Establishing Product Consistency in Nigerian Crude Palm Oil Via Predictive Modeling of Fruit Varietals for Enhanced Global Competiveness

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Abstract
Inconsistency in the yield and quality of crude palm oil (CPO) poses a major challenge to the competitiveness of Nigerian palm oil products. This study evaluated the influence of palm fruit varietals on CPO yield and product aesthetics with emphasis on establishing quality parameters and predictive relationships for tailored production. Native and improved (agricultural) palm fruit varietals were separately and jointly processed under uniform conditions. The native varietal yielded 0.157 L (2.62%) of CPO from a 6 L fruit volume while the agricultural varietal produced 0.511 L (8.52%), representing a threefold increase in extraction efficiency. A mixed 12 L batch of both varietals yielded 1.5 L (12.50%), indicating a synergistic interaction beyond the additive yield expectation. Comparative market assessments revealed marked inconsistencies in CPO aesthetics including colour tone, clarity and phase uniformity attributable to uncontrolled stearin–olein ratios and heterogeneous processing methods. Physicochemical analyses (free fatty acids, peroxide, acid, iodine, saponification and cholesterol values) further distinguished varietal and processing influences on oil quality. The study established that varietal composition critically determines CPO yield and visual properties while process variability underlies the lack of national product uniformity, emphasizing the potential of predictive modeling to harmonize stearin–olein profiles for consistent quality outcomes. These findings provide a scientific basis for product standardization, value chain optimization and branding strategies for Nigerian crude palm oil in domestic and export markets.

Keywords: *Crude palm oil; Palm fruit varietals; Product consistency; Stearin–olein ratio; Predictive modeling; Quality standardization*

1. INTRODUCTION

Crude palm oil (CPO) is one of Nigeria's most economically significant agricultural products, serving as a vital raw material for food, cosmetics, biofuel and industrial applications. Despite Nigeria's historical position as a major global producer, the country's palm oil industry has struggled to maintain competitiveness due to persistent issues of product inconsistency and declining quality standards. These inconsistencies stem from factors such as variations in fruit varieties, uneven harvesting practices, rudimentary processing techniques, inadequate postharvest handling and storage facilities (Abdullahi et al., 2023). Consequently, Nigerian-made crude palm oil often exhibits wide fluctuations in physicochemical properties such as free fatty acid (FFA) content, moisture level and colour aesthetics resulting in reduced consumer confidence and limited market access (Amata & Ozuor, 2024).

Quality uniformity is a crucial determinant of consumer acceptance and industrial suitability. In Nigeria, the predominance of smallholder farmers using traditional extraction methods leads to diverse oil characteristics even within the same region. Studies have shown that poor quality control, lack of standardization and contamination from processing equipment further exacerbate these inconsistencies (Onyegeme-Okerenta et al., 2024; FAO, 2022). This not only diminishes the aesthetic and nutritional quality of CPO but also hinders Nigeria's ability to meet international export standards.

Establishing product consistency in Nigerian crude palm oil production is, therefore, a strategic necessity for improving quality assurance and consumer appreciation. Standardized processing methods, improved storage, handling systems, adoption of predictive modeling and digital monitoring tools can help optimize oil quality parameters, reducing variability. Moreover, strengthening regulatory oversight, certification systems and producer education can create a culture of quality consciousness across the palm oil value chain (Ominyi & Isaac, 2024; FMARD, 2021).

Improved consistency will enhance consumer trust, promote the competitiveness of Nigerian CPO in both domestic and export markets, contribute to national efforts toward agricultural industrialization and import substitution (Esan et al., 2024). Therefore, research focused on developing and implementing frameworks for product consistency is timely and essential to revitalizing the Nigerian palm oil industry and ensuring sustainable economic growth. Moreover, the Nigerian palm oil industry lacks a nationally harmonized quality assurance and grading system comparable to those used in leading palm oil producing countries such as Malaysia and Indonesia. This absence of coordinated regulation and monitoring contributes to variations in product characteristics across different processing clusters and regions (Abdullahi et al., 2023). Research is therefore needed to develop standardized processing protocols, digital traceability mechanisms, and consumer-based quality benchmarks that can ensure consistent product outcomes.

Finally, there is minimal application of modern data-driven approaches such as predictive analytics, artificial intelligence (AI) or machine learning in modeling and maintaining quality consistency in Nigerian crude palm oil. These technologies have proven valuable in other agro-based quality-control systems but remain underexplored in palm oil production contexts in sub-Saharan Africa. Thus, a clear research gap exists in integrating scientific, technological and consumer-oriented approaches to establish product consistency in Nigerian crude palm oil. Addressing this gap will not only enhance the reliability and market competitiveness of Nigerian CPO but also strengthen consumer confidence in locally made agricultural products.

This line of inquiry on establishing product consistency and predictive modelling for Nigerian crude palm oil is very timely and impactful. It bridges data science, agro-processing innovation, and industrial quality assurance with the potential to transform local industries into globally competitive ones. Therefore, the justification for this study lies in its potential to identify and address the factors contributing to inconsistency in Nigerian crude palm oil production, provide scientific guidelines for process standardization and ultimately improve product quality and consumer acceptance. This effort aligns with Nigeria's goal of revitalizing its agro-industrial base and achieving self-sufficiency in palm oil production. This present study is the first step in bridging the observed gaps, striving to establish fruit varietal influence on the aesthetics, stearin-olein profile, yield and quality of Nigerian –based crude palm oil through predictive modelling.

2. MATERIALS AND METHODS

Two predominant varieties (Agricultural palm fruit - *Tenera* and Native palm fruit - *Dura*) were used in this study. The two varieties were procured from smallholder processors from Bayelsa. Oil extraction was achieved by combining the two varietals in different ratios of increasing agricultural varietal (33 %, 50%, 67%, and 100%) in the raw material mix. The reverse order of increasing content of native fruit varietal in the raw production material mix was also explored. Hot water extraction method was used to produce the oil without the use of any chemical solvent. Each trial used a fixed volume of palm fruit and the resulting oil yield was measured and expressed as a percentage. Stearin-olein profile, olein – stearin profile and quality of oil were evaluated following standard procedures of AOAC, (2012). Quality parameters investigated were free fatty acid (FFA), peroxide value, iodine value, saponification value and cholesterol level.

3. RESULTS AND DISCUSSION

3.1 Influence of Palm Fruit Varietals on the Yield of Crude Palm Oil

The impact of palm fruit varietals on crude palm oil yield is presented in Fig.1. A 6-Litre volume vessel of 100% native palm fruit (wild/local variety) gave 0.157 L of CPO, corresponding to 2.62% yield. Same capacity of agricultural fruit varietal (improved/hybrid) yielded 0.511 L of CPO, corresponding to 8.52% yield. A combination of both palm fruit varietals at 12 L capacity gave 1.5 L, corresponding to 12.50% yield. The native variety has a low oil yield (2.62%), suggesting that its mesocarp (oil-bearing portion) is less developed or contains more fibrous and watery tissues. This low yield aligns with what is often observed in traditional or wild palm fruits that have not been selectively bred for high oil content.

100% Native (*Dura*) 100% Agric (*Tenera*) 50% Native + 50% Agric

Fig.1: Impact of palm fruit varietals on crude palm oil yield

Agricultural varietal (*Tenera*) shows a significantly higher yield producing more than three times that of the native fruit**.** This reflects the genetic improvements in the hybrid or Tenera types, which are bred for higher mesocarp-to-fruit ratio, greater oil content per unit fruit and improved extraction efficiency. This confirms that varietal type strongly influences oil productivity. The combined varietal performance showed that the yield of 12.5% is greater than the sum of the individual yields (2.62% + 8.52% = 11. 14%). This synergistic increase suggests that mixing both varietals may enhance oil extraction efficiency (perhaps due to better pulp consistency or oil flow dynamics during processing). The presence of agricultural fruits may improve the thermal and mechanical extraction conditions for the native fruits, allowing more complete oil release. It also indicates a possible interactive effect between varietals in co-processing (Ugbah & Orji, 2021).

3.2 Aesthetics Outlook of Crude Palm Oil Found in Nigerian Markets

Typical aesthetics (physical outlooks) of representative crude palm oil products in the Nigerian indoor (super markets) and outdoor (open air) markets are shown in Fig.2. Products displayed in Fig.2 showed that there is little or no consistency in the product aesthetics. In essence, there is no consistency in the outlook, texture and colour of CPO across market outlets in Nigeria. There is no uniformity in appearance of crude palm oil products solid in the Nigerian markets, nationwide (Okoro et a; 2021; Udo et al., 2021; Eze et al., 2019). Crude palm oil naturally consists of two major fractions namely (i) Stearin (saturated fraction), which is the solid or semi-solid at room temperature that gives firmness or opacity to the oil and (ii) Olein (unsaturated fraction) which is the liquid at room temperature that gives fluidity and clarity to the oil.

Indoor market products

Outdoor market products

Fig.2: Quality in terms saturates and unsaturates of crude palm oil sold in Nigerian markets

The balance between these two fractions determines the oil's visual characteristics, such as colour shade (deep red to orange), texture (thick, creamy, or runny) and homogeneity (uniform or layered appearance). The lack of uniformity seen in Fig. 2 where some oils appear bright red, others dull; some clear, others cloudy or layered can be traced to several technical and environmental factors, including (i) different palm fruit varietal (native fruits often produce darker, more viscous oils due to higher carotene and impurity content & agricultural/hybrid fruits tend to produce lighter-colored, cleaner and more fluid oils), (ii) processing techniques and equipment: traditional (manual or artisanal) processing often results in incomplete clarification and varying moisture or impurity levels and mechanized or controlled processing yields more consistent texture and colour, (iii) storage and handling conditions: exposure to air, sunlight, or high temperatures can cause oxidation and colour darkening plus poor filtration or contamination that can alter clarity and odour and (iv) regional market differences : oils produced in different states or sold under varying environmental conditions such as open versus. enclosed spaces show differences in oxidation rate, phase separation, and sedimentation.

The observed lack of aesthetic consistency in Nigerian CPO indicates absence of standardized production protocols across producers, poor quality control and inadequate refinement before marketing, challenges for consumer confidence as appearance differences may be mistaken for adulteration or poor quality and difficulty in establishing brand identity or national market competitiveness. Above all the stearin–olein balance influences how the oil looks and behaves. Oils richer in olein are clearer and more fluid, often preferred for cooking oil production. Oils richer in stearin are opaque or semi-solid, useful for margarine or shortening. Inconsistent stearin–olein ratios among Nigerian CPO products, therefore, directly explain the non-uniform outlook seen in Fig.2. The differences in physical outlooks (aesthetics) of Nigerian crude palm oil products reflect variations in fruit varietals, processing methods and post-processing handling. These inconsistencies are primarily due to uncontrolled stearin–olein composition, leading to a lack of uniformity in the colour, texture and clarity of CPO products across Nigerian markets.

An attempt to understand the significance and influence of stearin-olein profile on consitency in astheics of crude palm oil gave the graph in Fig.3. where the relationship between stearin-olein profile of crude palm oil produced in this study is presented. The graph showed a positive linear relationship between the increasing content of agricultural fruit in the raw material mix and the stearin–olein profile. The trendline indicates that as the proportion of agricultural fruit in the raw material mix increases, the stearin–olein profile also increases. This suggests that higher agricultural fruit content enhances the oil composition or yield balance between stearin (solid fraction) and olein (liquid fraction). The regression equation of the line: ($Y= 0.0152x + 0.3944$) implies that for every 1% increase in agricultural fruit content, the stearin–olein profile increases by approximately 0.0152 units.

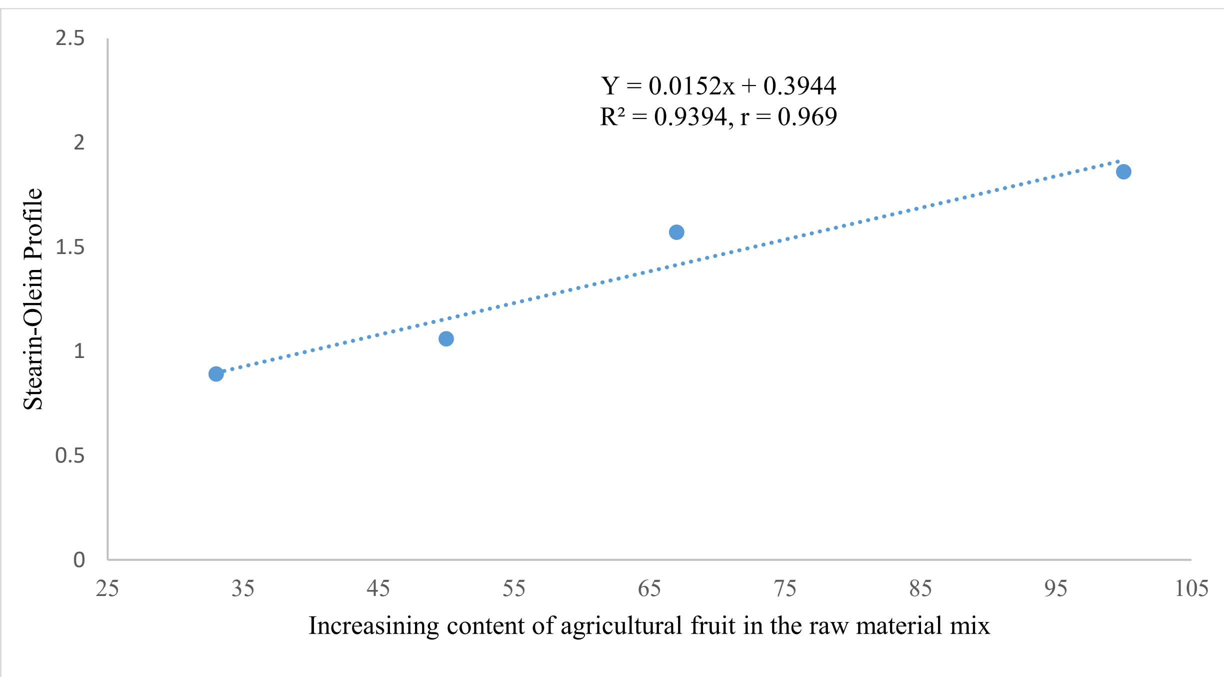

Fig.3: Correlation between stearin –olein profile as influenced by agricultural fruit varietal in raw material mix

The intercept (0.3944) represents the estimated baseline stearin–olein profile when the agricultural fruit content is minimal or near zero. The coefficient of determination ($R^2 = 0.9394$) indicates that about 93.94% of the variation in the stearin–olein profile can be explained by the variation in agricultural fruit content. This reflects a very strong model fit, suggesting the relationship is statistically significant. The correlation coefficient (r) of 0.969 confirms a strong positive correlation between the two variables (as one increase, the other rises proportionally), significant at $p \leq 0.05$. The results demonstrate that increasing the content of agricultural fruit in the raw material mix leads to a consistent and predictable enhancement in the stearin–olein profile. This indicates that optimizing fruit content could be a viable strategy for improving crude palm oil fractionation characteristics and overall product quality. In practical terms, the relationship suggests that formulating raw material mixes with higher agricultural fruit content may yield oils with more desirable physical and chemical balance, which can support stable production outcomes and better-quality Nigerian-made products.

Figure 4 suggests that increasing the proportion of native fruit varietal in the raw material mix does not strongly influence the olein–stearin ratio in crude palm oil. In contrast to the earlier graph (with a strong correlation), this one shows that native fruit varieties contribute less consistently to oil fractionation behavior. This may indicate that native fruit variants possess heterogeneous oil composition or less predictable yield patterns, likely due to genetic diversity or less optimized cultivation and processing conditions.

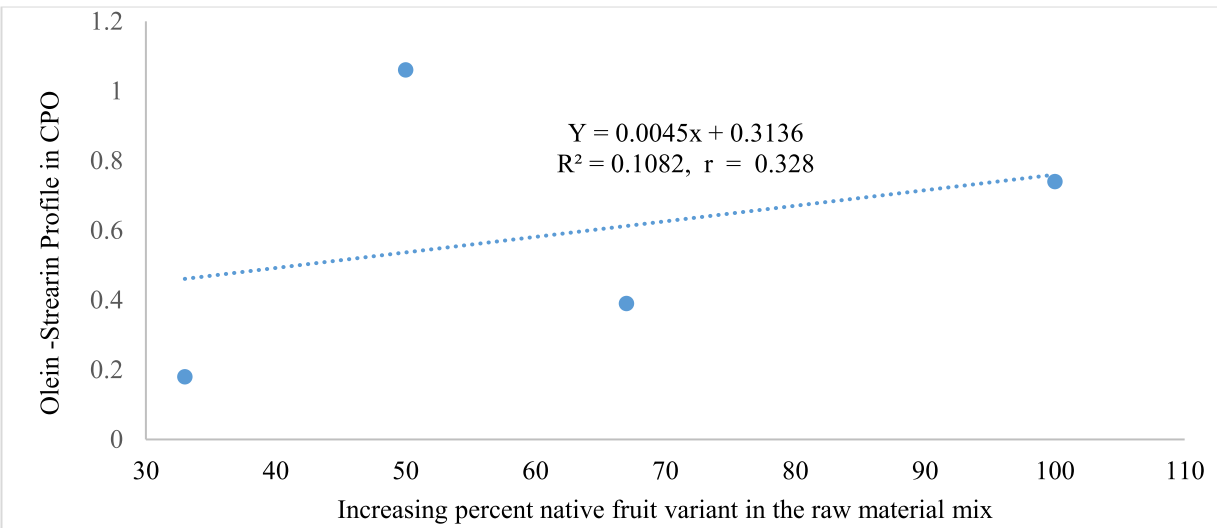

Fig.4: Correlation between olein - stearin profile as influenced by native fruit varietal in the raw material mix

The graph depicts the relationship between the increasing percentage of native fruit variant in the raw material mix and the olein–stearin ratio in crude palm oil (CPO). The regression equation is $Y=0.0045x+0.3136$. This indicates a slight positive relationship between the two variables. For every 1% increase in the native fruit variant content, the olein–stearin ratio increases by only 0.0045 units. The low slope suggests that the native fruit variant has a limited effect on this ratio. Coefficient of Determination (R^2) of 0.1082 means that only about 10.82% of the variation in the olein–stearin ratio can be explained by the proportion of native fruit variant in the raw material mix. This implies that the relationship is weak and not strongly predictive, demonstrating that most of the variation in the olein–stearin ratio is influenced by other factors not captured in this model such as fruit maturity, processing temperature, or extraction efficiency. Correlation coefficient (r) of + 0.328 indicates a weak positive correlation.

Although the olein–stearin ratio tends to increase slightly with native fruit content, the relationship is inconsistent and scattered. The data points showed considerable spread around the trendline, confirming weak linearity. This suggests variability in the performance of native fruit variants in determining oil phase balance. Overall, for achieving a stable crude palm oil outlook in Nigerian-made products, reliance solely on native fruit variants may not yield consistent olein–stearin characteristics. A more balanced mix of possibly integrating improved or hybrid fruit varieties might be needed to stabilize oil composition and quality for industrial use. The two graphs (Figs.3 and 4) illustrate contrasting relationships between fruit composition in the raw material mix and oil quality indices the stearin–olein profile in Fig.3 and the olein–stearin profile in Fig.4. Together, they provide insight into the degree of consistency and predictability that can be achieved in crude palm oil (CPO) production using different fruit compositions. In terms of relationship strength and predictability, Fig.3 exhibited a strong positive correlation ($r = 0.969$, $R^2 = 0.9394$), indicating that increases in agricultural fruit content lead to a predictable and consistent enhancement in the stearin–olein profile. This suggests that using improved or hybrid fruit types in the raw material mix contributes significantly to stable oil fraction characteristics. On the contrary, Fig.4, shows a weak correlation ($r = 0.328$, $R^2 = 0.1082$), meaning that increasing the proportion of native fruit variants has little or no consistent effect on the oil's phase composition. This implies that native fruits exhibit high variability in oil yield and fractionation behaviour.

In terms of implications for stability and quality, the contrasting trends highlight that not all fruit sources contribute equally to achieving a stable CPO outlook. Agricultural or hybrid fruit mixes (as in Fig.3) provide a stronger basis for consistent oil quality and processing outcomes, while native fruit variants (Fig.4) tend to introduce variability and uncertainty into oil composition. Hence, to achieve a stable and predictable crude palm oil outlook, the Nigerian palm oil industry should prioritize the cultivation and use of improved fruit cultivars with uniform oil characteristics, standardized processing techniques that minimize compositional fluctuations and blending strategies that optimize the stearin–olein balance across different fruit sources. These findings are important for the Nigeria's Palm Oil Sector. The findings support the broader feasibility of stabilizing crude palm oil characteristics through scientifically guided raw material selection and proportioning. By focusing on fruit types with high and consistent performance (as demonstrated in Fig.3), Nigeria can strengthen the dependability of locally produced CPO for industrial applications. In contrast, the weak trend in Fig.4 signals the need for further genetic improvement and agronomic refinement of native fruit variants to make them competitive and consistent contributors to the production mix. Results revealed that achieving a stable crude palm oil outlook in Nigeria is feasible, but it depends on the optimization of raw material composition. Enhanced fruit types yield a predictable oil profile essential for quality assurance, industrial processing, and market competitiveness, which are key factors in realizing a sustainable and self-sufficient Nigerian palm oil industry.

3.3 Tailored Product Preparation

Based on findings from this study, crude palm oil products of improved aesthetic consistency were produced using predictive models generated in this study resulting in tailored products as displayed in Fig.5. Predictive modeling enables customization of crude palm oil properties to meet specific market or industrial needs. By simulating the effects of different processing parameters and fruit sources, models can help producers formulate oil tailored for: edible use by optimizing taste, color, and nutritional profile; cosmetic applications by emphasizing purity, stability and mild odour and biofuel or industrial use: optimizing viscosity and oxidation stability. Thus, predictive analytics supports product diversification, ensuring Nigerian CPO aligns with various consumer and industrial preferences. Predictive models can also analyze historical production and market data to forecast yield trends, price fluctuations and quality performance across seasons. Consistent outlook and market predictability promote stable supply chains through informed production scheduling, market confidence due to reliable product outlooks and brand reputation built on measurable, data-backed quality assurance. A consistent product outlook builds trust and long-term consumer loyalty, which are crucial for Nigeria's palm oil industry to regain competitiveness regionally and internationally.

Fig.5: Demonstration of the feasibility of achieving a stable crude palm oil outlook for Nigerian-made products from this study

By continuously collecting and analyzing production data, predictive models can identify optimal conditions for consistent oil quality such as ideal fermentation time, temperature and pressure, detect early deviations in process parameters that might cause inconsistency, recommend corrective actions before quality deterioration occurs. This ensures uniform product appearance (outlook) and reduces batch-to-batch variability. Predictive modeling can also enhance quality control. It serves as a proactive quality assurance tool.

Traditional quality control methods detect flaws after production, whereas predictive models anticipate them before they occur. For example, models can predict FFA buildup based on storage conditions and temperature changes. They can estimate peroxide and moisture levels, enabling processors to adjust operations in real time. With integrated sensors and digital monitoring, predictive systems can maintain continuous feedback loops, ensuring the oil's chemical and physical properties remain within desired thresholds. This approach transforms quality control from reactive inspection to predictive quality management. Furthermore, by integrating predictive models with Internet of Things (IoT), sensors, machine vision and AI-based process control, palm oil producers can achieve near-real-time monitoring and precision regulation (Zarei et al., 2022; Radhakvishmann et al., 2021; Afolabi & Ojo, 2021). This results in reduced waste and energy consumption, optimized extraction efficiency and consistent sensory and chemical quality of the oil. Such digital transformation directly supports the goal of sustainable, standardized and high-value crude palm oil production in Nigeria.

3.4 Quality of the Crude Palm Oil Produced from this Study

Six important quality parameters for crude palm oil prepared in this study using 50% Agric + 50% Native are presented in Table 1. Explanations of key crude palm oil (CPO) quality parameters are briefly presented. Free Fatty Acids (FFA) measures the amount of fatty acids that have been released from triglycerides due to hydrolysis or lipase activity.

Table 1: Quantitative data on key quality indices for crude palm oil prepared in this study using 50% Agric + 50% Native

S/N	Parameters	CPO1	CPO2	CPO3	Mean	Mean deviation	CV(%)	Standard Value
1	FFA. Value (%)	3.14	3.11	3.13	3.13	0.012	0.38	3 to 5
2	Acid Value (mgKOH/g)	7.00	9.00	8.00	8.00	0.82	10.25	10
3	Iodine Value (g I_2/100 g)	15.00	13.00	15.00	14.00	0.94	6.71	50-55
4	Saponification value (mgKOH/g)	209	205	207	207	1.63	0.79	209
5	Peroxide value (meq/kg)	9	7	8	8	0.82	10.25	≤ 10
6	Cholesterol value(mg/100 g)	0. 2	0.3	0.2	0. 23	0.05	21.74	< 1 mg/100 g

CPO = Crude palm oil, CV = coefficient of variation

It is expressed as a percentage of palmitic acid in palm oil. High FFA indicates poor-quality oil, often resulting from overripe fruits, delayed processing, or improper storage. Excessive FFA contributes to rancidity, off-flavour, and reduced shelf life. Typical value for good-quality CPO is ≤ 5% FFA (Adelekan, & Alamu, 2018). Peroxide value (PV) quantifies the extent of primary oxidation of fats and oils by measuring the amount of peroxides and hydroperoxides formed. It is expressed in milliequivalents of oxygen per kilogram of oil (meq O_2/kg). High PV indicates the onset of rancidity and oxidative spoilage. It reflects how long the oil can remain stable during storage. Acceptable limit for fresh CPO is ≤ 10 meq O_2/kg (Aremu, & Ibrahim, 2014).

Acid value (AV) measures the milligrams of potassium hydroxide (KOH) required to neutralize the free fatty acids in 1 gram of oil. It is another indicator of hydrolytic rancidity. High acid value often parallels high FFA content, implying degradation or poor storage (Ekwu & Nwoye, 2017). Iodine value (IV) measures the degree of unsaturation (number of double bonds) in the oil, expressed as grams of iodine absorbed per 100 grams of oil. A high iodine value indicates more unsaturated (liquid) oil, while a low value indicates more saturated (solid) oil. This affects the oil's melting behavior, oxidative stability and product application. Typical range for palm oil is 50–55 g I_2/100 g (Norizzah et al., 2004). Saponification value (SV) represents the amount of KOH (mg) needed to saponify 1 gram of fat or oil. It provides information on the average molecular weight (chain length) of the fatty acids in the oil. Higher SV suggests shorter-chain fatty acids. It's crucial for soap-making and cosmetic applications. Typical range for palm oil is 195–205 mg KOH/g (Aremu, et al., 2013). Finally, cholesterol value indicates the amount of cholesterol present in the oil, typically in mg/100 g of oil. Vegetable oils like palm oil are naturally low in cholesterol, but improper refining or contamination can introduce trace amounts. Low cholesterol content is desirable for heart health and consumer appeal. Typical value for CPO is < 1 mg/100 g (Edem, 2002).

CONCLUSIONS AND RECOMMENDATIONS

Inconsistency in Nigeria's crude palm oil outlook undermines industrial efficiency, economic competitiveness and sustainability. Achieving stability is, therefore, essential for strengthening local industries, boosting farmer livelihoods, ensuring food security and positioning Nigeria as a reliable player in the global palm oil market. A coordinated national strategy anchored on improved fruit varieties, processing standardization and supply chain integration is vital for reversing these trends and building a resilient palm oil economy.

The comparative analysis demonstrates that achieving a stable crude palm oil outlook in Nigeria is feasible but strongly dependent on the selection and proportion of fruit variants in the raw material mix. Improved agricultural fruit sources yield more consistent oil quality and predictable fractionation behaviour, while native variants introduce variability. Therefore, a shift toward the adoption of optimized fruit varieties and integrated production management practices is essential to sustain Nigeria's palm oil industry and strengthen its contribution to national economic growth.

Predictive modelling offers Nigeria a practical and scientific pathway to achieving a stable, high-quality and market-responsive crude palm oil outlook. By integrating data analytics into the entire value chain from cultivation to processing and distribution, Nigeria can transition from reactive to proactive production management. This approach supports tailored oil production, fosters industrial competitiveness and aligns with national goals for economic diversification, food security and sustainable development.

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