbl)	89.9	101.3	97.2	98.6
Refining Cost ($/bbl)	10	9	9.5	11
Net Refinery Margin ($/bbl)	1.9	10.3	7.7	2.6

Table 16 indicates that Oso condensate achieves the highest GPW (101.3 $/bbl) and NRM (10.3 $/bbl), largely due to its high naphtha yield (35%) and reduced residue fraction (23%). In contrast, Antan crude oil records the lowest margin (1.9 $/bbl), attributed to its high residue yield (35%). The 40:60 blend improves performance (7.7 $/bbl), demonstrating the advantage of compositional optimization. Table 17 shows that profitability closely aligns with NRM. Oso condensate yields the highest annual profit (339.9 M$), with a short payback period (3.5 years) and a strong profitability index (2.40) [21]. The blend also exhibits favourable performance (254.1 M$, 4.7 years), whereas Antan crude oil is economically unviable (PI < 1; payback ≈ 19 years).

Table 18 reinforces these findings through NPV analysis. Oso condensate (+1693.6 M$) and the blend (+962.4 M$) are economically viable, while Antan crude oil (−666.4 M$) and Bonny light crude oil (−469.8 M$) yield negative returns, highlighting the significance of feedstock quality. Table 19 presents IRR values consistent with the NPV results. Oso condensate (24–26%) exceeds typical industry hurdle rates (10–15%), the blend (18–20%) remains attractive, while Antan crude oil (4–5%) is not economically feasible [22]. Table 20 shows that Antan crude oil and Bonny light crude oil operate near break-even, making them highly vulnerable to market fluctuations. In contrast, Oso condensate exhibits strong resilience due to its higher margin, while the blend maintains moderate stability.

Table 21 further supports this trend through sensitivity analysis. A 20% increase in refining cost results in losses for Antan crude oil (−0.1 $/bbl), whereas Oso condensate remains profitable (8.5 $/bbl). The blend retains reasonable margins (5.8 $/bbl), confirming its balanced and lower-risk profile [21, 22]. This implies, the results demonstrate that Oso condensate is the most economically robust feedstock, while blending significantly enhances the economic viability of heavier crude oils such as Antan crude oil.

Table 17: Annual profitability and investment performance indicators for refinery operations

Parameter	Antan crude oil	Oso condensate	40:60 Blend	Bonny light crude oil
Net Refinery Margin ($/bbl)	1.9	10.3	7.7	2.6
Refinery Capacity (bbl/day)	100,000	100,000	100,000	100,000
Operating Days (days/year)	330	330	330	330
Annual Profit ($)	62.7M	339.9M	254.1M	85.8M
Initial Investment ($)	1.2B	1.2B	1.2B	1.2B
Payback Period (years)	19.1	3.5	4.7	14.0
Discount Rate (%)	10	10	10	10
Project Life (years)	20	20	20	20
Profitability Index (PI)	0.85	2.40	1.85	1.10

Using the annuity factor at 10% for 20 years ≈ 8.51

Table 18: Net present value analysis of feedstocks at 10% discount rate

Feedstock	Annual Profit ($M)	PV of Cash Flow ($M)	NPV ($M)
Antan crude oil	62.7	533.6	-666.4
Oso crude oil	339.9	2893.6	+1693.6
Blend crude oil	254.1	2162.4	+962.4
Bonny light crude oil	85.8	730.2	-469.8

Only Oso and the 40:60 blend are economically viable (NPV > 0).
IRR is the discount rate where NPV = 0.

Table 19: Internal rate of return evaluation of crude oil feedstocks

S/N	Feedstock	IRR (%)
1	Antan crude oil	~4–5%
2	Oso condensate	~24–26%
3	Blend crude oil	~18–20%
4	Bonny light crude oil	~8–9%

Oso exceeds typical industry hurdle rates (10–15%). blend is attractive and Antan crude oil is not viable.
Break-even analysis occurs when the

$$NRM = 0 \Rightarrow GPW = Crude\ Cost + Refining\ Cost$$

Table 20: Break-even and market risk analysis based on Net refinery margin

Feedstock	Current NRM ($/bbl)	Break-even Condition
Antan crude oil	1.9	Slight drop in product price → loss
Oso condensate	10.3	Can tolerate price fluctuations
Blend crude oil	7.7	Moderately stable
Bonny light crude oil	2.6	Marginal

Antan crude, Bonny light crude oils are high-risk (near break-even) and Oso condensate is most resilient to market fluctuations. The operating cost sensitivity is carried out assume ± 20% change in refining cost:

Table 21: Sensitivity Analysis of Net Refinery Margin to Variations in Refining Cost

Feedstock	Base NRM	NRM (+20% cost)	NRM (−20% cost)
Antan crude oil	1.9	-0.1	3.9
Oso condensate	10.3	8.5	12.1
Blend crude oil	7.7	5.8	9.6
Bonny light crude oil	2.6	0.4	4.8

In summary, Crude characterization identified Antan crude oil as extra-heavy sour (API 20.89) and Oso condensate as light sweet (API 44.20). Blending improved properties, with the 40:60 ratio (API 34.60) showing optimal refinery compatibility and enhanced light fractions. Distillation confirmed increased naphtha, kerosene, and diesel yields with reduced residuum. The MATLAB-RSM framework enabled prediction and optimization of distillate yields beyond laboratory trial-and-error methods, improving process efficiency. Economically, Oso condensate remains superior, while blending Antan crude oil resulted into making the crude oil sample a competitive, viable feedstock.

4.0 Conclusions and Recommendations

4.1 Conclusions

The physicochemical evaluation confirms that Antan crude oil is a heavy, sour feedstock with high viscosity and residue content, whereas Oso condensate is light and sweet; blending significantly improves API gravity (20.89° to 34.60°) and reduces sulphur (1.2 to 0.45 wt%), enhancing refinery suitability. TBP distillation results show that pure Antan crude yields negligible light fractions, while the 40:60 blend produces substantial naphtha (25.60%), kerosene (15.37%), and diesel (12.49%), demonstrating that blending effectively redistributes hydrocarbons and reduces residuum. The TMATLAB-based optimization (RSM/ANOVA) significantly improves product recovery, achieving 34.11% naphtha, 24.26% kerosene, and 18.87% diesel with reduced residue (22.38%), confirming the robustness ($R^2 > 0.95$) and predictive capability of the computational model. The economic evaluation indicates that Oso condensate (NRM = 10.3 $/bbl, IRR ≈ 24–26%, NPV = +1693.6 M$) and the 40:60 blend (NRM = 7.7 $/bbl, IRR ≈ 18–20%, NPV = +962.4 M$) are economically viable, whereas Antan crude alone is not (NRM = 1.9 $/bbl, negative NPV). Sensitivity and risk analyses reveal that Oso condensate is the most resilient feedstock to cost and price fluctuations, while the blend provides a balanced, lower-risk alternative; in contrast, Antan crude and Bonny Light operate near break-even and are economically vulnerable.

4.2 Recommendations

The 40:60 Antan–Oso blend should be adopted as an optimal feedstock formulation for Nigerian refineries to enhance light product yields and improve economic returns.

The integration of MATLAB-based optimization and process modeling is recommended for refinery operations to enable accurate prediction, real-time optimization, and improved decision-making.

Additional upgrading processes such as hydrotreating and catalytic reforming should be incorporated to improve sulphur content and octane number of naphtha and kerosene fractions to meet Nigerian DPR specifications.

Refinery design and policy frameworks in Nigeria should prioritize blending strategies and flexible feedstock processing to maximize the utilization of heavy domestic crude oils while maintaining profitability and operational stability.

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