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# Sustainable Production and Physicochemical Evaluation of Soap From Locally Sourced Materials: A Comparative Study With Commercial Products

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**ABSTRACT**

This study investigated the sustainable production and comprehensive physicochemical evaluation of soap using locally available raw materials in Daura, Katsina State, Nigeria. Seven formulations were developed from blends of palm kernel oil (PKO), groundnut oil (GO), cow fat (CF), and used cooking oil (UCO), using alkali extracted from plantain (Musa paradisiaca) peel ash as a renewable substitute for commercial sodium hydroxide. Saponification was conducted by the semi-boiled method at 60–75 °C. Oil characterization by AOAC-validated methods yielded saponification values of 248.5 ± 2.3, 195.4 ± 2.8, 196.8 ± 2.5, and 189.4 ± 3.2 mg KOH/g for PKO, GO, CF, and UCO, respectively. Plantain peel ash extract provided a KOH-equivalent concentration of 1.85 ± 0.08 mol/L at pH 12.8 ± 0.3. The optimized formulation (Blend B: 65% PKO, 20% GO, 10% CF, 5% UCO) produced potassium soap with a total fatty matter (TFM) content of 76.8 ± 1.1%, pH 10.0 ± 0.2, hardness score 8.5 ± 0.3/10, foam stability 68.5 ± 2.8% at 5 min, and cleaning efficiency 78.1 ± 1.6%. Comparative analysis against seven commercial sodium soap brands under identical analytical conditions confirmed comparable or superior quality for the optimized blend. The ash-based process reduced per-kilogram production costs by 13.7% relative to conventional NaOH-based manufacture (₦1,450 vs. ₦1,680/kg). Valorization of plantain peel waste and used cooking oil addresses dual environmental challenges, supporting circular economy principles and scalable small-enterprise production in rural settings.

**Keywords:** Ash-Derived Alkali; Cow Fat; Palm Kernel Oil; Physicochemical Characterization; Plantain Peel; Saponification; Sustainable Soap Production; Waste Valorization

## INTRODUCTION

Soap, defined chemically as the alkali salt of long-chain fatty acids, is produced via saponification the base-catalyzed hydrolysis of ester bonds in triglycerides to yield glycerol and fatty acid carboxylate salts (Cerone et al., 2021). The amphiphilic architecture of soap molecules comprising a hydrophobic hydrocarbon tail and a hydrophilic carboxylate head group enables adsorption at oil–water interfaces and micelle formation, wherein non-polar contaminants are encapsulated within hydrophobic cores and suspended in aqueous media (Holmberg et al., 2003; Zahran, 2024). The choice of alkali governs soap character: sodium hydroxide (NaOH) yields hard bar soap, while potassium hydroxide (KOH) produces softer, more water-soluble products (Okunola et al., 2019). Despite its apparent simplicity, soap formulation is a multi-parameter optimization problem: hardness, foam stability, cleansing efficacy, skin mildness, and storage stability all depend on the interacting effects of fatty acid chain length, degree of unsaturation, alkali type, and processing conditions (Kuntom et al., 1996; Mijaljica et al., 2022; Warra et al., 2011).

Pre-industrial soap production relied on plant-derived alkali from wood and crop-residue ashes rich in potassium carbonate ($K_2CO_3$) and potassium hydroxide (Akunna et al., 2019; Vidal et al., 2018). In West Africa, this tradition persists in artisanal black soap production using plantain, cocoa pod, and palm-bunch ashes. Globally, demand for soap rose sharply during and after the COVID-19 pandemic as handwashing became a primary public-health intervention, reinforcing the need for affordable, locally available hygiene products in low- and middle-income countries (Chirani et al., 2021; Choi et al., 2021). In Nigeria, a multi-hundred-million-dollar soap market is served primarily by large manufacturers using imported NaOH (6Wresearch, 2021). Small and medium enterprises face barriers including volatile chemical supply chains, foreign-exchange constraints on NaOH procurement, and limited access to quality-control infrastructure (Ministry of Industry, Trade and Investment, 2014). Agricultural waste streams particularly plantain (Musa paradisiaca) peel ash represent an underutilized domestic alkali source: studies confirm potassium compound contents of 78–94%, with KOH-equivalent concentrations sufficient for industrial saponification (Onyegbado et al., 2002; Olabanji et al., 2012; Taiwo & Osinowo, 2001).

Functional soap properties hardness, foam stability, cleansing efficacy, conditioning, and storage stability are primarily determined by the fatty acid composition of feedstock oils and alkali purity (Kuntom et al., 1996). Saturated medium-chain fatty acids (lauric C12:0, myristic C14:0) impart hardness and copious lather, while long-chain unsaturated acids (oleic C18:1, linoleic C18:2) contribute conditioning and mild cleansing properties (Warra et al., 2011). Palm kernel oil (PKO), abundant in northern Nigerian markets, contains 45–55% lauric acid and exhibits saponification values of 245–255 mg KOH/g (Tan & Chong, 2011; Codex Alimentarius Commission, 2019). Groundnut oil (GO), widely cultivated in Katsina State, is oleic-acid-dominant (40–50%) and complements PKO in blended systems (Dean et al., 2009).

Cow fat (tallow), recovered from abattoir waste, provides palmitic and stearic acids that contribute hardness and stable lather at low cost (Isah & Abdulrahman, 2018; Zauro et al., 2016). Used cooking oil (UCO) retains saponifiable lipids despite elevated free fatty acid content, enabling waste valorization alongside cost reduction (Bhayana & Agarwal, 2025).

**Soap-making process:**

1. Solid and liquid fats are combined in a stainless-steel pot and heated until the solid fats melt, around 43 °C.
2. A lye solution is created by dissolving lye (Sodium Hydroxide) into goat's milk in a stainless steel or glass bowl. The combination of the lye and the milk creates an exothermic chemical reaction that heats the mixture to roughly 93 °C. The mixture is then cooled to 43 °C.
3. The lye and fat mixtures are combined at a high temperature and mixed vigorously. The mixing is complete when trace is reached. Trace occurs when the mixture is thick enough to maintain slight shape.

**Cold process:**

4. Essential oils (fragrance) are added to the mixture.
5. The mixture is poured into molds and insulated. Insulation can be as simple as wrapping the molds in a thick towel.
6. When the soap is cooled and hardened (about 24 hours after mixing), it is removed from the molds and cut into its final shape. The pieces are placed on a curing rack in a well-ventilated area where the saponification process will occur.
7. The soap is cured for an additional 6-8 weeks. The common test for saponification completion is touching the soap to the tongue, if the soap irritates the tongue upon contact, the curing is not yet complete. (This is not to standard and not recommended due to toxicity.)

**Hot process:**

4. The mixture is immediately heated to 68 °C for approximately two hours until the gel phase is reached. The gel phase is marked by a dramatic change in opaqueness of the mixture. This is where saponification occurs.
5. Essential oils (fragrance) are added to the mixture.
6. The hot mixture is poured into molds where it sits until it is cooled.
7. Once the soap is cooled, it is removed and cut into the desired shape. This soap is ready for use.

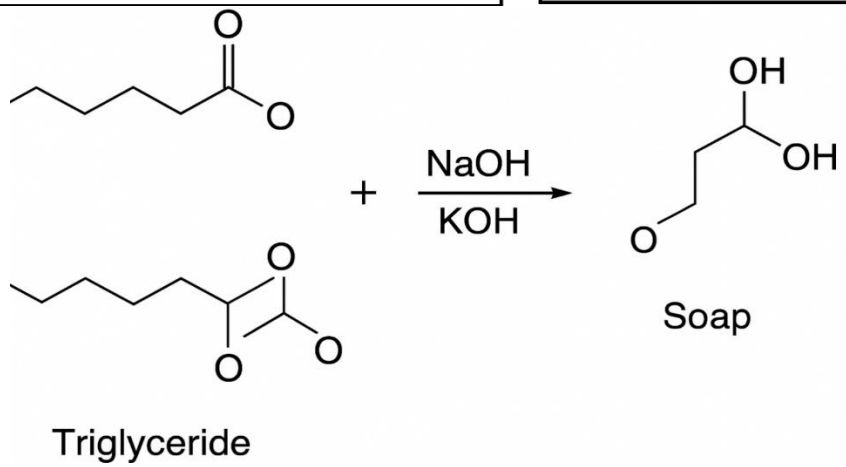


Figure 1: Reaction Scheme of Saponification showing triglyceride + NaOH/KOH → soap + glycerol]

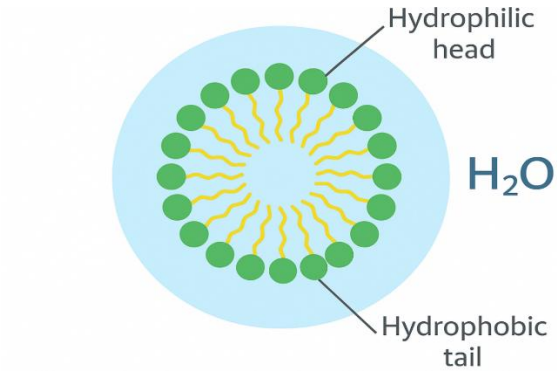


Figure 2: Micelle Formation Schematic showing Hydrophobic Tails Inward, Hydrophilic Heads Interacting with Water

Despite a growing body of literature on ash-derived alkali for soap production, no published study has simultaneously: (i) characterized all component oils using AOAC-validated methods; (ii) quantitatively characterized plantain peel ash

extract; (iii) produced and evaluated soaps from a systematically designed set of oil blends; and (iv) benchmarked the resulting products against commercially available brands under an identical analytical protocol. Addressing this gap is necessary to establish the technical and economic feasibility of replacing commercial NaOH with ash-derived alkali in small-scale Nigerian soap production, contributing to SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production) (United Nations, 2015). The present study therefore: (1) determines the physicochemical properties of PKO, GO, cow fat, and UCO; (2) extracts and characterizes the KOH-equivalent alkali from plantain peel ash; (3) formulates and saponifies seven systematic oil blends by the semi-boiled process; (4) evaluates key soap quality parameters; (5) compares locally produced soaps to seven commercial benchmark brands under identical conditions; and (6) assesses the economic viability of small-scale ash-based soap production.

## MATERIALS AND METHODS

### Study Area, Sample Collection, and Study Design

The study was conducted at the Chemistry Laboratory, Department of Science Laboratory Technology, Federal Polytechnic Daura, Katsina State, Nigeria (13.0339°N, 8.3226°E), from February to September 2024. Cow fat was collected fresh from Daura Municipal Abattoir; PKO and GO were obtained from reputable local processors; UCO (used three to five times for frying) was collected from local food vendors; and unripe plantain peels were gathered fresh from local food outlets. All analytical-grade chemicals (≥99% purity) were procured from Sigma-Aldrich (Merck KGaA, Darmstadt, Germany) and BDH Chemicals (VWR International, Radnor, PA, USA). This study produces potassium-based soft soap using KOH-equivalent alkali extracted from plantain peel ash. Potassium soaps differ intrinsically from commercial sodium-based hard bar soaps in physical properties being inherently softer and more water-soluble due to the larger ionic radius and lower charge density of $K^+$ relative to $Na^+$ and this distinction is acknowledged explicitly throughout the comparative analysis (Holmberg et al., 2003).

### Sample Preparation

#### *Cow Fat*

Fresh cow fat (5 kg) was washed with distilled water, cut into 2–3 cm cubes, and rendered at 80–90 °C for 3–4 h with continuous stirring. The melted fat was filtered through muslin cloth while hot to remove protein residues, cooled, re-melted, and re-filtered through Whatman No. 1 filter paper (GE Healthcare, Chicago, IL, USA). The purified fat was stored in sealed containers at 25 ± 2 °C.

#### *Used Cooking Oil*

UCO (3 L) was heated to 60 °C and filtered through muslin cloth. The filtrate was treated with 5% (w/v) activated charcoal at 80 °C for 30 min with stirring, then vacuum-filtered through Whatman No. 42 filter paper and stored in amber bottles away from light.

#### *Vegetable Oils*

PKO and GO were dried over anhydrous sodium sulfate (5 g/100 mL, 2 h) and filtered through Whatman No. 1 filter paper. Treated oils were stored in sealed amber bottles at 25 ± 2 °C.

#### *Plantain Peel Ash Extraction*

Plantain peel ash (20 kg, sieved through a 0.5 mm screen) was mixed with distilled water at a 1:5 (w/v) ratio, agitated for 5 min, and allowed to stand for 12 h. The supernatant was decanted, filtered through Whatman No. 1 filter paper, and concentrated by heating at 60 °C for 10 h to yield a consistent KOH-equivalent concentration. The concentrated extract was stored in sealed containers pending characterization and use.

### Physicochemical Analysis of Oils and Fats

All determinations were performed in triplicate at 25 ± 2 °C following AOAC (2000) and ISO standard methods, and results are expressed as mean ± SEM. Relative density was determined pycnometrically (AOAC Method 920.212; Equation 1). Saponification value (SV) was measured by reflux saponification with 0.5 mol/L alcoholic KOH and back-titration with 0.5 mol/L HCl (AOAC Method 920.160; Equation 2). Iodine value (IV) was determined by the Wijs method using 0.1 mol/L $Na_2S_2O_3$ (AOAC Method 993.20; Equation 3). Acid value (AV) and free fatty acid (FFA) content were determined by titration against 0.1 mol/L NaOH in neutralized ethanol–diethyl ether (1:1 v/v) with phenolphthalein indicator (AOAC Method 940.28; Equations 4 and 5).

$$\text{Relative density} = (W_3 - W_1) / (W_2 - W_1) \quad (1)$$

$$\text{SV (mg KOH/g)} = [(V_1 - V_2) \times M \times 56.1] / W \quad (2)$$

$$\text{IV (g } I_2\text{/100 g)} = [(V_1 - V_2) \times M \times 12.69] / W \quad (3)$$

$$\text{AV (mg KOH/g)} = (V \times M \times 56.1) / W \quad (4)$$

$$\text{FFA (\%)} = (V \times M \times M^{fA}) / (W \times 10) \quad (5)$$

where $W_1$ = empty pycnometer mass (g); $W_2$ = pycnometer + water (g); $W_3$ = pycnometer + oil (g); $V_1$ = blank titrant volume (mL); $V_2$ = sample titrant volume (mL); V = titrant volume (mL); M = reagent molarity (mol/L); W = sample mass (g); 56.1 = MW of KOH (g/mol); 12.69 = iodine value conversion factor (126.9/10); $M^{fA}$ = MW of the reference fatty acid (200.3 g/mol for lauric acid; 282.5 g/mol for oleic acid).

### Alkali Characterization

The KOH-equivalent concentration of the ash extract was determined by titrating 25 mL of extract against standardized 0.1 mol/L HCl with phenolphthalein indicator (Equation 6). Because the ash extract contains both KOH and $K_2CO_3$, the result is expressed as total alkali equivalents (KOH equiv., mol/L) rather than true KOH molarity. Specific gravity was measured with a calibrated hydrometer; total dissolved solids were determined gravimetrically at 105 °C; and potassium content was determined by flame photometry and expressed as % $K_2CO_3$.

$$\text{KOH equiv. (mol/L)} = (V^{HLL} \times M^{HLL}) / V_{ext}{}^{radt} \quad (6)$$

where V_HCl = volume of HCl consumed (mL); M_HCl = molarity of HCl (mol/L); V_extract = volume of ash extract titrated (mL).

### Oil Blending and Alkali Calculations

Seven blends were prepared in the proportions shown in Table 1 using an analytical balance (Mettler Toledo ME204, ±0.0001 g). Oils were heated to 60 °C and mixed at 300 rpm for 15 min (IKA RW 20 digital overhead stirrer). Blend saponification values and alkali requirements were calculated using Equations 7–10:

$$SV^{blend} = \Sigma(SV^I \times f^I) \quad (7)$$

$$KOH_t{}^{heor}\ (g) = (W^{oal} \times SV^{blend}) / 1000 \quad (8)$$

$$KOH^{adtual}\ (g) = KOH_t{}^{heor} \times 1.05 \quad (9)$$

$$V^{extradt}\ (mL) = [KOH^{adtual}\ (g) \times 1000] / [M \times 56.1] \quad (10)$$

where SV_i = saponification value of component oil i (mg KOH/g); f_i = mass fraction of component i; W_oil = oil

blend mass (g); M = KOH-equiv. concentration of extract (mol/L). A 5% excess alkali (Equation 9) was applied to ensure complete saponification and compensate for the mixed $K_2CO_3$/KOH composition of the ash extract.

**Table 1: Composition of the Seven Oil Blends Prepared for Soap Formulation**

| Blend | PKO (%) | GO (%) | CF (%) | UCO (%) | Blend Description |
|---|---|---|---|---|---|
| A | 60 | 20 | 15 | 5 | PKO-dominant blend |
| B | 65 | 20 | 10 | 5 | Optimized PKO blend |
| C | 20 | 60 | 15 | 5 | GO-dominant blend |
| D | 20 | 20 | 55 | 5 | CF-dominant blend |
| E | 100 | 0 | 0 | 0 | Pure PKO control |
| F | 0 | 100 | 0 | 0 | Pure GO control |
| G | 0 | 0 | 100 | 0 | Pure CF control |

Note. PKO = palm kernel oil; GO = groundnut oil; CF = cow fat; UCO = used cooking oil. Values are weight percentages; each blend was prepared in a 500 g batch.

**Soap Production**

Soap was produced by the semi-boiled saponification method (Mabrouk, 2005; Spitz, 2016). For each 500 g batch, the oil blend was heated to 60 °C in a 2 L grade-316 stainless-steel vessel with continuous stirring at 200 rpm. Concentrated ash extract (pre-heated to 50 °C) was added dropwise over 5 min at 250 rpm. Temperature was raised to 75–80 °C and maintained for 90 min. Completion of saponification was confirmed by the clarity test (absence of oil droplets when a sample is dispersed in hot water). Salting-out was induced by adding 100 mL of saturated NaCl solution (350 g/L, 60 °C); the glycerol-rich aqueous phase was drained after 30 min. The soap curd was washed twice with warm distilled water (200 mL, 50 °C), briefly reheated to 80 °C for 10 min to expel excess moisture, and poured into rectangular wooden molds (30 × 20 × 5 cm). After solidification at 25 ± 2 °C for 24 h, bars were cut and cured on wooden racks at 25 ± 3 °C and 60 ± 10% RH for 4 weeks, turned every 3 days to ensure uniform hardening and $CO_2$-mediated neutralization of residual alkali (Schumann & Siekmann, 2005).

**Physicochemical Analysis of Soap**

All soap analyses were performed in triplicate on freshly cured (4-week) and aged (8-week) soaps following ISO standard methods. Hardness was assessed qualitatively on a 1–10 hand-feel scale by three trained evaluators and quantitatively by cone penetrometer (Koehler K19500; standardized cone 102.5 g, 30°, 5 s at 25 °C; five readings per bar; n = 5). Foam stability was determined by a modified Ross–Miles method (10 vertical inversions of a 2 g/100 mL solution in a sealed 250 mL graduated cylinder); initial foam height ($H_0$) and height at 1 min intervals to 10 min were recorded; foam stability at time t was calculated by Equation 11. Moisture content was determined gravimetrically at 105 ± 2 °C to constant mass (AOAC Method 945.39; ISO 673:1981; Equation 12). pH of 1% (w/v) soap solutions was measured with a calibrated pH meter (Mettler Toledo SevenCompact S220; ISO 4316:1977). TFM was determined by ether extraction after HCl acidification of fatty acid salts (ISO 685:2020; Equations 13–14). Cleaning efficiency was assessed by reflectance colorimetry of standardized soiled cotton fabric (modified ASTM D4265; Equation 15). Free caustic alkali was titrated against 0.1 mol/L HCl in hot ethanol (ISO 4314:1977; Equation 16). Chloride content was determined by Mohr's argentometric method (Equation 17).

$$\text{Foam Stability (\%)} = (H^{t} / H_0) \times 100 \quad (11)$$

$$\text{Moisture Content (\%)} = [(W_1 - W_2) / (W_1 - W_0)] \times 100 \quad (12)$$

$$RCOOK + HCl \rightarrow RCOOH + KCl \quad (13)$$

$$\text{TFM (\%)} = [(W_1 - W_0) / W_{soap}] \times 100 \quad (14)$$

$$\text{CE (\%)} = [(R_u^{ashed} - R_{so}^{alled}) / (R^{dlean} - R_{so}^{alled})] \times 100 \quad (15)$$

$$\text{Free Alkali (\% KOH)} = (V \times M \times 56.1) / (W \times 10) \quad (16)$$

$$\text{Chloride (\% NaCl)} = (V \times M \times 58.5) / (W \times 10) \quad (17)$$

where H_t = foam height at time t (cm); $H_0$ = initial foam height (cm); $W_0$ = empty vessel mass (g); $W_1$ = vessel + sample, wet (g); $W_2$ = vessel + sample, dry (g); W_soap = soap sample mass (g); R = reflectance; V = titrant volume (mL); M = titrant molarity (mol/L); W = soap sample mass (g); 56.1 = MW of KOH; 58.5 = MW of NaCl.

**Comparison with Commercial Soaps and Sensory Evaluation**

Seven commercial brands (Eva, Viva, Septol, Lux, Joy, Give, and Imperial Leather) purchased from Daura markets were subjected to identical analyses. Sensory evaluation was conducted with 30 respondents using a 7-point hedonic scale; informed consent was obtained and institutional ethics approval was secured prior to evaluation.

**Statistical Analysis**

All experiments were performed in triplicate (n = 3 unless noted). Results are expressed as mean ± SEM. One-way ANOVA with Tukey's honest significant difference (HSD) post-hoc test (IBM SPSS v27.0) was applied to identify significant differences among treatments at $p < 0.05$. Pearson correlation coefficients were calculated to assess inter-variable relationships.

## RESULTS AND DISCUSSION

**Physicochemical Properties of Oils and Fats**

Table 2 summarizes the physicochemical parameters of the four feedstock oils and fats. PKO exhibited the highest saponification value (248.5 ± 2.3 mg KOH/g), significantly greater ($p < 0.001$) than GO (195.4 ± 2.8), CF (196.8 ± 2.5), and UCO (189.4 ± 3.2 mg KOH/g). This reflects PKO's dominance by short- to medium-chain saturated fatty acids principally lauric acid (~48%, C12:0) and myristic acid (~17%, C14:0) which require greater molar alkali per gram of oil (Tan & Chong, 2011). Correspondingly, PKO displayed the lowest iodine value (19.2 ± 1.1 g $I_2$/100 g), confirming minimal unsaturation. GO showed the highest IV (94.3 ± 2.6 g $I_2$/100 g), reflecting its predominantly unsaturated profile (oleic C18:1, linoleic C18:2); UCO was intermediate (87.6 ± 3.5 g $I_2$/100 g) owing to partial oxidative and hydrolytic degradation from repeated frying (Yılmaz, 2023). UCO also displayed the highest acid value (18.45 ± 0.89 mg KOH/g) and FFA content (9.23 ± 0.45%), significantly elevated ($p <$

0.001) relative to fresh oils, attributable to hydrolytic rancidity under repeated thermal cycling; the additional alkali demand was accommodated by the 5% excess factor in Equation 9. All parameters fell within FAO/Codex reference ranges for the respective oils (Codex Alimentarius Commission, 2019).

**Table 2: Physicochemical Properties of the Four Feedstock Oils and Fats**

| Parameter | PKO | GO | CF | UCO |
|---|---|---|---|---|
| Relative density (g/mL) at 25 °C | 0.924 ± 0.010a | 0.918 ± 0.012a | 0.895 ± 0.014b | 0.921 ± 0.016a |
| Saponification value (mg KOH/g) | 248.5 ± 2.3a | 195.4 ± 2.8b | 196.8 ± 2.5b | 189.4 ± 3.2c |
| Iodine value (g $I_2$/100 g) | 19.2 ± 1.1d | 94.3 ± 2.6a | 45.7 ± 2.1c | 87.6 ± 3.5b |
| Acid value (mg KOH/g) | 3.21 ± 0.18d | 8.14 ± 0.43b | 5.92 ± 0.35c | 18.45 ± 0.89a |
| Free fatty acid (%) | 1.61 ± 0.09d | 4.07 ± 0.22b | 2.96 ± 0.18c | 9.23 ± 0.45a |
| FAO/Codex standard range | 0.89–0.96 / 245–255 / 14–23 / ≤30 / <5 | | | |

Note: Values are mean ± SEM (n = 3). Different superscript letters within the same row indicate significant differences ($p < 0.05$) by Tukey's HSD test. PKO = palm kernel oil; GO = groundnut oil; CF = cow fat; UCO = used cooking oil. The FAO/Codex standard range row lists values for density / saponification value / iodine value / acid value / FFA in the order shown (Codex Alimentarius Commission, 2019)

**Physicochemical Properties of Plantain Peel Ash Extract**

The plantain peel ash extract yielded a KOH-equivalent concentration of 1.85 ± 0.08 mol/L at pH 12.8 ± 0.3 (Table 3), confirming sufficient alkalinity for saponification. The potassium compound content (82.3 ± 3.5% expressed as $K_2CO_3$) aligns with previous reports of 78–94% for plantain peel ash (Onyegbado et al., 2002; Olabanji et al., 2012), validating its use as a renewable alkali substitute. Because the extract contains both $K_2CO_3$ and KOH, HCl titration with phenolphthalein measures total alkali equivalents; values are therefore reported as KOH equivalents, and the 5% excess (Equation 9) compensates for the mixed composition.

**Table 3: Physicochemical Properties of the Plantain Peel Ash Extract**

| Parameter | Value |
|---|---|
| KOH-equivalent concentration (mol/L) | 1.85 ± 0.08 |
| pH | 12.8 ± 0.3 |
| Specific gravity | 1.18 ± 0.02 |
| Total dissolved solids (g/L) | 103.4 ± 4.2 |
| Potassium content (% as $K_2CO_3$) | 82.3 ± 3.5 |

Note. Values are mean ± SEM (n = 3). KOH-equivalent concentration is total alkali expressed as KOH; the extract contains both KOH and $K_2CO_3$ (see Section 2.4).

**Saponification Parameters and Soap Yield**

All seven blends were saponified successfully within 90–120 min. Soap yields (Table 4) ranged from 88.2 ± 2.2% (Blend F, 100% GO) to 95.9 ± 1.2% (Blend E, 100% PKO), with significant differences among blends ($p < 0.01$). Blends with higher PKO content (A, B, E) yielded 93.5–95.9%, consistent with the greater reactivity of saturated fatty acids toward alkali and more complete saponification (Abera et al., 2023). Lower yields in GO- and CF-dominant blends reflect greater losses of unsaponifiable matter and polyunsaturated triglycerides during purification (Ogunsuyi & Akinnawo, 2017).

**Table 4: Saponification Parameters and Soap Yield for Each Blend (Oil Batch: 500 g)**

| Blend | Calc. SV_blend (mg KOH/g) | Theor. KOH (g) | Actual KOH +5% (g) | Extract Volume (mL) | Soap Yield (g) | Yield (%) | Sig.[a] |
|---|---|---|---|---|---|---|---|
| A | 221.0 | 110.5 | 116.0 | 595 | 523 ± 8 | 93.5 ± 1.4 | a |
| B | 233.6 | 116.8 | 122.6 | 631 | 531 ± 9 | 94.6 ± 1.6 | a |
| C | 190.4 | 95.2 | 99.9 | 514 | 497 ± 11 | 88.6 ± 2.0 | b |
| D | 194.2 | 97.1 | 102.0 | 524 | 501 ± 10 | 89.4 ± 1.8 | b |
| E | 248.5 | 124.3 | 130.5 | 671 | 538 ± 7 | 95.9 ± 1.2 | a |
| F | 195.4 | 97.7 | 102.6 | 527 | 495 ± 12 | 88.2 ± 2.2 | b |
| G | 196.8 | 98.4 | 103.3 | 531 | 504 ± 11 | 89.9 ± 2.0 | b |

Note. Values are mean ± SEM (n = 3). a Significance column: different superscript letters denote significant differences in yield (%) at $p < 0.05$ (Tukey's HSD). SV_blend was calculated using Equation 7. Extract volume was calculated using Equation 10 with [KOH equiv.] = 1.85 mol/L.

**Physicochemical Quality of Produced Soaps**

***Hardness***

Hardness results (Table 5) showed a strong negative correlation between hand-feel scores and penetrometer readings ($r = −0.97$, $p < 0.001$), validating the consistency of subjective and objective measurements (Dastidar et al., 2023). Blend E (100% PKO) exhibited the highest hardness (9.2 ± 0.2; penetrometer 1.8 ± 0.2 mm) owing to the tight crystalline

packing of lauric and myristic acid chains. Blend B achieved excellent hardness (8.5 ± 0.3; 2.5 ± 0.2 mm) comparable to commercial sodium soap benchmarks a noteworthy outcome for a potassium soap, attributable to the dominant 65% PKO content (Holmberg et al., 2003). Blend F (100% GO) was softest (4.8 ± 0.5; 7.2 ± 0.5 mm) due to disruption of the crystal lattice by cis-double bonds of oleic and linoleic acids (Warra et al., 2011).

***Foam Stability***

Blend E produced the highest initial foam height (10.1 ± 0.4 cm) but the shortest foam half-life (2.1 ± 0.2 min), characteristic of medium-chain saturated fatty acid soaps whose micelles lack sufficient stabilizing inter-chain interactions for persistent foam (Rosen & Kunjappu, 2012). Blend B demonstrated a balanced profile: initial foam height 9.2 ± 0.5 cm, foam half-life 3.8 ± 0.4 min, and 68.5 ± 2.8% stability at 5 min confirming that blending GO and CF with PKO prolongs foam persistence through incorporation of longer-chain fatty acids (Mabrouk, 2005). Blend F exhibited the poorest lathering performance (foam stability 48.3 ± 3.8% at 5 min), consistent with the poor foaming characteristics of high-oleic oils.

***Moisture Content***

Fresh soap moisture content ranged from 8.9 ± 0.5% (Blend E) to 13.8 ± 0.8% (Blend F), all within the acceptable ≤15% limit, with significant reductions after 8 weeks of aging (3.2–6.5%). A strong negative correlation with hardness was observed ($r = -0.92$, $p < 0.01$), confirming that lower moisture promotes tighter crystalline structure (ISO 673:1981). Moisture losses during aging (52.8–64.0%) indicate proper curing with continued evaporation and $CO_2$-mediated neutralization of residual alkali.

***pH, TFM, and Functional Parameters***

All soaps yielded pH values in the 10.0–10.4 range (Table 5), consistent with toilet soap specifications (9.5–10.5; ISO 4316:1977). TFM values of 69.5–78.3% placed Blends B and E in BIS Grade 1 (≥76%; Bureau of Indian Standards, 1984), indicating efficient saponification and minimal impurities. Cleaning efficiency (65.2–81.7%) correlated positively with TFM ($r = 0.88$, $p < 0.01$) and hardness ($r = 0.76$, $p < 0.05$), supporting the relationship between soap content, firmness, and detergency (ASTM D4265-98, 2020; Odinga et al., 2024). All blends contained minimal free caustic alkali (0.09–0.15%), well below the 0.5% toilet-soap maximum (ISO 4314:1977), and chloride content (1.72–2.01%) was within the acceptable <3% limit (Myers, 2006).

**Table 5: Key Physicochemical Quality Parameters of the Seven Soap Blends**

| Blend | Hand-feel (1–10) | Penetrometer (mm) | Fresh MC (%) | pH | TFM (%) | BIS Grade | CE (%) | Free Alkali (%) |
|---|---|---|---|---|---|---|---|---|
| A | 7.8±0.4b | 3.2±0.3b | 10.5±0.6 | 10.2±0.2 | 74.5±1.2b | 2 | 72.4±1.8b | 0.12±0.01 |
| B | 8.5±0.3a | 2.5±0.2a | 9.8±0.5 | 10.0±0.2 | 76.8±1.1ab | 1 | 78.1±1.6ab | 0.11±0.02 |
| C | 5.2±0.5c | 6.8±0.5c | 12.3±0.7 | 10.1±0.3 | 71.2±1.5c | 3 | 68.5±2.1c | 0.14±0.02 |
| D | 6.9±0.4bc | 4.1±0.4bc | 11.4±0.6 | 10.3±0.2 | 73.8±1.3bc | 2 | 74.3±1.9b | 0.13±0.01 |
| E | 9.2±0.2a | 1.8±0.2a | 8.9±0.5 | 10.3±0.2 | 78.3±1.0a | 1 | 81.7±1.5a | 0.09±0.01 |
| F | 4.8±0.5c | 7.2±0.5c | 13.8±0.8 | 10.4±0.3 | 69.5±1.6c | 3 | 65.2±2.3c | 0.15±0.02 |
| G | 7.2±0.3b | 3.8±0.3b | 11.2±0.7 | 10.2±0.2 | 72.9±1.4bc | 2 | 71.8±2.0b | 0.12±0.01 |
| **Standard** | | | **≤15%** | **9.5–10.5** | **≥70%** | | | **≤0.5%** |

Note. Values are mean ± SEM (n = 3 for hand-feel, pH, TFM, MC, and CE; n = 5 for penetrometer). Different superscript letters within each column indicate significant differences ($p < 0.05$, Tukey's HSD). MC = moisture content; CE = cleaning efficiency at 5 min; BIS Grade: 1 ≥ 76%, 2 = 70–76%, 3 = 60–70% TFM (Bureau of Indian Standards, 1984). Standard column refers to toilet soap specifications

**Solubility in Different Water Conditions**

All blends dissolved completely in distilled water and 0.1 mol/L NaCl solution (soft water). In hard water (0.1 mol/L $CaCl_2$ and $MgCl_2$), varying degrees of precipitation occurred, with Blend E (100% PKO) exhibiting only minimal scum formation attributed to the higher solubility of calcium and magnesium laurate and myristate salts relative to long-chain analogs (Holmberg et al., 2003). Blends C and F (high unsaturated fatty acid content) showed the heaviest precipitation, consistent with the insolubility of calcium and magnesium salts of long-chain unsaturated fatty acids. Precipitation with 0.1 mol/L $FeCl_2$ was most pronounced across all blends owing to the very low solubility product of iron fatty acid salts (Smulders et al., 2007). These findings support selection of PKO-rich formulations (Blends A, B, E) for use in areas supplied with hard water.

**Comparison with Commercial Soaps**

Table 6 presents direct side-by-side comparison of the three best-performing experimental blends with seven commercial brands under identical analytical conditions. Blend E achieved the highest TFM (78.3 ± 1.0%), matching Septol (78.5 ± 1.2%) and surpassing Eva (76.2 ± 1.3%) and Viva (74.8 ± 1.4%). Blend B showed TFM (76.8 ± 1.1%) equivalent to Eva, with superior foam stability (68.5 vs. 64.2%) and competitive cleaning efficiency (78.1 vs. 79.3%). All locally produced soaps maintained free alkali well below commercial levels, and pH values were within the same 9.8–10.3 range across all products. It is explicitly noted that the experimental soaps are potassium-based while commercial brands are sodium-based; the comparable hardness achieved by Blend B (8.5 ± 0.3/10) is therefore a significant formulation achievement attributable to 65% PKO content (Holmberg et al., 2003).

**Table 6: Comparative Quality Parameters: Best Experimental Blends vs. Commercial Brands**

| Parameter | Blend A | Blend B | Blend E | Eva | Viva | Septol | Lux | Joy[a] | Standard |
|---|---|---|---|---|---|---|---|---|---|
| TFM (%) | 74.5±1.2 | 76.8±1.1 | 78.3±1.0 | 76.2±1.3 | 74.8±1.4 | 78.5±1.2 | 74.1±1.5 | 75.3±1.4 | ≥70 |
| pH (1% soln.) | 10.2±0.2 | 10.0±0.2 | 10.3±0.2 | 10.1±0.2 | 9.8±0.3 | 10.2±0.2 | 10.0±0.2 | 10.3±0.2 | 9.5–10.5 |
| Moisture (%) | 10.5±0.6 | 9.8±0.5 | 8.9±0.5 | 9.2±0.6 | 10.3±0.7 | 8.5±0.5 | 10.8±0.6 | 9.5±0.6 | ≤15 |
| Free alkali (%) | 0.12±0.01 | 0.11±0.02 | 0.09±0.01 | 0.10±0.01 | 0.13±0.02 | 0.08±0.01 | 0.11±0.01 | 0.10±0.01 | ≤0.5 |
| Hardness (1–10)[b] | 7.8±0.4 | 8.5±0.3 | 9.2±0.2 | 8.3±0.4 | 7.9±0.5 | 8.8±0.3 | 8.0±0.4 | 7.8±0.5 | |
| Foam stability (%, 5 min) | 62.4±3.1 | 68.5±2.8 | 45.8±3.2 | 64.2±3.0 | 58.6±3.5 | 63.8±2.9 | 60.1±3.2 | 61.5±3.3 | |
| Cleaning efficiency (%) | 72.4±1.8 | 78.1±1.6 | 81.7±1.5 | 79.3±1.7 | 73.5±2.0 | 82.1±1.6 | 76.8±1.9 | 74.2±2.0 | |
| Chloride (%) | 1.85±0.12 | 1.92±0.14 | 2.01±0.15 | 1.01±0.03 | 0.17±0.04 | 0.35±0.03 | 0.51±0.03 | 0.82±0.05 | <3 |

Note. Values are mean ± SEM (n = 3). a Give and Imperial Leather data not shown; full seven-brand data are available from the corresponding author. b Experimental blends are potassium-based soaps; commercial brands are sodium-based. Hardness scores are indicative only and are not directly equivalent across soap types. Standard column refers to toilet soap specifications (Bureau of Indian Standards, 1984; ISO 685:2020)

**Sensory Evaluation**

Consumer acceptability results (Table 7) demonstrated strong market potential for the locally produced soaps. Blend B received the highest positive ratings among locally produced soaps (83.4% rated moderately liked or better), closely matching the commercial reference (86.7% positive). Blend E also showed high acceptance (83.3%), though some respondents noted texture roughness as a minor drawback. Blend A received 73.3% positive ratings. Respondents cited pleasant natural fragrance, good lathering, perceived skin mildness, and environmental sustainability as key positive attributes. Minor concerns included color variability and absence of commercial packaging and branding factors readily addressable through post-production finishing (Ogunsuyi & Akinnawo, 2017).

**Table 7: Sensory Evaluation Results Percentage of Respondents per Acceptability Category (n = 30)**

| Acceptability Category | Blend A (%) | Blend B (%) | Blend E (%) | Commercial Soap (%) |
|---|---|---|---|---|
| Extremely liked | 13.3 | 20.0 | 23.3 | 26.7 |
| Very much liked | 26.7 | 36.7 | 30.0 | 33.3 |
| Moderately liked | 33.3 | 26.7 | 30.0 | 26.7 |
| Slightly liked | 16.7 | 10.0 | 10.0 | 6.7 |
| Neither liked nor disliked | 6.7 | 6.7 | 3.3 | 6.6 |
| Moderately disliked | 3.3 | 0.0 | 3.4 | 0.0 |
| Extremely disliked | 0.0 | 0.0 | 0.0 | 0.0 |
| **Total positive (≥ moderately liked)** | **73.3** | **83.4** | **83.3** | **86.7** |

Note. Percentages are rounded to one decimal place; column totals equal 100.0%. Commercial soap = Eva brand used as reference.

**Economic Analysis**

Table 8 presents the cost comparison for 1 kg of finished soap. The primary saving arises from alkali substitution: plantain peel ash (₦50/batch) versus commercial NaOH (₦280/batch) represents an 82.1% reduction in alkali cost and a 13.7% reduction in total per-kilogram production cost (₦1,450 vs. ₦1,680/kg). For a producer manufacturing 100 kg/week, projected annual savings are ₦1,104,000. With a total initial investment of approximately ₦500,000 (equipment, raw material stock, and working capital), the payback period is approximately 5–6 months. Commercial toilet soap retails at ₦3,000–10,000/kg, yielding achievable gross margins of 40–60% above the ₦1,850/kg fully-loaded production cost confirming strong economic viability (Taiwo, 2006).

**Table 8: Comparative Production Cost Analysis per Kilogram of Finished Soap**

| Cost Item | Ash-Based Production (₦) | NaOH-Based Production (₦) |
|---|---|---|
| **Raw Materials** | | |
| Oils and fats | 850 | 850 |
| Alkali (plantain ash / NaOH) | 50 | 280 |
| Sodium chloride (salting-out) | 20 | 20 |
| Water and utilities | 80 | 80 |
| **Processing Costs** | | |
| Labor | 450 | 450 |
| **Total production cost** | **1,450** | **1,680** |
| **Cost reduction** | **13.7%** | |

Note: Exchange rate: US$1 ≈ ₦1,550 (September 2024; Central Bank of Nigeria). Costs are calculated per kilogram of finished soap at laboratory scale and should be revised for pilot or industrial scale.

## CONCLUSION

This study demonstrated that commercial-quality potassium soap can be sustainably produced using locally sourced raw materials in rural northern Nigeria. Comprehensive physicochemical characterization of four feedstock oils established that PKO, with the highest saponification value (248.5 ± 2.3 mg KOH/g) and lowest iodine value (19.2 ± 1.1 g $I_2$/100 g), is the primary driver of soap hardness and lathering performance, while GO, CF, and UCO contribute complementary fatty acid profiles that optimize foam stability, conditioning, and cost efficiency. Plantain peel ash yielded a renewable KOH-equivalent alkali at 1.85 ± 0.08 mol/L and pH 12.8 ± 0.3, confirming viability as a substitute for commercial NaOH. Among seven systematically formulated blends, the optimized formulation (Blend B: 65% PKO, 20% GO, 10% CF, 5% UCO) produced soap with TFM 76.8% (BIS Grade 1), pH 10.0, hardness 8.5/10, foam stability 68.5% at 5 min, and cleaning efficiency 78.1% parameters comparable to or exceeding those of established commercial brands tested under identical conditions. The simultaneous valorization of plantain peel waste and used cooking oil addresses dual environmental challenges and supports a circular economy model with 13.7% lower production costs than conventional NaOH-based methods. It is acknowledged that the potassium-based nature of the soaps intrinsically limits direct physical equivalence with commercial sodium soaps, a distinction relevant to any regulatory or scale-up context. Future research should address long-term storage stability (>6 months), comprehensive microbiological safety profiling, blended KOH–NaOH alkali systems for targeted hardness specifications, and design and testing of pilot-scale production systems appropriate for small and medium enterprises in rural settings.

## DECLARATIONS

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**Institutional Review Board Statement**

Sensory evaluation was approved by the Institutional Review Board of Federal Polytechnic Daura. Informed consent was obtained from all participants prior to evaluation.

**Data Availability Statement**

The primary data supporting the findings of this study are available from the corresponding author upon reasonable request.

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