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Comparative analysis of oil palm extraction rates and nutritional profiles of indigenous and introduced hybrid genotypes cultivated in selected districts of Uganda

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ABSTRACT

Oil palm (*Elaeis guineensis* Jacq. L.) is the leading global source of plant-based oil. However, Uganda relies on imported hybrid varieties because it lacks a domestic breeding program. To inform potential breeding efforts, this study evaluated oil extraction rates and nutritional profiles of indigenous and introduced hybrid oil palm genotypes cultivated in Bundibugyo, Kanungu, and Kalangala districts. Seventy-five ripe fruit bunches were collected, and palm oil was extracted using a screw press. Measurements of oil extraction rate and stearin mass recovery were performed. Nutritional analysis of olein samples included carbohydrate quantification via the Anthrone method; fatty acid quantification (linolenic, linoleic, oleic, palmitic, and stearic acids) using High-Performance Liquid Chromatography (HPLC) with UV detection; and beta-carotene concentration determined using spectrophotometry. Statistical differences between groups were assessed using the non-parametric Kruskal-Wallis H test, as data for most variables did not meet the assumptions for parametric tests. Indigenous genotypes showed slightly higher mean oil extraction rates (23.3%) and stearin recovery (22.6%) than hybrids (22.8 and 17.9%, respectively). These results highlight the potential of indigenous genotypes as promising candidates for breeding programs aimed at enhancing oil yield and nutritional quality under Uganda's agro-ecological conditions. The study provides foundational data to support the development of a sustainable, locally adapted oil palm breeding initiative.

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Introduction

African oil palm (*Elaeis guineensis* Jacq. L.) is a monocotyledonous plant of the order Arecales, family Arecaceae, and genus *Elaeis* (Bakewell-Stone, 2022; Chinedu *et al*., 2017). *E. guineensis* Jacq. originated in West and Central Africa, while its wild relative, *Elaeis oleifera* HBK, is native to South America. *E. oleifera* is distinguished from *E. guineensis* by its dwarf stature, inclined trunk, enhanced resistance to pests and diseases, and its higher concentrations of unsaturated fatty acids, carotenoids, and vitamin E (Godswill *et al*., 2016) in its oil. Oil palm is currently the world's leading source of plant-based oil (Tiemann *et al*., 2018) with an annual global production exceeding 79 million metric tons in 2024 (USDA, 2024). Indonesia and Malaysia together account for approximately 83% of the global palm oil supply, with Thailand and Colombia also being significant contributors.

In Africa, while precise annual palm oil production statistics are not well documented, estimates indicate substantially lower output compared to Southeast Asia (Ovwigho *et al*., 2024). In Uganda and globally, commercial planting material primarily consists of *tenera* palms, a hybrid of thick-shelled *dura* and

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shell-less *pisifera* (D×P) (Bakewell-Stone, 2023). Despite the global importance of oil palm, there are limited studies on the oil extraction rates and nutritional characteristics of indigenous oil palm genotypes and introduced hybrid varieties under Ugandan conditions. This gap in knowledge limits efforts aimed at developing breeding programs to enhance local production. This study, therefore, sought to answer the hypothesis that there is no difference in oil extraction rate, mass of stearin recovery, and nutritional profiles of indigenous genotypes and introduced hybrids.

The selection of potential parental lines for Uganda's oil palm improvement efforts can be guided by assessing indigenous germplasm for agronomic traits. Oil palm breeding programs prioritize traits associated with high yield, including bunch number, bunch weight, and oil extraction rate; evaluating these components in indigenous genotypes can help identify potential parental lines for Uganda's breeding efforts (Constantin *et al*., 2017; Ithnin *et al*., 2021). In palm oil processing, the extraction rate is the efficiency with which olein and stearin are extracted from the palm fruit (Basyuni *et al*., 2017; Obibuzor *et al*., 2012). Determining the oil extraction rate is vital, as it represents the proportion of oil successfully extracted from the fruit and mesocarp relative to the total oil content in the fruit. This rate has a direct impact on the yield and profitability of the oil palm industry as millers prioritize achieving a high oil extraction rate to maximize the output of crude palm oil (Basyuni *et al*., 2017). Higher oil extraction rates indicate greater efficiency in extracting oil from the fruit (Obibuzor *et al*., 2012). Consequently, breeding programs select for traits that are linked to higher oil content and improved extraction characteristics.

Palm oil contains about 50% saturated fats, mainly palmitic acid, 40% monounsaturated fats like oleic acid, and 10% polyunsaturated fats such as linoleic acid. Its nutritional profile influences health, with unsaturated fats linked to reduced cholesterol and a lower risk of cardiovascular diseases, making it a significant dietary fat (Koushki *et al*., 2015; Phan Tai & Brunner, 2019). The unprocessed red palm oil typically comprises palmitic acid, stearic acid, oleic acid, and linoleic acid, reflecting its balanced mix of saturated and unsaturated fatty acids (Mba *et al*., 2015). Fats and oils are essential nutrients supplying energy and vital fatty acids and act as carriers for fat-soluble vitamins A, D, E, and K, playing a vital role in improving the nutritional value, flavor, and shelf life of food products (Samuel *et al*., 2018). Carotenoids, including beta-carotenes, are essential antioxidants and precursors of vitamin A, widely utilized in the food, pharmaceutical, and cosmetic industries, and reduce cancer risks (Ebadi *et al*., 2023; Rowles III & Erdman Jr, 2020). The carotenoid profiles of indigenous and hybrid oil palm varieties in Uganda remain undocumented.

In Uganda, commercial oil palm production is carried out in the Kalangala district islands and began under a public-private producer partnership (4P) within the Vegetable Oil Development Project (VODP) launched in 2001 (Jiménez-Mcinnis, 2020). The primary objective was to alleviate poverty and promote import substitution by producing palm oil domestically (Ddamulira *et al*., 2020, 2024). Although plantations have been established over the years, and efforts to expand cultivation to other regions of the country are ongoing, the lack of a local oil palm breeding program remains a major challenge (Masika *et al*., 2020). This is exacerbated by dependence on imported oil palm hybrids, restricting the ability to enhance local production and preventing the development of high-yielding and disease-resistant varieties adapted to local conditions. To improve productivity and support farmers, establishing domestic oil palm breeding programs is crucial for creating better-suited and sustainable cultivars (Budiman *et al*., 2019; Malike *et al*., 2019). There is no comprehensive data on oil extraction efficiency and nutritional profiles of indigenous oil palm genotypes, cultivated by Ugandan smallholders near the Democratic Republic of Congo (DRC) border. These parameters vary significantly with genotype, plant age, fruit maturity, soil type, climate, and processing methods, underscoring the need for systematic evaluation to inform potential breeding and production strategies through the identification of potential parental breeding lines (Gesteiro *et al*., 2019; Koushki *et al*., 2015; Prada *et al*., 2011; Prasetyo *et al*., 2024).

Therefore, to establish a breeding program in Uganda, a comprehensive analysis of oil extraction efficiency and nutritional attributes of locally cultivated oil palm genotypes is imperative. Prior research underscores that yield potential and nutrient composition critically influence a variety's suitability for industrial processing and dietary use, guiding selection of optimal breeding lines (Mensink *et al*., 2003; Sambanthamurthi *et al*., 2000). The current study evaluated whether oil extraction rate and stearin yield differ between indigenous and introduced hybrid oil palms in Uganda. It aimed to quantify extraction

efficiency, stearin mass, and olein nutritional profiles across age group factors that critically influence palm oil's overall yield, quality, and commercial value.

Materials and methods

The sampling and data collection were carried out in three districts of Kalangala (for introduced hybrid varieties), Kanungu, and Bundibubyo (for the indigenous genotypes), whose characteristics are described below (Table 1, Figure 1).

Table 1. Summary of study sites and sample characteristics from three districts where oil palm bunches were sampled.

Characteristic	Kalangala district	Bundibugyo district	Kanungu district
Oil palm genotype	Introduced hybrid	Indigenous	Indigenous
Scale of cultivation	Primary commercial hub	Small-scale, rudimentary	Small, isolated stands
Elevation (masl)	1,552	946.8	1,000 – 2,503
Mean annual rainfall (mm)	1,125 - 2,250	479.7	1,000 – 1,200
Climate type	Warm	Tropical rainforest	Tropical
Primary economic activities	Subsistence and commercial oil palm farming	Agriculture (cocoa, coffee, bananas) and livestock	Agriculture (tea and coffee)
Genotype	Introduced hybrids	Indigenous	Indigenous
Oil palm variety	*Tenera*	*Dura* and *Pisifera*	*Dura* and *pisifera*
Key variety morphological traits	Thin-shelled fruits	Thick-shelled fruits	Very thin shelled fruits
Number of samples	33	20	16
Plant age range of samples	3 to 30	<3 to >30	<3 to >30
Agronomic practices	High input, commercial	Very low input, organic, smallholder	Very low input, organic, smallholder

Note: Data for Kalangala, Bundibugyo, and Kanungu districts were sourced from Amugoli *et al*. (2020), Weather and Climate (2025), and Government of Uganda (2024b), respectively. Information on Bundibugyo's oil palm scale is from Government of Uganda (2024a).

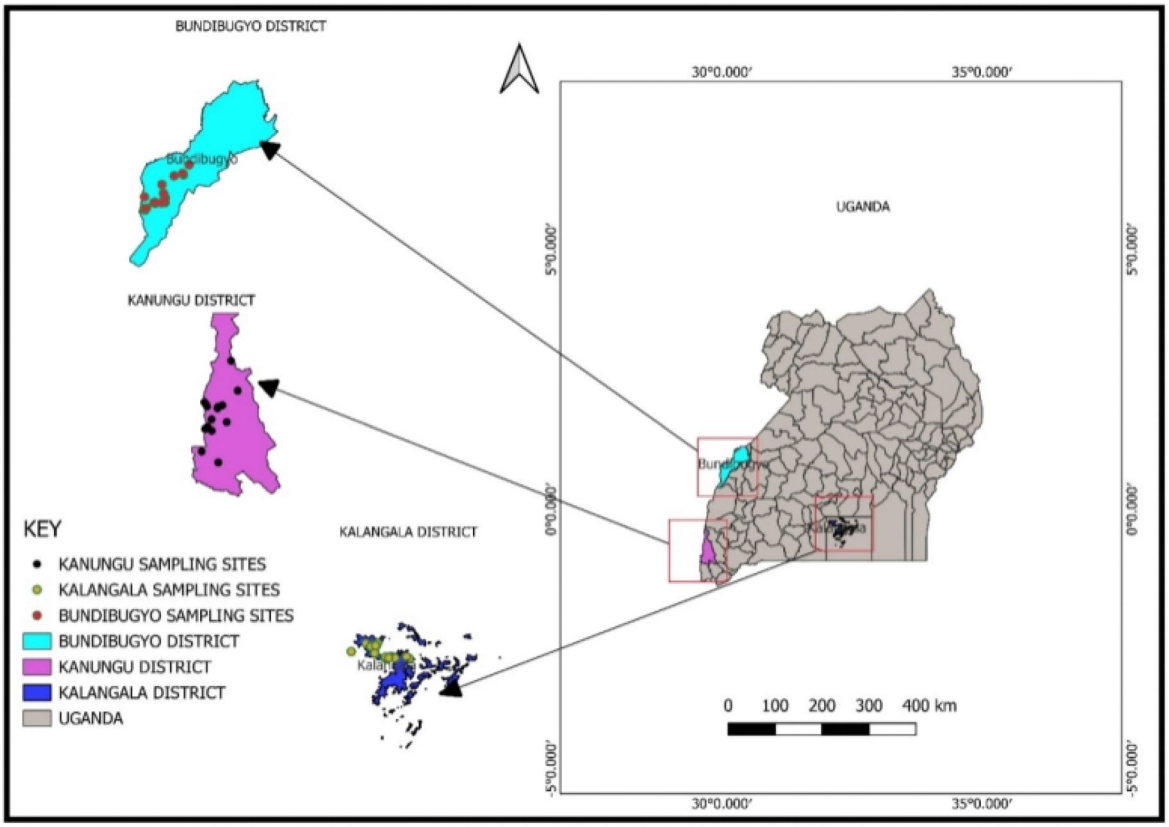

Figure 1. A map showing the districts (Bundibugyo, Kanungu, and Kalangala) where oil palm samples were collected (Map created using QGIS 3.38.0. Credit: Caku Jimmy).

Sampling

The ripe oil palm fruit bunches were identified according to the standards set by the Malaysian Palm Oil Board (Ruswanto *et al*., 2020; Shabdin *et al*., 2016), which classifies an oil palm bunch as underripe, ripe or overripe when 1 – 9%, 10 – 50%, and greater than 50% of the fruits have naturally detached from the bunch, respectively (Ruswanto *et al*., 2020; Shabdin *et al*., 2016). Bunches were considered ripe when 10–50% of fruits had naturally detached. In Bundibugyo and Kanungu districts, where indigenous genotypes are grown by smallholder farmers, ripe bunches were located using snowball sampling and then purchased from farmers. In the Kalangala district, sampling was conducted in three blocks with the assistance of extension officers from the Kalangala Oil Palm Growers Trust (KOPGT) and farmers of the respective fields by systematically moving through the field to identify ripe fruit bunches. This was possible because in the Kalangala district, introduced hybrids are cultivated commercially. The oil palm trees from which the bunches were sampled were georeferenced using a Global Positioning System (GPS). A total of 75 ripe oil palm bunches were bought, weighed, labeled, and transported to the Food and Nutrition Laboratory at the National Crops Resources Research Institute (NaCRRI) for oil extraction. No wild plant species such as *Elaeis oleifera* were collected for this study, and ripe oil palm bunches used for this study were procured from farmers who have planted these plants for many years, and no special permits or licenses were required. Furthermore, Dr Masika Fred Bwayo and Dr Ddamulira Gabriel confirmed the identity of the oil palm variety used in this study. Dr Ddamulira Gabriel is a Principal Research Officer and Head of the Department of Horticulture and Oil Palm, National Crops Resources Research Institute (NaCRRI) of National Agriculture Research Organization (NARO), Uganda. The identification was based on morphological traits and varietal records. In addition, no separate herbarium voucher specimens were deposited for this study. However, the original seed lots of the oil palm varieties are maintained at the institution/seed bank, at the Biodiversity Conservation Unit of the National Crops Resources Research Institute for future reference.

Reagents used

All reagents used in the analysis were of analytical grade. Distilled water was consistently used for dilutions and washing. For carbohydrate analysis using the Anthrone method, absolute ethanol (99.9%) and 98% sulfuric acid were used. In fatty acid methyl ester analysis, a 0.5 M methanolic potassium hydroxide solution was prepared by dissolving potassium hydroxide pellets in methanol. Furthermore, 10.0 mL of dichloromethane (99.8%, HPLC grade) was used as the extracting solvent. Ultrapure water (HPLC grade) was used for multiple washings. A single fatty acid methyl ester (FAME) standard mix was prepared using linolenic acid, linoleic acid, palmitic acid, stearic acid, and oleic acid, each at stock concentrations of 10 mg/mL. For the determination of beta-carotene, absolute hexane (95%, HPLC grade) was used as the extraction solvent.

Determination of oil extraction rate and mass of stearin recovered

The fruits were carefully detached from the spikelets and thoroughly washed to eliminate contaminants and impurities. The mesocarp was separated from the fruits using a sharp scalpel and then dried in a solar dryer for 24 h to reduce the moisture. A 50 g sample of the dried mesocarp was measured and placed in an electric screw press (PAD and T Group, SUS304 stainless steel, Denmark). The initial pressing temperature was set to 40 °C, which increased to 100 °C during extraction. Samples were centrifuged at 55,865 g for 25 minutes at 30 °C, and the resulting mass of olein and stearin was measured. The oil extraction rate was calculated using the formula described by Corley and Tinker (2015) and Supriyatin (2021).

$$\mathrm{OER} = \frac{\text{mass of oil produced}}{\text{mass of fruit bunch}} \text{x} 100\%$$

Similarly, the percentage mass of stearin recovered (MOSR) was calculated as:

$$\text{MOSR} = \frac{\text{mass of stearin produced}}{\text{mass of fresh fruit bunch}} \text{x} 100\%$$

Determination of carbohydrate content

The analysis of carbohydrates was conducted using the Anthrone method adopted from Achour *et al*. (2022) to quantify soluble carbohydrates (e.g., simple sugars such as sucrose, glucose, and fructose, as well as soluble fiber components like pectins) that may be present in the crude oil. These are likely introduced from residual fruit mesocarp. Briefly, a palm olein sample was mixed with absolute ethanol (99.9%) in an Eppendorf tube. The mixture was incubated for 2 h at 70 °C, then cooled to 4 °C and centrifuged at 55,865 g. One milliliter of the supernatant was transferred to a borosilicate glass tube, to which 98% sulfuric acid was added. The mixture was incubated for 7 minutes at 99 °C. Absorbance was measured at 620 nm using a spectrophotometer (SpectraMax Plus 384, California 94089, USA), with a reagent blank for calibration (Achour *et al*., 2022). The procedure was performed in triplicate for each sample, and the mean total carbohydrate concentration per sample was calculated using the formula Abs = 1.7X + 0.013, where Abs represents the absorbance at 620 nm, and X denotes the carbohydrate concentration in µg/mL.

Fatty acid methyl ester analysis

The analysis of five fatty acids, including linolenic acid, linoleic acid, palmitic acid, stearic acid, and oleic acid, was performed on the palm olein using HPLC-UV as previously described (Aremu & Nweze, 2017). A 0.5 g palm oil sample was weighed in duplicate into a clean saponification flask. To each flask, 7.0 mL of 0.5 M methanolic potassium hydroxide solution was added. The mixture was then periodically shaken at room temperature for 1 hour. The sample was washed five times with 14.0 mL of ultrapure water (HPLC grade). Dichloromethane was added, and the upper organic layer, containing the fatty acid methyl esters (FAMEs), was collected. The two aliquots were pooled together. The methyl ester derivative extract was allowed to stand over magnesium sulfate, filtered, and the volatiles were removed under reduced pressure. The analysis was performed using a SHIMADZU HPLC system (Tokyo, Japan) with a CTO-10AS oven, LC-20AD Prominence liquid chromatograph, SPD-20A Prominence UV-VIS detector, and SIL-20A HT autosampler. Separation was performed using a C18 Zorbax Eclipse Plus Agilent column, and detection was carried out at 205 nm.

All chromatograms were processed with Lab Solutions software (Shimadzu, Japan). An isocratic elution method was employed, with the mobile phase consisting of 100% acetonitrile. The column oven temperature was maintained at 40 °C, and the total chromatographic run time was 18.5 minutes. An injection volume of 10 µL was used, with a flow rate set at 0.8 mL/min. Individual methyl ester standards, including linolenic acid, palmitic acid, stearic acid, and oleic acid, were prepared at stock concentrations of 10 mg/mL each in a combined mixed standard solution. Compound identification was based on specific retention times. Calibration and quantification were conducted by comparing the peak areas of the standard esters with those of the unknown samples. The relationship of the results was determined according to Carvalho *et al*. (2012), adopted from Ichihara *et al*. (1996).

$$\text{Concentration of sample} = \frac{\textit{Peak area}(\textit{sample})}{\textit{Peak area}(\textit{standard})} \text{ x concentration of sample } (^{mg}/_{mL}),$$

and final concentrations were transformed into mg/100 with the formula;

$$\text{Concentration in mg}/100\text{g} = \frac{\left(\frac{\text{mg}}{\text{L}}\right) * \text{Total volume of dilution}(\text{L}) * 10}{\text{Weight of sample in Kg}}$$

Determination of beta-carotene

The determination of beta-carotene was carried out as described previously by Sanusi and Adebiyi (2009) and adopted by Aremu and Nweze (2017). To the olein sample in an Eppendorf tube was added absolute hexane (95%), and the mixture was allowed to settle for 1 h. Absorbance was measured at 449 nm using a spectrophotometer, with hexane serving as the blank. The cuvette was thoroughly cleaned and rinsed between each sample measurement to avoid cross-contamination. The concentration of beta-carotene in the sample was calculated using the Beer-Lambert law, expressed as:

$$C = \frac{\text{AxVx}10^6}{\text{ExDxW}};$$

where: C = Concentration of beta-carotene (µg/g); A = Absorbance at 449 nm; V = Volume of hexane used for extraction (mL); E = Molar extinction coefficient of beta-carotene in hexane (2592 L/mol·cm); D = Path length of the cuvette (1 cm); W = Weight of the sample (g).

Statistical analysis

Data were initially recorded in a Microsoft Excel spreadsheet and subsequently imported into IBM SPSS Statistics version 26 for analysis. Before conducting statistical tests, a box plot was used to visualize the data to reveal outliers, which were then removed. The outliers included KU17, KL34, KL35, KL36, KL37, and KL38. The normality of data distribution for each variable was assessed using the Shapiro-Wilk test, and homogeneity of variances was confirmed with Levene's test. Since most variables could not meet both the assumptions of normality and homogeneity of variances, the non-parametric Kruskal-Wallis H test was employed for all group comparisons. This test was used for comparing oil extraction rate and mass of stearin recovery across the two genotypes and the different districts; carbohydrate concentrations across genotypes, age categories, and districts; linolenic acid (C18:3), linoleic acid (C18:2), and palmitic acid (C16:0) concentrations between genotypes and across districts; and beta-carotene concentrations across age categories and districts where data were non-normal or variances were unequal. Statistical significance was determined at a 95% confidence interval ($p < 0.05$). Graphical representations of the results were generated using Microsoft Excel.

Results

Oil extraction rate (OER) and mass of stearin recovery (MOSR)

The indigenous genotypes exhibited a broader range of oil extraction rates (6.00–54.0%) compared to the introduced hybrid oil palm varieties, which ranged from 10.00 to 40.0%. The mean oil extraction rate for indigenous genotypes was 23.3%, slightly higher than the 22.8% recorded for the introduced hybrid varieties. However, this difference was not statistically significant ($p = 0.76$). Similarly, the indigenous genotypes demonstrated a wider range in the mass of stearin recovered (3.80-47.6%) relative to the introduced hybrids (2.50–36.8%). The average mass of stearin recovered from indigenous genotypes was 22.6%, marginally exceeding the 17.9% obtained from the hybrid varieties (Figure 2; Table 2 & S1). The difference in stearin recovery between the indigenous genotypes and the introduced hybrid varieties was also not statistically significant ($p = 0.18$).

Among the different age groups, palms aged over 30 years exhibited the widest range of oil extraction rates (12.00–45.0%) and the highest mean extraction rate of 31.7%. In comparison, the overall mean oil extraction rate across all age categories was 23.02%. However, the differences in extraction rates among the age groups were not statistically significant ($p = 0.35$). For the mass of stearin recovery, oil palm plants < 3 years old showed the broadest range (7.70–43.6%) and achieved the highest mean stearin recovery at 27.2%, while the lowest mean value was recorded in the 27–30 years group (13.9%). The overall mean mass of stearin recovery across all age categories was 20.4%. Similar to extraction rates, differences in stearin recovery between the various age groups were not statistically significant ($p = 0.90$) (Table S1).

Figure 2. (a) ripe oil palm fruit bunch, (b) longitudinal cross-section of an oil palm fruit, detailing that it is a *tenera*, (c) extracted crude palm oil, (d) oil palm stearin recovered, (e) extracted palm olein. Credit: Caku Jimmy.

Table 2. Mean oil extraction rate (OER) and mass of stearin recovery (MOSR) of indigenous genotypes and introduced hybrid oil palm varieties.

Property	Genotype	N	Mean	Minimum	Maximum	SD	Kruskal-Wallis H	df	*p*
OER (%)	Indigenous genotypes	36	23.3	6	54	12.18	0.09	1	0.76
	Introduced hybrids	33	22.8	10	40	7.82			
MOSR (%)	Indigenous genotypes	36	22.6	3.8	47.6	12.26	1.83	1	0.18
	Introduced hybrids	33	17.9	2.5	36.8	9.18			

Note: SD = Standard Deviation, df = degrees of freedom.

Table 3. Oil extraction rate and mass of stearin recovery across different districts.

Parameter	District	Mean (%)	Range (%)	SD	Kruskal-Wallis H	df	*p*-value
OER	Bundibugyo	22.1	6.00–54.00	12.84	0.66	2	0.72
	Kanungu	24.69	10.00–52.00	11.57			
	Kalangala	22.77	10.00–40.00	7.82			
MOSR	Bundibugyo	20.18	5.70-41.50	10.01	2.67	2	0.26
	Kanungu	25.66	3.80-47.60	14.35			
	Kalangala	17.91	2.50-36.80	9.18			

The oil extraction rate across Bundibugyo, Kanungu, and Kalangala districts had mean values of 22.10, 24.69, and 22.77%, respectively. The differences in extraction rates were not statistically significant ($p = 0.72$). The mass of stearin recovery varied, with Kanungu recording the highest mean (25.66%), followed by Bundibugyo (20.18%) and Kalangala (17.91%) (Table 3). The variation in stearin recovery among districts was not statistically significant ($p = 0.263$).

Table 4. Mean carbohydrate concentration of indigenous genotypes and introduced varieties.

Carbohydrate concentration in µg/mL							
	N	Mean	Minimum	Maximum	SD	Kruskal-Wallis H	df	*p*-value
Indigenous genotypes	36	0.185	0.011	0.369	0.099	0.139	1	0.71
Introduced hybrids	33	0.177	0.025	0.364	0.092			
Total	69	0.181	0.0112	0.369				

Table 5. The variation of carbohydrate concentrations across different age categories of oil palm as depicted by the Kruskal–Wallis *H* test.

Carbohydrate concentration in µg/mL	
N	69
Kruskal–Wallis H	12.2
df	9
p	0.2

Determination of oil quality based on carbohydrate content contamination

The indigenous genotypes exhibited a slightly broader range of carbohydrate concentrations (0.011–0.369 µg/mL) compared to the introduced hybrid oil palm variety (0.025–0.364 µg/mL). The mean carbohydrate content in the indigenous genotypes (0.185 µg/mL) was marginally higher than that of the introduced hybrids (0.177 µg/mL) (Table 4). However, the differences in carbohydrate composition between the two groups were not statistically significant ($p = 0.71$).

Among the different age groups, oil palms of age category 18–21 years exhibited the widest range of carbohydrate concentrations (0.034–0.369 µg/mL). The highest mean carbohydrate concentration was observed in this age group (0.241 µg/mL), while the lowest was recorded in palms aged 27–30 years (0.060 µg/mL). The overall mean carbohydrate concentration across all age categories was 0.181 µg/mL. Differences in carbohydrate concentrations across age categories were also not statistically significant ($p = 0.20$) (Table 5).

Carbohydrate concentrations were relatively consistent across the three districts, with mean values of 0.177 µg/mL in Bundibugyo, 0.195 µg/mL in Kanungu, and 0.177 µg/mL in Kalangala (Table S2). Kruskal–Wallis *H* test also indicated that these differences were not statistically significant ($p = 0.89$).

Fatty acid profile

Linolenic acid concentrations were highly variable, with indigenous genotypes exhibiting a broader range (45.50–3,461.70 mg/100g) and a higher mean (694.05 mg/100g) compared to the introduced hybrids (mean = 665.08 mg/100g; range: 175.60–3,451.60 mg/100g). However, this difference was not statistically significant ($p = 0.56$). Linoleic acid levels were higher in the indigenous genotypes (mean = 3,724.73 mg/100g; range: 824.19–13,813.50 mg/100g) than in the introduced hybrids (mean = 3,112.70 mg/100g; range: 62.47–13,271.80 mg/100g). This difference was also not statistically significant ($p = 0.96$). A notable difference was observed in oleic acid. Indigenous genotypes had a substantially higher mean oleic acid concentration (4,783.93 mg/100g) compared to introduced hybrids (3,449.10 mg/100g), and this difference was found to be statistically significant ($p = 0.02$). Although the hybrids reached a higher maximum value (10,169.70 mg/100g), the average concentration was clearly lower. For palmitic acid, the mean concentration was slightly higher in indigenous genotypes (2,242.71 mg/100g) than in hybrids (2,158.20 mg/100g). The difference between the groups was not statistically significant ($p = 0.96$). Stearic acid concentrations were significantly higher in indigenous genotypes (mean = 746.17 mg/100g) than in introduced hybrids (mean = 568.77 mg/100g), which was statistically significant ($p = 0.04$).

Linolenic acid concentrations varied, with the highest value observed in the 18–21 years age category (7,850.1 mg/100g) and the lowest in the 27–30 years group (364.3 mg/100g). Linoleic acid levels ranged from 2,475.0 to 5,327.6 mg/100g, with the highest concentration recorded in the 18–21 years category and the lowest in the 27–30 years category. Oleic acid concentrations were generally high across all age groups, with the highest value recorded in the 24–27 years category (7,116.4 mg/100g) and the lowest in the 15–18 years group (2,404.3 mg/100g). Palmitic acid levels varied from 1,449.8 mg/100g in the

Table 6. Summary of fatty acid concentrations of indigenous genotypes and introduced hybrids.

Concentration in mg/100g							
Category	Location	N	Linolenic acid (C18:3)	Linoleic acid (C18:2)	Oleic acid (C18:1)	Palmitic acid (C16:0)	Stearic acid (C18:0)
Indigenous	Bundibugyo	20	777.9	3,733.80	4,492.20	2,453.90	785.7
	Kanungu	16	589.3	3,713.40	5,148.62	1,978.70	696.8
Introduced	Kalangala	33	665.1	3,112.70	3,449.10	2,158.20	568.8
	Kruskal–Wallis H		3.22	3.76	6.59	0.94	4.05
	Df		2	2	2	2	2
	p-value		0.2	0.15	0.34	0.62	0.13

Table 7. Variation of beta-carotene concentration across different age categories.

Age category	N	N indi	N intro	Mean beta-carotene concentration (µg/100g)	Std. deviation	Kruskal–Wallis *H*	df	*p*-value
<3	3	3	0	8290.90	3884.60	10.75	9	0.23
3–6	15	7	8	9976.85	2455.57			
6–9	7	5	2	7865.96	2847.80			
9–12	9	0	9	11677.38	2776.89			
12–15	13	5	8	11523.03	2653.06			
15–18	8	2	6	9299.77	3127.83			
18–21	5	5	0	8910.49	4302.23			
24–27	4	4	0	10368.44	3681.836			
27–30	2	2	0	11122.69	6094.43			
>30	3	3	0	11352.88	1879.18			

27–30 years group to 2,613.1 mg/100g in the 18–21 year group. Stearic acid was present in lower concentrations across all age categories, ranging from 507.5 to 1,005.2 mg/100g. The differences in the concentrations of linolenic acid, linoleic acid, oleic acid, palmitic acid, and stearic acid across the age categories were not statistically significant ($p = 0.42$, 0.34, 0.13, 0.94, and 0.18), respectively.

Linolenic acid mean concentrations were highest in Bundibugyo (777.9 mg/100g), followed by Kalangala (665.1 mg/100g), and lowest in Kanungu (589.3 mg/100g). For linoleic acid, the mean concentration was highest in Bundibugyo (3,733.8 mg/100g), almost similar in Kanungu (3,713.4 mg/100g), and lowest in Kalangala (3,112.7 mg/100g). A significant difference was observed in oleic acid concentrations ($p = 0.04$). The mean was highest in Kanungu (5,148.6 mg/100g), followed by Bundibugyo (4492.2 mg/100g), and was substantially lower in Kalangala (3,449.1 mg/100g). Palmitic acid levels were highest in Bundibugyo (2,453.9 mg/100g), with Kalangala (2,158.2 mg/100g) and Kanungu (1,978.7 mg/100g) showing lower means. Stearic acid concentrations showed a clear gradient, with the highest mean in Bundibugyo (785.7 mg/100g), an intermediate mean in Kanungu (696.8 mg/100g), and the lowest mean in Kalangala (568.8 mg/100g). The variations of the different fatty acid concentrations across the three districts were not statistically significant (Table 6).

Beta-carotene concentration

The concentration of beta-carotene in palm oil ranged from 3,688.27 to 15,432.10 µg/100g in indigenous genotypes and from 4,440.59 to 14,888.12 µg/100g in introduced hybrids. The mean concentration was slightly higher in indigenous genotypes (10,389.12 µg/100g) compared to introduced hybrids (9,915.24 µg/100g). However, this difference was not statistically significant ($p = 0.529$).

The highest mean beta-carotene concentration was observed in the 9–12 years category (11,677.40 µg/100g), while the lowest was found in the 6–9-year category (7,866.00 µg/100g). Interestingly, oil palms aged over 30 years exhibited a high mean beta-carotene concentration of 11,352.90 µg/100g (Table 7). The differences in beta-carotene concentration across the various age categories of oil palms were not statistically significant ($p = 0.22$). Bundibugyo district recorded the highest mean concentration of beta-carotene (10,927.28 µg/100g), followed by Kalangala district (9,915.24 µg/100g) and Kanungu district (9,716.44 µg/100g). Despite these numerical differences, the variation in beta-carotene concentration across the districts was not statistically significant ($p = 0.42$).

Discussion

Palm oil plays a vital role across diverse sectors, including food, cosmetics, and energy. This study evaluated the oil extraction rate and nutritional profiles of indigenous and introduced hybrid oil palm varieties. Although not statistically significant, the observed trends of higher mean oil recovery and unsaturated fatty acids in indigenous genotypes warrant further investigation with larger sample sizes and standardized milling trials to determine their potential value for breeding. These findings suggest that indigenous varieties possibly contain advantageous traits for breeding (Setiowati *et al*., 2024). Integrating molecular tools such as marker-assisted selection could accelerate the identification of genetic markers associated with enhanced oil yield and stearin recovery, supporting targeted breeding improvement strategies (Shaha *et al*., 2024).

The elevated oil extraction rate in palms >30 years is consistent with reports that older trees sustain production through established root systems and optimized metabolism (Corley & Tinker, 2015). However, this pattern should be interpreted cautiously, as it may reflect selective survival of healthy, high-performing individuals rather than inherent physiological superiority. In contrast, the lowest oil extraction rates found in the mid-age (15–18 years) and older (27–30 years) oil palm categories indicate a decline in oil yield as the palms reach mid- and late-maturity stages. This decline could be attributed to factors such as physiological stress, nutrient limitations, or reduced fruit bunch efficiency as the trees age (Woittiez *et al*., 2017). In addition, the lower oil content in mid-aged and older palms may contribute to the reduced oil extraction rate observed in these trees (Singh *et al*., 2013). The highest stearin recovery was observed in oil palm trees in the less than 3 years and 6–9 years age categories, suggesting that younger palms not only produce higher-quality oil but also retain more oil in their mesocarp tissues. This finding aligns with studies showing that young oil palms exhibit peak oil synthesis before reaching physiological maturity (Singh *et al*., 2013).

The lower stearin recovery observed in the 27–30-year-old category indicates a decrease in recovery efficiency in aging palms. This reduction is likely attributed to an increase in fiber content and structural changes within the fruit mesocarp (Corley & Tinker, 2015). A study conducted in Nigeria found that the *tenera* hybrid variety yielded significantly higher oil content (26.0–28.2%) compared to the *dura* variety, which produced only 9.4–12.8% (Ohimain *et al*., 2013). Commercial *tenera* hybrids from Southeast Asia have been recorded to have oil extraction rates of 25–27% under ideal conditions (Corley & Tinker, 2015; Murphy, 2014). Indigenous genotypes yielded a higher mean mass of stearin recovery of 22.6% compared to hybrids of 17.9%. This anomalous result diverges from the standard yield of 20–30% stearin of commercial palm oil (Deffense, 2013; Kellens *et al*., 2007). Additionally, factors such as the position from which fruit samples were obtained within the fresh fruit bunch and the degree of ripeness play a significant role in influencing the palm oil extraction rate and stearin mass recovery (Hudori *et al*., 2023; Supriyatin, 2021).

The higher mean concentration of linolenic acid in indigenous genotypes, compared to the introduced hybrid varieties, suggests that palm oil from indigenous genotypes may offer greater health benefits due to its elevated omega-3 fatty acid content. The increased variability observed in indigenous genotype samples could be attributed to genetic diversity and environmental factors influencing fatty acid biosynthesis (Pamba Boundena *et al*., 2017). Both categories exhibit similar linoleic acid concentrations; however, the introduced hybrid varieties display greater variation. Linoleic acid is essential for human health and essential in the synthesis of hormones such as prostaglandins, thromboxanes, and leukotrienes. Its higher levels indicate a more stable fatty acid profile (Afify *et al*., 2012). Oleic acid, a key monounsaturated fatty acid recognized for its health benefits, was found to be more concentrated in indigenous genotypes than in introduced hybrid varieties. However, the introduced hybrid varieties contained higher levels of palmitic acid, which is significant due to its influence on oil stability and shelf life. Stearic acid levels were relatively similar between the two categories. Further, indigenous genotypes demonstrated a high concentration of unsaturated fatty acids compared to that in introduced hybrids, which contrasts with previous study reports (Chowdhury *et al*., 2016; Phan Tai & Brunner, 2019).

Unsaturated fatty acids are beneficial as they help lower serum and low-density lipoprotein (LDL) cholesterol levels, whereas saturated fatty acids tend to increase cholesterol levels (Chowdhury *et al*., 2016). The concentration of unsaturated fatty acids in this study varies from those reported in an earlier study (Arias *et al*., 2023), where the compositions of palmitic acid were higher, stearic acid was similar,

oleic acid was slightly higher, linoleic acid was higher, and linolenic acid was higher. In addition, Nigerian palm oil has been reported to contain higher palmitic acid, slightly higher oleic acid, and higher linoleic acid (Chowdhury *et al*., 2016). Studies on oil palm have shown that climate, soil conditions, and cultivation practices play a significant role in shaping the fatty acid profiles (Suresh & Behera, 2020).

The variations in fatty acid composition can be leveraged in breeding programs to develop palm varieties with higher unsaturated fatty acid content, which is a critical indicator of superior oil quality (Arias *et al*., 2023). A review of oilseed crops found that genetic modifications, selective breeding for industrial applications, and local environmental conditions often influence variations in oleic and linoleic acid (Jain, 2020). Similar findings have been observed in other oil-producing crops, such as sunflower and soybean, where selective breeding for specific fatty acid compositions has led to notable differences between traditional and modern cultivars (Abul-Fadl *et al*., 2011).

The presence of water-soluble carbohydrates in the extracted oil is not typical of refined palm olein and is likely indicative of contaminating soluble sugars or polysaccharides from fruit mesocarp cellular debris that persisted through the extraction and centrifugation process (Achour *et al*., 2022). The low and consistent levels across all samples (0.011–0.369 µg/mL) suggest that the screw press method, followed by centrifugation, was largely effective in separating the oil from the aqueous fruit components. The absence of significant differences between genotypes or districts indicates that this is a factor related to the processing methodology rather than the genetic origin of the fruit. Indigenous oil palm genotypes showed slightly higher carbohydrate levels than hybrids, with peak concentrations in the 18–21-year age group and lowest in the 27–30-year age group. These findings align with research on age-related carbohydrate variation driven by developmental and metabolic factors (Corley & Tinker, 2015).

The mean carbohydrate values, 0.185 µg/mL for indigenous genotypes and 0.177 µg/mL for introduced hybrids, are exceptionally low and align with international quality standards for crude palm oil, which specify minimal residual impurities (Sambanthamurthi *et al*., 2000). Carbohydrate reserves are vital for plant growth and reproduction (Longvah *et al*., 2017). Studies also stress the importance of rigorous quality control in palm oil production, particularly using portable NIR spectroscopy to detect adulteration and ensure authenticity. Such measures are essential for maintaining nutritional integrity and market value across both indigenous and hybrid oil palm varieties cultivated in Uganda. Indigenous oil palm genotypes exhibited slightly higher average beta-carotene concentrations than introduced hybrids. The notable variability in beta-carotene levels aligns with previous studies on palm oil mesocarps (Aguirre *et al*., 2018).

Age-related differences in β-carotene content support existing evidence that younger palms tend to accumulate fewer carotenoids, likely due to underdeveloped metabolic pathways (Habi Mat Dian, 2018). The mean beta-carotene concentration found to be 10,389 µg/100g for indigenous genotypes and 9,915 µg/100g for introduced hybrids indicates that Ugandan palm oils are a rich source of provitamin A carotenoids. When placed in a global context, the concentrations are consistent with the typical range for unrefined red palm oil but exhibit notably high variability (Zou *et al*., 2012). Nigerian palm oil has been reported to contain even higher beta-carotene contents (Eze *et al*., 2021).

Environmental factors such as rainfall, soil type, altitude, and local climate varied across the three districts, which may have influenced oil composition and extraction efficiency (Rival, 2017). For instance, Kanungu's higher elevation and rainfall may contribute to the observed higher oleic acid levels, as environmental conditions can affect physiological and metabolic pathways in oil palm plants (Rival, 2017). Agronomic practices such as fertilizer application, pruning, and pest management were not standardized across farms, which could introduce variability in oil yield and quality (Thoumazeau *et al*., 2024). These genotype-by-environment interactions underscore the importance of multi-location trials in future breeding programs to identify varieties best suited to local growing conditions (Dassou *et al*., 2022).

Limitations of the study

This study provides a comparative assessment of indigenous and introduced oil palm genotypes in Uganda, yet several limitations are acknowledged. Sample sizes across age groups and genotypes were uneven, reflecting the dispersed and smallholder nature of indigenous cultivation and potentially introducing statistical bias. Sampling strategies also differed, with snowball sampling for indigenous palms and

systematic sampling for introduced hybrids, raising the risk of selection bias linked to farmer accessibility. Although pragmatic in smallholder contexts, this non-random approach constrains generalizability; stratified random sampling is recommended for future work. These methods, however, were necessary given the dispersed, smallholder nature of indigenous cultivation, where random sampling was logistically infeasible. By explicitly noting this limitation, we underscore the practical challenges of field-based genotype assessments in smallholder systems. Agronomic practices (fertilizer application, pruning, and pest management) varied across farms and were uncontrolled, while environmental factors (soil type and microclimate) were not fully characterized, both of which may confound genotype-related differences. Indigenous palms exhibited favorable traits, including higher unsaturated fatty acid content and competitive extraction rates, but also potential vulnerabilities such as greater pest and disease susceptibility and reduced yield stability under intensive management due to limited prior selection. Future studies should adopt larger, balanced, multi-season randomized designs with controlled agronomic and environmental monitoring to enhance robustness and applicability. Despite these constraints, our study provides the first comparative insights into indigenous and introduced palms in Uganda, establishing a foundation for future work.

Conclusion

The study shows that indigenous genotypes exhibited higher oil extraction rates, mass of stearin recovery, and unsaturated fatty acid compositions. While the differences were not statistically significant, the observed trends suggest that indigenous genotypes may be more suited to local conditions. The variability in carbohydrate, carotenoid, and beta-carotene concentration across different age categories emphasizes the influence of genetic diversity, developmental stages, and environmental factors on palm oil quality. These findings support a strategic approach that combines indigenous genotypes with introduced hybrid varieties to select potential parents for developing a breeding program for enhanced oil yield and overall quality.

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Author contributions

CRediT: **Jimmy Caku**: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing; **Gabriel Ddamulira**: Conceptualization, Data curation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing; **Ephraim Nuwamanya**: Investigation, Methodology, Writing – original draft, Writing – review & editing; **Gerald Ddumba**: Investigation, Methodology, Writing – original draft; **Kesawat Singh Mahipal**: Validation, Visualization, Writing – original draft, Writing – review & editing; **Alex Asiimwe**: Investigation, Methodology, Writing – original draft; **Otuba Moses Amugoli**: Investigation, Methodology, Writing – original draft; **Titus Alicai**: Project administration, Resources, Supervision, Visualization; **Fred Bwayo Masika**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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The authors declare that there is no conflict of interest.

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Data availability statement

The raw datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

References

Abul-Fadl, M. M., El-Badry, N., & Ammar, M. S. (2011). Nutritional and chemical evaluation for two different varieties of mustard seeds. *World Applied Sciences Journal*, *15*(9), 1225–1233.

Achour, H. Y., Mamar, A. S., Saadi, S. A., Bouras, N., & Khali, M. (2022). Chemical characterization of date seeds (Phoenix dactylifera L.) cultivated in Algeria for its application as functional ingredients. *Acta Universitatis Cibiniensis, Series E: Food Technology*, *26*(2), 147–156. https://doi.org/10.2478/aucft-2022-0012

Afify, A. E. M. M., El-Beltagi, H. S., Abd El-Salam, S. M., & Omran, A. A. (2012). Oil and fatty acid contents of white sorghum varieties under soaking, cooking, germination and fermentation processing for improving cereal quality. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *40*(1), 86–92. https://doi.org/10.15835/nbha4017585

Aguirre, M., Kiegle, E., Leo, G., & Ezquer, I. (2018). Carbohydrate reserves and seed development: An overview. *Plant Reproduction*, *31*(3), 263–290. https://doi.org/10.1007/s00497-018-0336-3

Amugoli, O. M., Ddamulira, G., Asiimwe, A., Joseph, K., Ddumba, G., Mutyaba, E., & Ramathani, I. (2020). Occurrence, distribution and farmers' knowledge on the management of Fusarium wilt of oil palm among smallholders in Kalangala, Uganda. *Journal of Oil Palm Research*, *32*(3), 488–496. https://doi.org/10.21894/jopr.2020.0045

Aremu, S. O., & Nweze, C. C. (2017). Determination of vitamin A content from selected Nigerian fruits using spectrophotometric method. *Bangladesh Journal of Scientific and Industrial Research*, *52*(2), 153–158. https://doi.org/10.3329/bjsir.v52i2.32940

Arias, A., Rizo Patron, A., Simmons, S., Bell, H., & Alvarez, V. (2023). Palm oil and coconut oil saturated fats: Properties, food applications, and health. *World Journal of Food Science and Technology*, *7*(1), 9–19. https://doi.org/10.11648/j.wjfst.20230701.12

Bakewell-Stone, P. (2022). *Elaeis guineensis* (African oil palm). CABI Compendium. https://doi.org/10.1079/cabicompendium.20295

Bakewell-Stone, P. (2023). *Elaeis guineensis* (African oil palm). CABI Compendium (pp. 1–28). https://doi.org/10.1079/cabicompendium.20295

Basyuni, M., Amri, N., Putri, L. A. P., Syahputra, I., & Arifiyanto, D. (2017). Characteristics of fresh fruit bunch yield and the physicochemical qualities of palm oil during storage in North Sumatra, Indonesia. *Indonesian Journal of Chemistry*, *17*(2), 182–190. https://doi.org/10.22146/ijc.24910

Boundena, H. R. P., Bikanga, R., & Silo, T. (2017). Study physicochemical of the raw palm oils of the Republic of Gabon and Congo. *International Journal of Environment, Agriculture and Biotechnology*, *2*(6), 3056–3067. https://doi.org/10.22161/ijeab/2.6.36

Budiman, L. F., Apriyanto, A., Pancoro, A. D. I., & Sudarsono, S. (2019). Genetic diversity analysis of *tenera* × *tenera* and *tenera* × *pisifera* crosses and D self of oil palm (*Elaeis guineensis*) parental populations originating from Cameroon. *Biodiversitas Journal of Biological Diversity*, *20*(4), 937–949. https://doi.org/10.13057/biodiv/d200402

Carvalho, M. S., Mendonça, M. A., Pinho, D. M., Resck, I. S., & Suarez, P. A. (2012). Chromatographic analyses of fatty acid methyl esters by HPLC-UV and GC-FID. *Journal of the Brazilian Chemical Society*, *23*(4), 763–769. https://doi.org/10.1590/S0103-50532012000400023

Chinedu, E. E., Ebere, E. C., & Emeka, A. C. (2017). Quality assessment of palm oil from different palm oil local factories in Imo State, Nigeria. *World Scientific News*, *88*, 152–167.

Chowdhury, R., Steur, M., Patel, P. S., & Franco, O. H. (2016). Individual fatty acids in cardiometabolic disease. In R. R. Watson & F. De Meester (Eds.), *Handbook of lipids in human function: Fatty acids.* (pp. 207–318). Academic Press. https://doi.org/10.1016/B978-1-63067-036-8.00010-X

Constantin, M., Ridwani, S., Syukur, M., & Suwarno, W. B. (2017). Performance, heritability and genetic advance for oil yield and some economical characters in oil palm (*Elaeis guineensis* Jacquin) of Cameroon. *Jurnal Agronomi Indonesia (Indonesian Journal of Agronomy)*, *45*(2), 212–219. https://doi.org/10.24831/jai.v45i2.14110

Corley, R. H. V., & Tinker, P. B. (2015). *The oil palm*. John Wiley & Sons. https://doi.org/10.1002/9781118953297

Dassou, O. S., Ollivier, J., Vanhove, W., Aholoukpè, H., Impens, R., Bonneau, X., Flori, A., Durand-Gasselin, T., Augustin Sinsin, B., Adjanohoun, A., & Van Damme, P. (2022). Oil palm (Elaeis guineensis Jacq.) genetic differences in mineral nutrition: Environmental effects on leaflet mineral concentrations of four oil palm progenies. *OCL*, *29*, 23. https://doi.org/10.1051/ocl/2022016

Ddamulira, G., Asiimwe, A., Masika, F., Amugoli, M., Ddumba, G., & Maphosa, M. (2024). Agronomic suitability for oil palm growing in Uganda. *Journal of Agricultural Science*, *16*(4), 14. https://doi.org/10.5539/jas.v16n4p14

Ddamulira, G., Asiimwe, A., Masika, F., Amugoli, M., Ddumba, G., Nambuya, A., Wetaala, P., & Maphosa, M. (2020). Growth and yield parameters of introduced oil palm crop in Uganda. *Journal of Agricultural Science*, *12*(11), 299. https://doi.org/10.5539/jas.v12n11p299

Deffense, E. (2013). Palm oil fractionation: From dry to detergent fractionation. *OCL*, *20*(2), 63–69. https://doi.org/10.1051/ocl/2013007

Ebadi, M., Mohammadi, M., Pezeshki, A., & Jafari, S. M. (2023). Health benefits of beta-carotene. In S. M. Jafari, A. Rashidinejad, & J. Simal-Gandara (Eds.), *Handbook of food bioactive ingredients: Properties and applications*. (pp. 1–26). Springer. https://doi.org/10.1007/978-3-030-81404-5_51-1

Eze, S. O., Orji, J. N., Okechukwu, V. U., Omokpariola, D. O., Umeh, T. C., & Oze, N. R. (2021). Effect of processing method on carotenoid profiles of oils from three varieties of Nigerian palm oil (*Elaeis guineensis*). *Journal of Biophysical Chemistry*, *12*(03), 23–31. https://doi.org/10.4236/jbpc.2021.123003

Gesteiro, E., Guijarro, L., Sánchez-Muniz, F. J., Vidal-Carou, M. D. C., Troncoso, A., Venanci, L., Jimeno, V., Quilez, J., Anadón, A., & González-Gross, M. (2019). Palm oil on the edge. *Nutrients*, *11*(9), 2008. https://doi.org/10.3390/nu11092008

Godswill, N. N., Frank, N. E. G., Walter, A. N., Edson, M. Y. J., Kingsley, T. M., Arondel, V., & Emmanuel, Y. (2016). Oil palm. In S. K. Gupta (Ed.), *Breeding oilseed crops for sustainable production*. (pp. 217–273). Academic Press. https://doi.org/10.1016/B978-0-12-801309-0.00010-0

Government of Uganda. (2024a). *Bundibugyo district local government*. Retrieved April 26, 2025, from https://www.bundibugyo.go.ug/lg/overview/

Government of Uganda. (2024b). *Kanungu district Local Government*. Retrieved April 26, 2025, from https://www.kanungu.go.ug/

Habi Mat Dian, N. L. (2018). Palm oil and palm kernel oil: Versatile ingredients for food applications. *Journal of Oil Palm Research*, *29*(4), 487–511. https://doi.org/10.21894/jopr.2017.00014

Hudori, M., Iskandar, I., & Setyanto, D. (2023). Model formulation for estimating oil extraction rate to measure oil extraction efficiency in palm oil mill. *Journal of System*. *Technology and Industry*, *25*(1), 146–154. https://doi.org/10.32734/jsti.v25i1.10596

Ichihara, K., Shibahara, A., Yamamoto, K., & Nakayama, T. (1996). An improved method for rapid analysis of the fatty acids of glycerolipids. *Lipids*, *31*(5), 535–539. https://doi.org/10.1007/BF02522648

Ithnin, M., Vu, W. T., Shin, M.-G., Suryawanshi, V., Sherbina, K., Zolkafli, S. H., Serdari, N. M., Amiruddin, M. D., Abdullah, N., Mustaffa, S., Marjuni, M., Nookiah, R., Kushairi, A., Marjoram, P., Nuzhdin, S. V., Chang, P. L., & Singh, R. (2021). Genomic diversity and genome-wide association analysis related to yield and fatty acid composition of wild American oil palm. *Plant Science: An International Journal of Experimental Plant Biology*, *304*, 110731. https://doi.org/10.1016/j.plantsci.2020.110731

Jain, T. (2020). Fatty acid composition of oilseed crops: A review. In M. Thakur, R. Khedkar, & D. Khedkar (Eds.), *Emerging technologies in food science: Focus on the developing world*. (pp. 147–153). Springer. https://doi.org/10.1007/978-981-15-2556-8_13

Jiménez-Mcinnis, L. (2020). Public–private–producer partnerships (4Ps) in agricultural value chains. *Bulletin de l'OIE*, *2019*(3), 1–2. https://doi.org/10.20506/bull.2019.3.3043

Kellens, M., Gibon, V., Hendrix, M., & De Greyt, W. (2007). Palm oil fractionation. *European Journal of Lipid Science and Technology*, *109*(4), 336–349. https://doi.org/10.1002/ejlt.200600309

Koushki, M., Nahidi, M., & Cheraghali, F. (2015). Physico-chemical properties, fatty acid profile and nutrition in palm oil. *Archives of Advances in Biosciences*, *6*, 117–134.

Longvah, T., Ananthan, R., Bhaskarachary, K., & Venkaiah, K. (2017). *Indian food composition tables*. National Institute of Nutrition, Indian Council of Medical Research.

Malike, F. A., Rajanaidu, N., Kushairi, A., Mohd Din, A., & Norziha, A. (2019). Oil palm (Elaeis spp.) breeding in Malaysia. In J. M. Al-Khayri, S. M. Jain, & D. V. Johnson (Eds.), *Advances in plant breeding strategies: Industrial and food crops*. (Vol. 6, pp. 489–535). Springer. https://doi.org/10.1007/978-3-030-20310-3_15

Masika, F. B., Danso, I., Nangonzi, R., Amugoli, O. M., Asiimwe, A., Ddumba, G., & Ddamulira, G. (2020). Occurrence and severity of physiological disorders of oil palm (*Elaeis guineensis* Jacq. L.) in Uganda. *Journal of Agricultural Science*, *12*(10), 86–96. https://doi.org/10.5539/jas.v12n10p86

Mba, O. I., Dumont, M.-J., & Ngadi, M. (2015). Palm oil: Processing, characterization and utilization in the food industry–A review. *Food Bioscience*, *10*, 26–41. https://doi.org/10.1016/j.fbio.2015.01.003

Mensink, R. P., Zock, P. L., Kester, A. D., & Katan, M. B. (2003). Effects of dietary fatty acids and carbohydrates on the ratio of serum total to HDL cholesterol and on serum lipids and apolipoproteins: A meta-analysis of 60 controlled trials. *The American Journal of Clinical Nutrition*, *77*(5), 1146–1155. https://doi.org/10.1093/ajcn/77.5.1146

Murphy, D. J. (2014). The future of oil palm as a major global crop: Opportunities and challenges. *Journal of Oil Palm Research*, *26*(1), 1–24. https://jopr.mpob.gov.my/the-future-of-oil-palm-as-a-major-global-crop-opportunities-and-challenges/

Obibuzor, J. U., Okogbenin, E. A., & Abigor, R. D. (2012). Oil recovery from palm fruits and palm kernel. In. *Palm oil*. (pp. 299–328). Elsevier. https://doi.org/10.1016/B978-0-9818936-9-3.50014-9

Ohimain, E. I., Izah, S. C., & Obieze, F. A. (2013). Material-mass balance of smallholder oil palm processing in the Niger Delta, Nigeria. *Advances in Journal of Food Science and Technology*, *5*(3), 289–294. https://doi.org/10.19026/ajfst.5.3259

Ovwigho, A. C., Otunaruke, E. P., & Joseph, O. O. (2024). Efficiency of oil palm production in Nigeria: A review-pathway. *World Journal of Advanced Research and Reviews*, *21*(1), 2558–2565. https://doi.org/10.30574/wjarr.2024.21.1.2736

Phan Tai, H., & Brunner, G. (2019). Extraction of oil and minor compounds from oil palm fruit with supercritical carbon dioxide. *Processes*, *7*(2), 107. https://doi.org/10.3390/pr7020107

Prada, F., Ayala-Diaz, I. M., Delgado, W., Ruiz-Romero, R., & Romero, H. M. (2011). Effect of fruit ripening on content and chemical composition of oil from three oil palm cultivars (*Elaeis guineensis* Jacq.) grown in Colombia. *Journal of Agricultural and Food Chemistry*, *59*(18), 10136–10142. https://doi.org/10.1021/jf201999d

Prasetyo, D. W., Kurniawan, L., Andriani, M., Putra, G. I. S., Pernando, R. D., Taufiq, (2024). Relationship pattern of nutrient content in leaves, rachis, stalk, spikelet, and mesocarp to oil content of fresh fruit bunches of 3 varieties (Socfindo, Topaz, Damimas) of oil palm plants in mineral soils of Central Kalimantan. *IOP Conference Series: Earth and Environmental Science*, *1308*(1), 012041. https://doi.org/10.1088/1755-1315/1308/1/012041

Rival, A. (2017). Breeding the oil palm (*Elaeis guineensis* Jacq.) for climate change. OCL – *Oilseeds and Fats*. *Crops and Lipids*, *24*(1), D107. https://doi.org/10.1051/ocl/2017001

Rowles, J. L., III., & Erdman, Jr, J. W. (2020). Carotenoids and their role in cancer prevention. *Biochimica et Biophysica Acta. Molecular and Cell Biology of Lipids*, *1865*(11), 158613. https://doi.org/10.1016/j.bbalip.2020.158613

Ruswanto, A., Ramelan, A. H., Praseptiangga, D., & Partha, I. B. B. (2020). Effects of ripening level and processing delay on the characteristics of oil palm fruit bunches. *International Journal on Advanced Science, Engineering and Information Technology*, *10*(1), 389–394. https://doi.org/10.18517/ijaseit.10.1.10987

Sambanthamurthi, R., Sundram, K., & Tan, Y. A. (2000). Chemistry and biochemistry of palm oil. *Progress in Lipid Research*, *39*(6), 507–558. https://doi.org/10.1016/S0163-7827(00)00015-1

Samuel, C. B., Barine, K. K. D., & Joy, E. E. (2018). Comparative assessment of the physicochemical properties and fatty acid profile of fluted pumpkin seed oil with some commercial vegetable oils in Rivers State, Nigeria. *Research Journal of Food and Nutrition*, *2*(2), 32–40. https://doi.org/10.22259/2637-5583.0202004

Sanusi, R. A., & Adebiyi, A. E. (2009). Beta carotene content of commonly consumed foods and soups in Nigeria. *Pakistan Journal of Nutrition*, *8*(9), 1512–1516. https://doi.org/10.3923/pjn.2009.1512.1516

Setiowati, R. D., Panjaitan, F. R., Mardiana, C., Lubis, M. I., Ernayunita, (2024). Prospective oil palm (Elaeis sp.) materials for high tocotrienol content. *IOP Conference Series: Earth and Environmental Science*, *1308*(1), 012050. https://doi.org/10.1088/1755-1315/1308/1/012050

Shabdin, M. K., Shariff, A. R. M., Johari, M. N. A., Saat, N. K., & Abbas, Z. (2016). A study on the oil palm fresh fruit bunch (FFB) ripeness detection by using Hue, Saturation and Intensity (HSI) approach. *IOP Conference Series: Earth and Environmental Science*, *37*(1), 012039. https://doi.org/10.1088/1755-1315/37/1/012039

Shaha, F. R. M., Liew, P. L., Zaman, F. Q., Nulit, R., Barin, J., Rolland, J., Yong, H. Y., & Boon, S. H. (2024). Genotyping by sequencing for the construction of oil palm (*Elaeis guineensis* Jacq.) genetic linkage map and mapping of yield-related quantitative trait loci. *PeerJ*, *12*, e16570. https://doi.org/10.7717/peerj.16570

Singh, R., Ong-Abdullah, M., Low, E.-T. L., Manaf, M. A. A., Rosli, R., Nookiah, R., Ooi, L. C.-L., Ooi, S.-E., Chan, K.-L., Halim, M. A., Azizi, N., Nagappan, J., Bacher, B., Lakey, N., Smith, S. W., He, D., Hogan, M., Budiman, M. A., Lee, E. K., … Sambanthamurthi, R. (2013). Oil palm genome sequence reveals divergence of interfertile species in Old and New worlds. *Nature*, *500*(7462), 335–339. https://doi.org/10.1038/nature12309

Supriyatin, W. (2021). Palm oil extraction rate prediction based on the fruit ripeness levels using C4.5 algorithm. *ILKOM Jurnal Ilmiah*, *13*(2), 92–100. https://doi.org/10.33096/ilkom.v13i2.714

Suresh, K., & Behera, S. K. (2020). Variations in fatty acid profiles, oil and moisture content during fruit ripening in oil palm crosses grown in India under sub-tropical environment. *Journal of Oil Palm Research*, *32*(1), 50–56. https://doi.org/10.21894/jopr.2020.0017

Thoumazeau, A., Mettauer, R., Turinah, T., Junedi, H., Baron, V., Chéron-Bessou, C., & Ollivier, J. (2024). Effects of fertilization practices and understory on soil health and oil palm performances in smallholdings: An Indonesian case study. *Agricultural Systems*, *213*, 103802. https://doi.org/10.1016/j.agsy.2023.103802

Tiemann, T. T., Donough, C. R., Lim, Y. L., Härdter, R., Norton, R., Tao, H. H., Jaramillo, R., Satyanarayana, T., Zingore, S., & Oberthür, T. (2018). Feeding the palm: A review of oil palm nutrition. *Advances in Agronomy*, *152*, 149–243. https://doi.org/10.1016/bs.agron.2018.01.003

USDA. (2024). *Oilseeds: World markets and trade*. U.S. Department of Agriculture, Foreign Agricultural Service.

Weather & Climate. (2025). *Climate and average weather in Bundibugyo, Uganda*. Retrieved April 26, 2025, from http://weatherandclimate.com/uganda/bundibugyo

Woittiez, L. S., van Wijk, M. T., Slingerland, M., van Noordwijk, M., & Giller, K. E. (2017). Yield gaps in oil palm: A quantitative review of contributing factors. *European Journal of Agronomy*, *83*, 57–77. https://doi.org/10.1016/j.eja.2016.11.002

Zou, Y., Jiang, Y., Yang, T., Hu, P., & Xu, X. (2012). Minor constituents of palm oil: Characterization, processing, and application. In O.-M. Lai, C.-P. Tan, & C. C. Akoh (Eds.), *Palm oil: Production, processing, characterization, and uses.* (pp. 471–524). AOCS Press. https://doi.org/10.1016/B978-0-9818936-9-3.50019-8