

Preliminary Characterization of *Uapaca kirkiana* Fruit Pomace: Nutritional, Phytochemical, Functional, and Aroma Profiling as a Potential Feed Ingredient

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Abstract

Large-scale and small-scale fruit processing generates large amounts of fruit pomace, which is rich in bioactive compounds and offers an eco-friendly opportunity for valorization as a livestock feed ingredient. This study aimed to preliminarily characterize the nutritional, phytochemical, functional, and aroma properties of *Uapaca kirkiana* pomace powder. Chemical composition was determined by standard proximate methods, phytochemical profiling by gas chromatography-mass spectrometry (GC-MS), functional properties by gravimetric tests, and aroma by olfactory analysis. The pomace had an acidic pH (4.36 ± 0.02) and a low moisture content ($8.74 \pm 1.12\%$). Proximate composition was as follows: crude protein $13.62 \pm 0.58\%$, crude fibre $21.65 \pm 1.39\%$, crude fat $4.40 \pm 0.17\%$, and nitrogen-free extract $46.56 \pm 0.43\%$. Neutral detergent fibre and acid detergent fibre were $47.17 \pm 1.02\%$ and $32.77 \pm 1.12\%$, respectively. The calcium-to-phosphorus ratio was 3.7:1, while the tannin content was negligible (0.453 ± 0.14 mg/100 g DM). The bulk and tapped densities were 0.46 ± 0.01 and 0.57 ± 0.01 g/ml, respectively, yielding a Carr index of 19.3%, indicating good flowability. The GC-MS revealed a complex phytochemical profile dominated by linoleic (22.09%), palmitic (16.77%), and stearic (3.58%) acids. The pomace had a mild, fruity aroma with no off-notes. These preliminary findings indicate that *U. kirkiana* pomace possesses attributes warranting further investigation as a potential feed ingredient. However, as the study was conducted on a single batch without in vivo feeding trials or safety evaluations, all inferences remain hypothesis-generating and require empirical validation before practical recommendations can be advanced.

Categories: Poultry nutrition, Ruminant nutrition, Sustainable climate smart agriculture

Keywords: uapaca kirkiana, fruit pomace, chemical composition, functional properties, gc-ms, sensory evaluation

Introduction

The global demand for livestock products has intensified pressure on conventional feed resources, particularly maize and soybean meal, whose prices and availability are becoming increasingly unstable [1-2]. This situation has sparked renewed interest in underutilized agro-industrial by-products, which can be valorized into cost-effective, locally available feed ingredients [3-4]. Among such resources, fruit pomace, a solid residue remaining after juice or pulp extraction, has gained attention for its high fibre content, bioactive compounds, and low economic value, making it a promising candidate for circular bioeconomy models [5-6]. Additionally, using fruit pomaces is environmentally friendly for livestock nutrition, aligning with a zero-waste philosophy while also offering the economic advantage of reduced feeding costs [7].

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Uapaca kirkiana Müell. Arg., commonly known as Wild loquat or sugar plum, is a fruit-bearing tree commonly found in Zimbabwe and other Southern African countries, such as Zambia, Malawi, and Mozambique [8]. *Uapaca kirkiana* fruits are widely harvested by rural communities for fresh consumption, traditional processing, and small-scale commercial juice and wine production [9]. Preliminary studies have indicated that *U. kirkiana* fruits can contain significant amounts of carbohydrates, fibre, and phenolic compounds [10]. The pulp is considered the valuable part and constitutes about 15-28.6% of the whole fruit [11-12]. The seeds and peels therefore constitute the remaining fraction (71.4% to 85%). When combined with the post-harvest losses, which are reported to be 40-60% [13], the total residue from industrial pulp processing can cumulatively exceed 80% per 100 kg of fruit. *Uapaca kirkiana* pomace (seeds, peels, and fruit rejects) is typically discarded as waste, both after individual consumption and industrial processing of the fruit pulp, representing the underutilization of this potentially valuable resource.

Documented studies on the nutritional composition, phytochemical profile, functional properties, or feed utilization of *U. kirkiana* fruit pomace are limited. To evaluate the suitability of *U. kirkiana* pomace for livestock nutrition, a critical multi-dimensional assessment is required. The chemical composition of a material indicates the fundamental building blocks and intrinsic characteristics, which directly determine its potential applications, safety, reactivity, nutritional value, and physical behaviour [14]. Phytochemical screening investigates the presence of bioactive compounds that exert antioxidant, anti-inflammatory, as well as anti-nutritional effects [15]. Functional properties such as bulk density, tapped density, flowability, and water absorption index (WAI) determine the physical behaviour of the powder during handling, mixing, storage, and pelleting, which are crucial in feed manufacturing [16-18]. Sensory evaluation influences voluntary feed intake, particularly in monogastric species that rely heavily on olfactory cues [19-20].

This preliminary study aimed to comprehensively evaluate the nutritional composition, phytochemical profile, functional properties, and aroma attributes of *U. kirkiana* pomace, as well as assess its potential as a feed ingredient for livestock, especially under smallholder farming conditions. While the observed nutritional and functional properties are discussed in relation to their theoretical relevance for livestock feeding, it is important to emphasize that this study is strictly analytical in scope. No in vivo feeding trials or digestibility assessments were conducted. The results are expected to provide a scientific basis for the utilization of this underutilized by-product, contributing to food-feed synergy and waste reduction in rural agro-processing systems.

Materials And Methods

Sample collection and preparation

Uapaca kirkiana fruits were sourced from Mazowe District, Mashonaland Central, Zimbabwe in January 2025 (the peak fruiting season). To control for maturity-related biochemical variability, fruits were hand-harvested at a uniform maturity stage, as defined by Nemapare et al. [12]. A single batch comprising 40 kg of fresh fruit was transported to the Department of Food Science and Dietetics, University of Zimbabwe, within 4 hours of harvest for pulp extraction.

Pulp extraction was performed using a mechanical screw press, replicating small-scale industrial practice, to separate the juice from the solid fraction. The resultant pomace (comprising seeds, peels, rejects, and residual pulp) was immediately collected and processed using standard methods as suggested by Chatepa et al. [21]. It was initially solar-dried for 24 h, followed by forced-air oven drying at 60°C for 24 h to prevent thermal cooking of the matrix. The dried pomace was ground through a 1 mm sieve using a laboratory mill (Thomas-Wiley Model 4 Laboratory Mill) to obtain a uniform particle size. The pomace powder was then stored in airtight polythene bags pending analysis. The pomace powder was then analyzed for chemical, phytochemical, functional, and aroma properties. All analyses were conducted in triplicate (technical replicates), as recommended by the Association of Official Analytical Chemists (AOAC) [22] guidelines for analytical method validation, to ensure accuracy, precision, and statistical reliability of the data.

This source was preferred to roadside vendors from rural communities to ensure analytical repeatability across determinations of proximate, phytochemical, and functional properties. Using a controlled supply chain minimized variability associated with fruit origin, maturity, post-harvest handling, and spoilage. This approach generates a reliable

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dataset that can later inform community-level applications. The pomace was used without separating the seeds, peels, or residual pulp. This is because the pomace matrix represents the real by-product generated after pulp extraction. Separation would add to operational costs and affect the applicability of this study.

It is critical to acknowledge that this study was conducted on a single batch of pomace derived from fruits harvested from a single geographic origin, during one specific season, and at a fixed maturity stage, under controlled processing conditions. Although this strategy was intentionally adopted to maximize analytical repeatability by minimizing extrinsic variability (agro-ecological differences, seasonal fluctuations, and handling practices), it inherently restricts the generalizability of the absolute compositional values.

Nutritional analysis

pH

The pH of *U. kirkiana* pomace powder was determined using a standard extraction procedure. Briefly, 1 g of the pomace powder was thoroughly mixed with 10 ml of distilled water (1:10 w/v ratio) and allowed to stand for 30 minutes at room temperature to enable equilibrium between the solid and liquid phases. After the equilibration period, the pH of the supernatant was measured using a pre-calibrated digital pH meter (AnaMatrix LmPh-10, India). The pH measurements were performed in triplicate, and the meter was calibrated prior to each measurement using standard buffer solutions of pH 4.0 and 7.0 to ensure the accuracy and reliability of the readings.

Proximate Composition

Proximate analysis was conducted in triplicate in the Bioassay Laboratory of the Department of Livestock Sciences at the University of Zimbabwe. The analyses included the determination of dry matter (DM), mineral ash, crude protein (CP), crude fat, crude fibre (CF), and the calculation of nitrogen-free extract (NFE) following the methods described by the AOAC [23]. Moisture content was determined by oven-drying samples at 105°C until a constant weight was achieved. CP was quantified using the Kjeldahl method (AOAC Method 976.05 D), while crude fibre was assessed through acid and alkali digestion (AOAC Method 962.09 A). Ether extract was measured via Soxhlet extraction (AOAC Method 920.39B), and ash content was determined by incinerating samples at 550°C (AOAC Method 942.05 A). NFE, representing soluble carbohydrates, was obtained by difference:

$$\text{NFE (\%)} = 100 - [\% \text{ Moisture} + \% \text{ Crude protein} + \% \text{ Ether extract} + \% \text{ Ash} + \% \text{ Crude fibre}]$$

Acid Detergent Fibre and Neutral Detergent Fibre Analysis

The techniques described by Van Soest et al. [24] were used to determine neutral detergent fibre (NDF) and acid detergent fibre (ADF) concentrations.

Mineral Composition

Analysis of calcium (Ca) and phosphorus (P) strictly followed the protocol described by AOAC [23]. *Uapaca kirkiana* samples were initially subjected to nitric-perchloric acid digestion, a standard wet-ashing procedure that effectively releases minerals from bound elements. Following sample digestion, Ca and P were determined by atomic absorption spectrophotometry using a Perkin Elmer AAnalyst 300 spectrophotometer. Phosphorus was determined using a spectrophotometer at a wavelength of 660 nm (as a phosphomolybdate complex).

Vitamin C Determination

Vitamin C (ascorbic acid) content was determined by titration with 2,6-dichlorophenolindophenol (DCIP), a standard redox method widely used for food and feed samples (AOAC Method 967.21). An aliquot of the sample extract containing approximately 2 mg of ascorbic acid was combined with 5 ml of a stabilizing solution composed of metaphosphoric acid and acetic acid. This mixture was then titrated with a standardized DCIP solution until a persistent rose-pink endpoint was observed, indicating that all ascorbic acid had been oxidized and the first excess of unreduced dye had appeared. The concentration of ascorbic acid in the original sample was calculated based on the volume of DCIP titrant consumed,

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the titre of the standardized DCIP solution (expressed as mg ascorbic acid equivalent per millilitre), and the appropriate dilution factor. All determinations were performed in triplicate, and results were expressed as mean $\pm$ standard deviation (mg ascorbic acid per 100 g sample).

Tannin Analysis

Tannin content was determined using an adapted protocol from Makkar et al. [25] and Makkar [26]. Summarily, 1 g of polyvinylpyrrolidone (PVPP) was dissolved in 1 ml of distilled water. One millilitre of sample extract was then added to the PVPP solution. The mixture was vortex-mixed for 30 seconds and incubated at 4°C for 15 minutes. Following incubation, samples were centrifuged at $1,107 \times g$ for 10 minutes using an Eppendorf® Centrifuge 5702 R (Berlin/Heidelberg, Germany). The supernatant was collected, and total phenolic content was determined by measuring absorbance at 725 nm using a Spectronic Genesys spectrophotometer (Genesys 5, Thermo Fisher Scientific, Waltham, MA, USA). Tannin concentration was calculated by subtracting the total phenolics after binding with PVPP from the total phenolics before binding with PVPP, as shown below.

Phytochemical properties

Phytochemical extraction and screening were performed using a Gas Chromatography-Mass Spectrometry (GC-MS) system (ThermoQuest, Milan, Italy), following the methods described by Anuradha et al. [27]. This widely recognized protocol involves drying and coarse powdering of the samples, preparation of a methanolic extract via Soxhlet extraction, and subsequent GC-MS profiling to identify the chemical constituents. The abundance of each identified compound was expressed as the percentage of its peak area relative to the total integrated peak area of the total ion chromatogram. Consequently, these data are presented for comparative profiling purposes to identify major semi-volatile constituents, rather than for absolute quantification or direct nutritional valuation.

Functional properties

Water Absorption Index and Water Solubility Index

WAI and water solubility index (WSI) were analyzed for the pomace powder following the protocol adapted from Pavani et al. [28]. A 2.5 g sample of the pomace powder was placed in a Corning® 50 ml centrifuge tube (Sigma-Aldrich, Darmstadt, Germany). Distilled water (30 ml) was added, and the mixture was vortexed for 30 seconds using a Corning® LSE™ vortex mixer (Sigma-Aldrich, Darmstadt, Germany) to ensure uniform dispersion. The suspension was then centrifuged at $3,000 \times g$ for 15 minutes in an Eppendorf® Centrifuge 5702 R (Berlin/Heidelberg, Germany). After centrifugation, the supernatant was carefully decanted into a pre-weighed drying bottle (ChemLand, Stargard, Poland) and dried at 135°C until a constant mass was achieved (samples were weighed at hourly intervals to confirm constant weight). The remaining hydrated pellet was also weighed. All measurements were performed in triplicate. The following equations were used:

$$\text{Water Absorption Index (WAI)} = \frac{\text{Weight of hydrated sample (g)} - \text{Weight of dry sample (g)}}{\text{Weight of dry sample (g)}} \cdot 100$$

$$\text{Water Solubility Index (WSI)} = \frac{\text{Weight of dried supernatant (g)}}{\text{Weight of dry sample (g)}} \cdot 100$$

The Angle of the Slide

The angle of repose was determined as the minimal angle formed between the inclined plane and the horizontal base, following the tilting-box method (Figure 7) and the procedures described by Wojtczak et al. [29]. This angle represents the threshold at which a bulk powder, under its own weight, begins to slide down a flat plane due to gravitational forces [29-30]. In practice, a 30 g sample of *U. kirkiana* pomace powder was placed on a flat, smooth horizontal surface. The surface was then slowly and uniformly inclined until the material just started to move. The angle of the plane relative to the horizontal at the onset of movement was recorded as the angle of repose.

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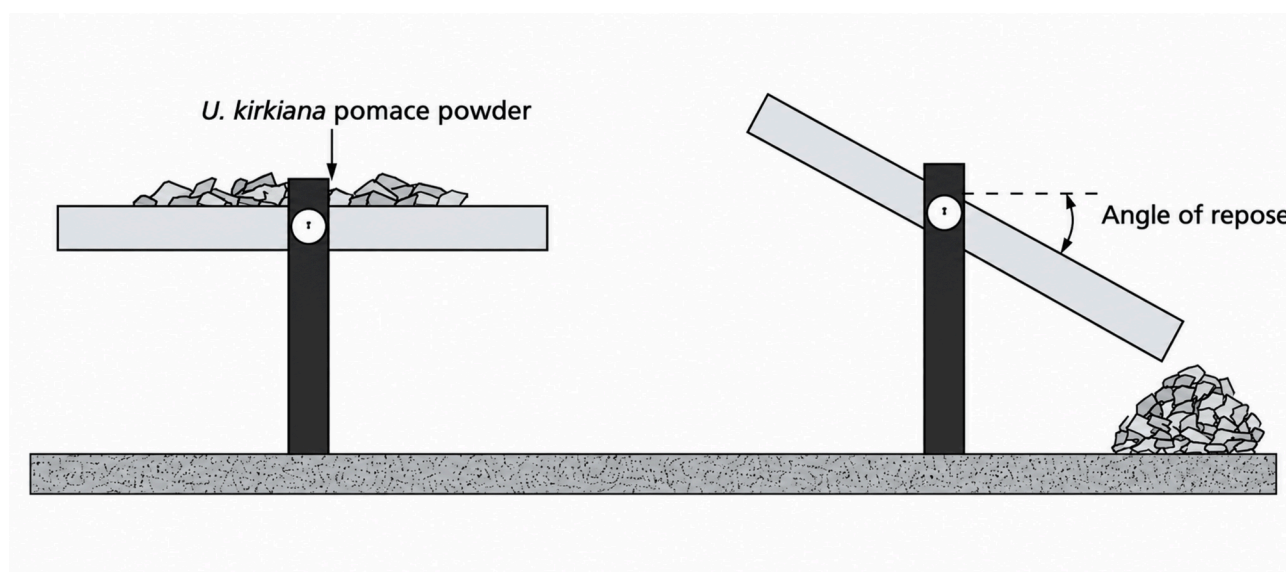


FIGURE 1: Determination of the slide angle of *U. kirkiana* pomace

Source: Hodzi et al. [93]

Bulk Density

The bulk density of *U. kirkiana* fruit pomace powder was determined using a standard gravimetric method [31]. A clean, dry container of known volume was weighed empty. The container was then carefully filled with the powder to the brim without deliberate compaction, and the filled container was weighed. Bulk density was calculated using the following equation:

$$\text{Bulk Density (g/ml)} = \frac{\text{Weight of pomace powder (g)}}{\text{Volume of pomace powder (ml)}}$$

Tapped Density

The tapped density of *U. kirkiana* pomace powder was determined following the method adopted from Gopalraaj and Velayudhannair [18]. A known weight of the powder sample was transferred into a dry graduated measuring cylinder. The cylinder was then manually tapped until no further reduction in the powder volume was observed. The final tapped volume was recorded, and the tapped density was calculated using the following equation.

$$\text{Tapped Density (g/ml)} = \frac{\text{Weight of pomace powder (g)}}{\text{Final tapped volume (ml)}}$$

Flowability and Cohesiveness

The flowability and cohesiveness of the *U. kirkiana* pomace powder were quantitatively evaluated using the Carr index (CI) and the Hausner ratio (HR), following the methodology described by Jinapong et al. [32]. These two dimensionless parameters are fundamental indicators of powder flow behaviour, derived directly from the bulk and tapped density measurements. The CI expresses the powder's compressibility, or the tendency of particles to consolidate under their own weight or vibration, while the HR describes the increase in packing efficiency after the material has been subjected to tapping and mechanical settling [33]. Both indices were calculated from the bulk density and tapped density of the pomace powder using the following equations:

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$$\text{Carr Index (CI)} = \frac{\text{Tapped density} - \text{Bulk density}}{\text{Bulk density}} \cdot 100$$
$$\text{Hausner's Ratio (HR)} = \frac{\text{Tapped density}}{\text{Bulk density}}$$

According to the widely recognized classification of powder properties, the flow behaviour and cohesiveness of a powder can be categorized on a standardized scale, as outlined in Table 1.

Carr Index (CI) (%)	Flowability	Hausner's Ratio (HR)	Cohesiveness
<15	Very Good	<1.2	Low
15-20	Good	1.2-1.4	Intermediate
20-35	Fair	>1.4	High
35-45	Bad		
>45	Very Bad		

TABLE 1: Classification of powder properties
Source: Association of Official Analytical Chemists (AOAC) [23] and Sahni and Shere [33]

Aroma profile

Aroma analysis studies were conducted in the microbiology laboratory at the Department of Livestock Sciences, University of Zimbabwe. This laboratory is well-ventilated and designed according to ISO standards [34]. All analyses in this laboratory are carried out according to the 1975 Helsinki Declaration, which was revised in 2013. A total of 20 trained panelists with no known olfactory disorders and a willingness to evaluate fruit powders were recruited for aroma profiling. Before the analysis, panelists were briefed on the aim of the research and assured that there were no known risks, and informed consent was obtained. The panelists were informed that they would not receive direct benefits but that their contribution would support research on indigenous fruit products. Panelists were also informed that their responses would be anonymized, that no personal identifying information would be published, that participation was entirely voluntary, and that they could withdraw at any time without penalty. Following this informed consent, a brief training on the aroma descriptors using reference standards was done before doing this analysis. Ten grams of *U. kirkiana* pomace powder were placed in a 50 ml odourless glass jar with a tight-fitting lid. The sample was left at room temperature (24°C) for 30 minutes before evaluation to allow headspace to develop. Six aroma descriptors were assessed: Sweet/Caramel-like, Earthy/Woody, Fermented, Mouldy, Herbal, Vinegary aroma. The panelists were seated separately with dividers between them. The panelists removed the lid and immediately sniffed the headspace with short, gentle sniffs. The panelists then rated each aroma parameter on a 1-5 intensity scale, with appropriate descriptors ranging from “undetectable” to “very intense”:

- 1 = Undetectable (no perception)
- 2 = Slight (barely perceptible)
- 3 = Moderate (clearly noticeable but not overpowering)

4 = Intense (strong)

5 = Very intense (overwhelming, unpleasant)

Dry samples were assessed, whereby 10 g samples were left in closed containers for 10 minutes prior to analysis to enable the accumulation of headspace volatiles. While wet pomace may have its own aroma profile, it is the dry product that serves as the practical feed ingredient. Analyzing dry samples ensures that the results are directly applicable to the intended use, namely dry feeding in livestock production systems.

Statistical analysis

Data were presented as mean $\pm$ standard error (SE) using Origin® for Windows, version 7.0 (OriginLab Co., Northampton, MA, USA). The means and SE values were calculated from the technical replicates. No inferential statistics were applied, as the experimental design consisted of a single homogenized biological sample and therefore did not permit estimation of population-level variance or between-sample comparisons.

Results And Discussion

Nutritional composition

The chemical composition of *U. kirkiana* fruit pomace powder, as presented in Table 2, shows its fundamental building blocks and intrinsic characteristics, which directly determine its potential applications, safety, reactivity, nutritional value, and physical behaviour [35].

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Parameter	Quantity
Proximate composition (g/100g DM) OR (% DM)	
Moisture	8.74±1.12
Ash	5.03±0.27
Crude protein	13.62±0.58
Crude fibre	21.65±1.39
Ether extract	4.40±0.17
Nitrogen-free extract (NFE)	46.56±0.43
Acid detergent fibre (ADF)	32.77±1.12
Neutral detergent fibre (NDF)	47.17±1.02
Hemicellulose	14.40 ±1.01
Vitamin C and Tannins (mg/100g)	
Tannins	0.453±0.14
Vitamin C	6.60±0.41
Minerals (% DM)	
Phosphorus	0.18±0.01
Calcium	0.664±0.03
pH (1:10 w/v ratio)	4.36±0.02

TABLE 2: Chemical composition of *U. kirkiana* pomace powder

DM, Dry Matter

The pH of *U. kirkiana* pomace was 4.36 ± 0.02, indicating an acidic nature and similar to that of its pulp (4.3-4.6) as previously reported [9]. This pH value is typical of fruit pomaces, which often exhibit a low pH (<4.5) due to the presence of organic acids such as citric acid, malic acid, and others retained from the fruit flesh [36-37]. From a processing perspective, the low pH contributes to intrinsic microbiological stability by inhibiting the growth of acid-sensitive spoilage and pathogenic microorganisms. Together with a low moisture content, this could help extend shelf life without much reliance on chemical preservatives.

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The moisture content of *U. kirkiana* pomace powder was $8.74 \pm 1.12\%$. This is notably lower than that of apple (9.00%) and orange (10.55%) pomaces [38]. Low moisture content in feeds is advantageous as it reduces transport weight and improves shelf life [39]. Additionally, low moisture content also concentrates other nutrients, making the material more energy-dense per unit weight [40]. However, extremely low moisture content can lead to increased dustiness and handling challenges during feed processing [41]. Therefore, the observed moisture content suggests that *U. kirkiana* could exhibit good keeping quality under appropriate storage conditions.

The ash content of *U. kirkiana* pomace powder was $5.03 \pm 0.27\%$, indicating a moderate range. Compared to other fruit pomaces, the observed ash content is higher than the 2.2% reported in apple pomace [42] and 3.40% reported in gooseberry pomace [43]. Compared to conventional feed ingredients, the observed ash content was higher than the 1.4% found in maize but slightly lower than the 7.3% reported in soybean meal [44]. Ash represents the mineral content, including macro-elements such as calcium, phosphorus, potassium, and magnesium, and trace minerals such as iron, zinc, and copper [45]. In ruminants, these minerals support rumen microbial activity, bone development, and metabolic functions [46]. In poultry and pigs, the mineral fraction of *U. kirkiana* may help meet dietary requirements for electrolytes and trace elements, potentially reducing the need for supplemental mineral premixes at moderate inclusion levels. The mineral profile of *U. kirkiana* pomace ($0.664 \pm 0.03\%$ Ca, $0.18 \pm 0.01\%$ P; DM basis) gives a Ca:P ratio of approximately 3.7:1. For monogastrics, the wide Ca:P ratio and low total P limit the safe inclusion level, set at 2.0:1 in broilers and 2.15:1 in growing pigs [47]; hence, supplementation of *U. kirkiana* pomace with available phosphorus and phytase would be necessary to prevent deficiency.

The CP level of *U. kirkiana* fruit pomace powder was $13.62 \pm 0.58\%$. Compared to other fruit and vegetable pomaces used in livestock nutrition, the observed CP level is higher than the 6.60% reported for yam peels [48], 3.4% reported for apple pomace, 4.2% reported for orange pomace [49], and 6-9% documented in banana pomace [50]. Relative to conventional feed ingredients, the observed CP is significantly higher than the 10.5% reported for maize but lower than the 43-53% reported for soybean meal [44]. However, CP is a bulk nitrogen estimate that does not reflect amino acid composition, protein bioavailability, or potential interference from fibre-bound proteins or anti-nutritional factors. Thus, while the CP level provides a preliminary nutritional rationale, definitive assessment of protein quality requires comprehensive amino acid profiling and digestibility studies.

The crude fibre content was at $21.65 \pm 1.39\%$. This high fibre level can increase water-binding/viscosity effects in the gut and may influence digestibility and overall feed utilization [51]. Compared to other fruit pomaces used in animal nutrition, the observed fibre level is higher than 11.09-14.38% reported for banana peels [50], while lower than 26-70% documented in grape pomace [52], and the 45.2% for pineapple pomace. Such fibre content is typical of fruit pomace. Compared to conventional feed ingredients, the observed crude fibre is higher than 2.4% found in yellow maize and 4.4% reported for soybean meal [44]. In monogastric animals, poorly balanced fibre can impair nutrient absorption, increase maintenance energy needs, or elevate digesta viscosity [51]. While the high fibre content suggests that elevated inclusion of *U. kirkiana* pomace could constrain energy digestibility in monogastrics, moderate inclusion may be worth exploring. However, because no in vivo digestibility or performance trials were performed, this remains a preliminary hypothesis requiring experimental confirmation before any practical inclusion levels can be recommended.

The ether extract ($4.40 \pm 0.17\%$) indicates a low-to-moderate fat content, similar to maize (4.3%) and maize bran (4.6%), but lower than full-fat soybean meal (21.4%) [44]. This fat fraction could contribute modest dietary energy, particularly in monogastric diets where lipids are efficiently utilized.

The calculated NFE of *U. kirkiana* fruit pomace powder was $46.56 \pm 0.43\%$, indicating substantial energy-yielding carbohydrates. Relative to other fruit pomaces, the observed carbohydrate level is higher than 43.4% found in pineapple pomace [42,53] and 29.20% reported in grape pomace [54]. Compared to conventional feed ingredients, this NFE value is lower than that of yellow maize (70-75%) but higher than that of soybean meal (30-35%) [44]. NFE comprises starches, simple sugars, and certain hemicelluloses and pectins that are digestible by endogenous enzymes in monogastric animals or rapidly fermentable in the rumen [55-56]. The observed NFE level suggests that *U. kirkiana* pomace is not simply a bulk fibre source but may contribute meaningful energy, especially when included in balanced rations.

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The NDF and ADF of *U. kirkiana* pomace were $47.17 \pm 1.02\%$ and $32.77 \pm 1.22\%$, respectively. These values are consistent with those reported for apple pomace (NDF: 30-48.2%; ADF: 25-42%) and fall within the broader range documented for fruit pomaces (NDF: 18-87%; ADF: 16-57%) [57-58]. The observed NDF and ADF values are, however, higher than the quantities observed in pomegranate pomace, which had 39.43% NDF and 27.21% ADF [59]. ADF and NDF predict voluntary feed intake in ruminants, with high NDF being undesirable as it makes the feed bulkier, physically filling the rumen and triggering false satiety sooner [60]. In poultry, fibre has some newly pronounced benefits, including improved intestinal integrity, enhanced gut health, and greater digestive efficiency [61]. However, high ADF and NDF restrict nutrient absorption, especially in young birds and piglets [62-63]. However, the observed ADF and NDF levels are considered moderate-to-high and could make *U. kirkiana* fruit pomace a valuable feed ingredient for ruminants. In non-ruminants, its use could be limited to low inclusion levels.

The tannin level of *U. kirkiana* fruit pomace was 0.453 ± 0.14 mg/100 g, similar to that of its pulp (1.4-1.8 mg/100 g), as previously reported [11]. This level is very low, indicating that the pomace contains a negligible concentration of these phenolic compounds. Fruits often contain hydrolysable tannins which, during ripening, are polymerized as acetaldehyde is converted into sugars or consumed during respiration [64]. This explains the low tannin concentration observed in *U. kirkiana* fruits and fruit pomace. There is also a perception that some of the tannins and other flavonoids in plant materials are lost or experience certain chemical transformations into other phytochemical metabolites during fruit ripening, as well as in the course of sun-drying the fruit before analysis [11]. As high levels of tannins are known to reduce feed palatability, inhibit digestive enzymes, bind dietary proteins, and lower nutrient digestibility, especially in monogastric animals [65-66], the observed level in *U. kirkiana* is many orders of magnitude below such thresholds. The negligible tannin content observed in *U. kirkiana* pomace is a favorable preliminary indicator, as it suggests a reduced risk of protein precipitation and astringency, common sensory and nutritional drawbacks associated with this specific class of polyphenols.

The vitamin C content of *U. kirkiana* fruit pomace was 6.60 ± 0.41 mg/100 g DM, indicating a low to moderate level. Compared to fresh *U. kirkiana* fruits, the observed vitamin C concentration is marginally lower than 14.5-16.8mg/100g reported by Chawafambira et al. [9]. The processing methods (drying, milling) used for the pomace could have reduced the vitamin C level. The observed vitamin C concentration may offer some antioxidant properties when the pomace is included in livestock diets. Research has shown that vitamin C plays critical roles in collagen synthesis, immune function, and iron absorption in animals [67]. Vitamin C levels between 100 and 200 mg/kg of feed have been established as an effective nutritional strategy to ameliorate the adverse effects of stress in poultry, enhancing both productivity and physiological resilience [68]. The concentration observed is insufficient to serve as a primary dietary source and would require supplementation to meet stress-related requirements in livestock. Nevertheless, the residual vitamin C contributes modestly to the overall functional value of the pomace.

Overall, the chemical composition of the sampled *U. kirkiana* pomace indicates a feed material containing moderate crude protein and ether extract and relatively high crude fibre. These characteristics suggest potential nutritional value, but the relatively high fibre content and Ca ratio may limit its use, particularly in monogastric diets, unless inclusion levels are appropriately evaluated and diets are adequately balanced. However, the values reported in this study were obtained from a single batch collected from one location and one harvesting season. Therefore, the observed composition should be considered a preliminary characterization and may not represent the nutritional composition of *U. kirkiana* pomace across different locations, seasons, fruit maturity stages, or processing batches. Further studies involving multiple batches and sampling locations and seasons are recommended to establish the extent of compositional variation and provide a more robust basis for evaluating its potential as a livestock feed ingredient.

Phytochemical analysis

Based on the GC-MS screening report for *U. kirkiana* fruit pomace powder, 212 distinct compound entries were detected, based on a full count of retention time entries with match scores ranging from 80.1% to 99.0%. The relative peak area for each entry was based on the peak-area percentages reported in the GC-MS output, expressed relative to the total ion chromatogram (TIC). Of the 212 entries, only 13 were classified as dominant compounds based on a relative peak area of

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≥1.0% of the TIC, while the remaining 199 entries were classified as non-dominant compounds because their relative peak areas were <1.0% of the TIC. Of the 13 dominant compounds, eight were considered true plant-derived phytochemicals after excluding known GC-MS contaminants and artefacts. The predominant compounds, including the contaminants and artefacts, and their chemical structures and chromatogram are shown in Table 3 and Figure 2, respectively. Compounds identified as synthetic chemicals, plasticizers, nitrosamines, or Maillard-reaction artefacts were retained in Table 3 for transparency but excluded from Table 4 as well as from the phytochemical interpretation.

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Peak #	RT (min)	Identified compounds	Formula	Match score	Molecular weight (g/mol)	Area	Area %
1	7.619	6-(N-Piperidinylethyl)-2,5-dimethylphenol	C ₁₄ H ₂₁ NO	94.9	233.35	163805171	2.39
2	7.796	2-Butyn-1-ol	C ₄ H ₆ O	85.1	70.09	399643534	5.84
3	9.907	2H-Pyran-2,6(3H)-dione	C ₅ H ₄ O ₃	93.3	112.08	156,175,748	2.28
4	15.188	4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl-	C ₆ H ₈ O ₄	95.2	144.13	249413556	3.64
5	18.521	5-(Hydroxymethyl)-2-furancarboxaldehyde (HMF)	C ₆ H ₆ O ₆	95.7	126.11	511628161	7.47
6	33.953	(1R,5R,12S)-2-(2,2-Diethoxyethyl)-12-ethyl-1,2,3,4,5,6-hexahydro-1,5-methanoazocino[4,3-b]indole	C ₂₂ H ₃₂ N ₂ O ₂	90.9	380.50	111,338,534	1.63
7	39.290	Hexadecanoic acid – Palmitic acid	C ₁₆ H ₃₂ O ₂	97.0	256.42	1148295613	16.77

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8	43.152	Cyclohexene, 1-[3-[2,2,2-trifluoro-1-(trifluoromethyl)ethoxy]propyl]-	C ₁₂ H ₁₆ F ₆ O	94.8	292.27	149,414,558	2.18
9	43.235	Methyl (2-chloro-2-cyanoethyl)-1-cyclohexanecarboxylate	C ₁₁ H ₁₆ CLNO ₂	96.1	229.70	124,128,251	1.81
10	43.280	9, 12-Octadecadienoic acid (Z,Z) – (Linoleic acid)	C ₁₈ H ₃₂ O ₂	80.7	280.45	1512289270	22.09
11	43.388	cis-13-Octadecenoic acid	C ₁₈ H ₃₄ O ₂	89.9	282.50	679657762	9.93
12	43.774	1-Heptadecanecarboxylic acid (Stearic acid isomer)	C ₁₈ H ₃₆ O ₂	97.3	284.48	244863904	3.58
13	49.591	Geranyl-α-terpinene	C ₂₀ H ₃₂	90.1	272.47	112,388,480	1.64

TABLE 3: Compounds identified in U. kirkiana pomace powder by GC-MS analysis (including known artefacts and contaminants)

Compounds 6-(N-Piperidinyloxy)-2,5-dimethylphenol (C₁₄H₂₁NO); 2-Butyn-1-ol (C₄H₆O); (1R,5R,12SR)-2-(2,2-Diethoxyethyl)-12-ethyl-1,2,3,4,5,6-hexahydro-1,5-methanoazocino[4,3-b]indole (C₂₂H₃₂N₂O₂); Cyclohexene,1-[3-[2,2,2-trifluoro-1-(trifluoromethyl)ethoxy]propyl]- (C₁₂H₁₆F₆O); and Methyl (2-chloro-2-cyanoethyl)-1-cyclohexanecarboxylate (C₁₁H₁₆CLNO₂) are the known GC-MS artefacts and contaminants. They are also uncommon in fruit pomaces.

GC-MS, Gas Chromatography-Mass Spectrometry; RT, Retention Time

Rank	RT (min)	Identified compounds	Formula	Match score	Molecular weight (g/mol)	Area	Area %
1	43.280	9,12-Octadecadienoic acid (Z,Z) (linoleic acid)	C ₁₈ H ₃₂ O ₂	80.7	280.45	1,512,289,270	22.09
2	39.290	Hexadecanoic acid (palmitic acid)	C ₁₆ H ₃₂ O ₂	97.0	256.42	1,148,295,613	16.77
3	43.388	cis-13-Octadecenoic acid	C ₁₈ H ₃₄ O ₂	89.9	282.50	679,657,762	9.93
4	18.521	5-(Hydroxymethyl)-2-furancarboxaldehyde (HMF)	C ₆ H ₆ O ₆	95.7	126.11	511,628,161	7.47
5	15.188	4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl-	C ₆ H ₈ O ₄	95.2	144.13	249,413,556	3.64
6	43.774	1-Heptadecanoic acid (stearic acid isomer)	C ₁₈ H ₃₆ O ₂	97.3	284.48	244,863,904	3.58
7	9.907	2H-Pyran-2,6(3H)-dione	C ₅ H ₄ O ₃	93.3	112.08	156,175,748	2.28
8	49.591	Geranyl-α-terpinene	C ₂₀ H ₃₂	90.1	272.47	112,388,480	1.64

TABLE 4: Major natural phytochemicals identified in *U. kirkiana* pomace powder by GC-MS (artefacts and contaminants)

removed, ranked by area%)

GC-MS, Gas Chromatography-Mass Spectrometry; RT, Retention Time

The chromatogram showed well-resolved peaks with retention times ranging from 5.938 to 71.906 minutes. Among the validated phytochemicals, the predominant constituents were 9,12-Octadecadienoic acid (Z,Z), commonly known as linoleic acid (22.09%); Hexadecanoic acid (palmitic acid) (16.77%); cis-13-Octadecenoic acid (9.93%); and 5-(Hydroxymethyl)-2-furancarboxaldehyde (HMF) (7.47%). Additional minor phytochemicals include 4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl- (3.64%), 1-Heptadecanecarboxylic acid (Stearic acid) (3.58%), 2H-Pyran-2,6(3H)-dione (2.28%), and Geranyl- α -terpinene (1.64%). The remaining 199 compounds each accounted for less than 1.5% of the total peak area.

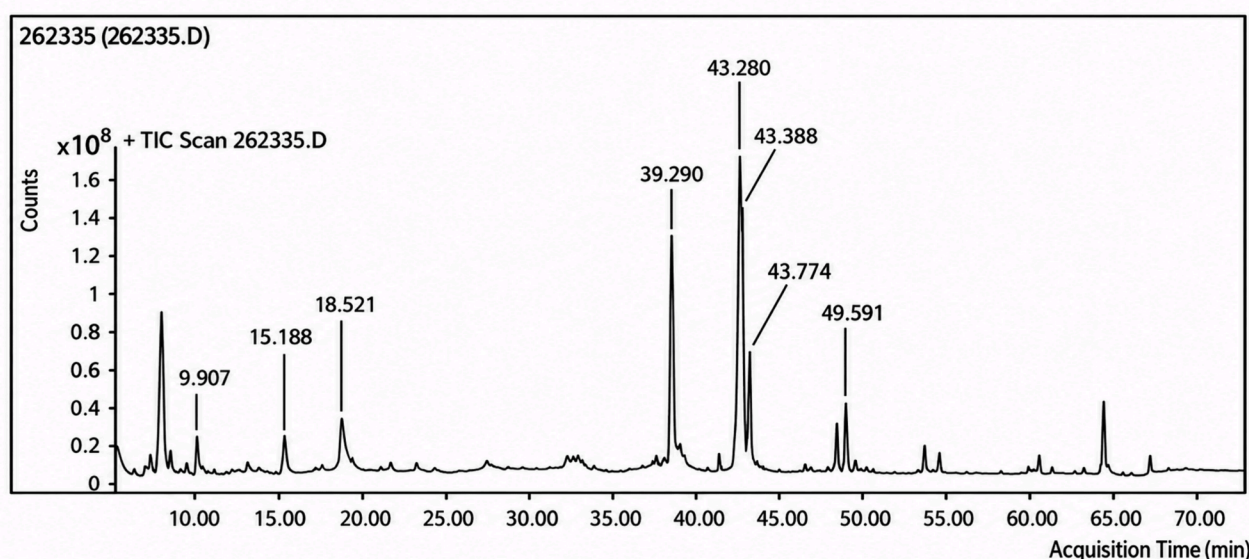


FIGURE 2: Total chromatogram (counts vs acquisition time) from *U. kirkiana* pomace powder obtained by GC-MS analysis

Major compounds (excluding possible contaminants and artefacts) are annotated with their RT (min) corresponding to Table 4 [2H-Pyran-2,6(3H)-dione (RT: 9.907); 4H-Pyran-4-one, 2,3-dihydro-3,5-dihydroxy-6-methyl- (RT: 15.188); 5-(Hydroxymethyl)-2-furancarboxaldehyde (HMF) (RT: 18.521); Hexadecanoic acid (palmitic acid) (RT: 39.290); 9,12-Octadecadienoic acid (Z,Z) (linoleic acid) (RT: 43.280); cis-13-Octadecenoic acid (RT: 43.388); 1-Heptadecanecarboxylic acid (stearic acid isomer) (RT: 43.774); and Geranyl- α -terpinene (RT: 49.591)]

GC-MS, Gas Chromatography-Mass Spectrometry; RT, Retention Times; TIC, Total Ion Chromatogram

The GC-MS analysis revealed a complex array of naturally occurring compounds, dominated by two distinct groups: fatty acids (primarily linoleic, palmitic, stearic, and their derivatives) and Maillard reaction products (HMF and the pyran-4-one derivatives). The detection of such a wide diversity of compounds is consistent with the established reputation of *U. kirkiana* as a fruit rich in bioactive phytochemicals with functional health benefits [11].

Linoleic acid was the most abundant compound identified, at 22.09% of the total chromatographic area. Linoleic acid is an essential omega-6 polyunsaturated fatty acid, which must be obtained from the diet in monogastric animals [69]. In monogastric animals (poultry, swine), linoleic acid contributes to cell membrane integrity, immune function, and eicosanoid synthesis [70]. In ruminants, although much dietary unsaturated fat is biohydrogenated in the rumen [71], moderate levels of linoleic acid can still influence milk fatty acid profiles [72]. Additionally, linoleic acid has documented antioxidant and anti-inflammatory properties [73-74]. The presence of linoleic acid in *U. kirkiana* pomace, similar to grape pomace [75], represents a notable nutritional attribute of this by-product.

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Palmitic acid/palmitate was the second-most abundant phytochemical (16.77%). It is a saturated fatty acid that is readily utilizable as energy for livestock and plays structural and signaling roles in animal cells. Palmitate has also shown antibacterial activities against *Pseudomonas aeruginosa*, as well as some anti-inflammatory mechanisms [15]. In dairy cows, the inclusion of palmitate increased milk fat percentage and yields [76]. The identification of stearic acid (3.58%) and cis-13-octadecanoic acid (9.93%) further confirms a complex, nutritionally valuable fatty acid profile of *U. kirkiana* pomace powder. Cis-13-octadecanoic acid is a positional isomer of oleic acid, a monounsaturated fatty acid [77-78]. Oleic acid has documented cardioprotective properties [77].

The detection of 5-(hydroxymethyl)-2-furancarboxaldehyde (HMF) at 7.47% of the total area is particularly noteworthy. HMF is not a true plant metabolite but a heat-induced by-product formed during Maillard reactions and caramelization of sugars under acidic conditions and elevated temperatures [15,79]. Moderate levels of HMF may indicate desirable caramelization and antioxidant activity, but very high levels could signal excessive heat damage [80]. The presence of HMF in *U. kirkiana* pomace powder is therefore a direct consequence of the oven-drying process used to stabilize the material for grinding purposes. At moderate levels, HMF is generally considered safe and even exhibits some antioxidant and antibacterial properties [81]. Additionally, 5-HMF also exhibits remarkable anti-biofilm properties through inhibition of quorum-sensing genes in several pathogens [15,82]. HMF could be associated with cytotoxic, genotoxic, and mutagenic effects in animal models [80,83,84], making its quantification an important quality-control measure for processed feed ingredients. HMF presence is typical for many heat-processed fruit pomaces [85-86].

Similarly, the two pyran-4-one derivatives (4H-pyran-4-one and 2H-pyran-2,6(3H)-dione) are established markers of thermal processing and have been identified alongside HMF in the GC-MS profiles of other heat-treated plant materials, including pomegranate peels [87] and pineapple peels [88]. These compounds, while not primary nutrients, provide further evidence of the pomace's processing history and can be monitored alongside HMF as part of routine feed quality assessment.

Additionally, the GC-MS showed that *U. kirkiana* pomace contains geranyl- α -terpinene (1.64%). It is a monoterpene hydrocarbon commonly found in the essential oil fractions of many fruits [89] and their peels [90]. It may contribute to the aroma profile of the pomace and could influence feed palatability, a factor that is particularly important for monogastric species such as pigs, which are sensitive to feed flavour and odour [20]. The presence of this volatile terpene is consistent with the retention of lipophilic aroma compounds within the pomace matrix and may account for some of the subtle olfactory characteristics of the dried product.

The outcomes of the GC-MS phytochemical profiling confirm that *U. kirkiana* fruit pomace is a complex natural product containing a substantial fraction of essential and other nutritionally valuable fatty acids. While linoleic acid appears to be the dominant fatty acid, the pomace appears to be a promising functional feed ingredient. The flavour compound adds to the aroma and acceptability of the pomace in animal feeding. However, the presence of HMF and the pyran-4-one derivatives suggests that caution needs to be taken when drying the pomace for livestock nutrition. Importantly, these findings are based on a single batch collected from one location and one harvesting season and therefore should be regarded as preliminary. Variation in chemical composition may occur among batches, locations, and seasons. Further studies involving samples from multiple locations, seasons, and processing batches are therefore necessary to confirm the consistency of the observed phytochemical profile and its implications for livestock nutrition.

Functional properties

The physicochemical properties of the peel powders can help in understanding their applications in various sectors of the food and feed industry [17-18]. The functional properties of *U. kirkiana* pomace powder, as presented in Table 5, collectively indicate that the material has excellent handling characteristics and a strong affinity for water, both of which are highly relevant for its use as a livestock feed ingredient.

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Property	Quantity
Water absorption index (WAI)	67.12±0.01%
Water solubility index (WSI)	6.4±0.02%
Angle of slide (°)	26±0.02
Bulk density	0.46±0.01 g/ml
Tapped density	0.57±0.01 g/ml
Flowability	Good
Hausner's ratio (HR)	1.24±0.01
Carr index (CI)	19.2±0.01%

TABLE 5: Functional properties of *U. kirkiana* pomace powder

WAI and WSI

The powder shows a high WAI of $67.12 \pm 0.01\%$, suggesting that it can retain more than two-thirds of its weight in water. This feature is typical of fibre-rich fruit pomaces [18]. This could help reduce dustiness in mash feeds and increase digesta viscosity and water retention in the animal's gut [41], though very high inclusion levels might limit nutrient absorption in monogastrics [91]. Fibre sources with high water holding capacity and water binding capacity retain more water, improve microbial fermentation, increase microbial enzyme interaction, and enhance satiety. These properties provide valuable tools for selecting fibre sources that achieve specific physiological outcomes in monogastric animals [51].

In contrast, the WSI is low at only $6.4 \pm 0.01\%$, confirming that it consists of insoluble fibre and structural carbohydrates, positioning it as a structural fibre source rather than an energy-dense feed component. An abundance of structural carbohydrates is a characteristic of most fruit pomaces [92-93]. In non-ruminants, *U. kirkiana* fruit pomace could be a source of insoluble fibre that supports gut motility without causing rapid sugar fermentation [94].

Angle of Slide

Uapaca kirkiana fruit pomace powder had a low angle of $26 \pm 0.02^\circ$. A lower angle of slide is also beneficial for transporting feed to feeders during feeding [29,95-97]. This suggests that *U. kirkiana* pomace powder could move readily through hoppers, feeders, and mixing equipment without bridging or clogging, which is beneficial for industrial feed processing. Low slide angle indices may also lead to reduced surface roughness of pellets [98] and smooth particle surfaces [29]. Moreover, the observed angle of slide facilitates consistent mixing with other feed ingredients without segregation, thereby improving the homogeneity of the final compound feed.

Bulk Density

Uapaca kirkiana fruit pomace powder showed a bulk density of 0.46 ± 0.01 g/ml. The observed bulk density is lower than 0.5447 for apple pomace and 0.6293 for chokeberry pomace [99], but higher than 0.43 for *Carica papaya* peels [18]. Bulk density is an excellent indicator of the possible structural changes that could occur during food processing, and it affects

the instantaneity and flowability of the powder [100]. The observed bulk density shows that *U. kirkiana* pomace powder is a loosely packed powder per unit volume. This means that *U. kirkiana* pomace powder is neither too heavy (which could cause settling) nor too light (which would increase storage/transport costs), and could be suitable for incorporation into mash or pelletized feeds.

Tapped Density

Uapaca kirkiana fruit pomace powder had a tapped density of 0.57 ± 0.01 g/ml. The observed value suggests that the powder contains appreciable inter-particle voids that can be reduced by tapping, which is relevant for accurate diet formulation and for predicting how the ingredient may behave during feed mixing. The moderate tapped density also allows economical transport and storage while preventing excessive settling or dust formation.

Flowability and Cohesiveness

Understanding the flow properties of the powder is very important for determining the handling, measuring, and transportation during the production process [16]. Flowability increases with higher moisture content due to greater powder cohesion. *Uapaca kirkiana* pomace powder showed an HR of 1.24 ± 0.01 , indicating good flowability. The observed HR is, however, higher than 1.1795 found in apple pomace [100] and lower than 1.91 found in *Carica papaya* pomace [18]. The CI of 15-20% indicates good flowability and cohesiveness [23]. *Uapaca kirkiana* pomace powder had a CI of $19.2 \pm 0.01\%$, which falls within the 15-20% limit for good flow, confirming the powder has intermediate cohesiveness. Compared to vegetable pomaces used in animal nutrition, the observed CI is lower than those of apple pomace powder, carrot pomace powder, and beetroot pomace powder, which were 19.64% of apple, 21.56% of carrot, and 23.07% of beetroot pomaces [33]. This indicates that *U. kirkiana* pomace possesses better flowability than these commonly studied vegetable pomaces. The CI value obtained for *U. kirkiana* pomace powder suggests relatively low inter-particulate friction and cohesiveness, indicating potentially favourable flow characteristics for powder handling applications.

Altogether, these functional properties provide an initial empirical profile of the handling and hydration behaviour of *U. kirkiana* pomace powder. Nevertheless, these laboratory-scale functional tests are screening tools, not performance guarantees. Furthermore, the findings were based on a single batch of pomace collected from one location and season and may not capture variability associated with different sources, harvest seasons, or batches. The findings do not account for the dynamic mechanical forces, moisture migration, or temperature fluctuations encountered in commercial feed mills, nor do they confirm palatability, intake, or digestibility in target livestock species. Therefore, the observed flow properties should be interpreted as encouraging indicators that warrant further validation under pilot-scale or industrial conditions.

Aroma profile of *U. kirkiana* fruit pomace

Figure 3 presents the aroma intensity scores (on a 1-5 scale, where 1 = undetectable and 5 = very strong) for the dry *U. kirkiana* fruit pomace powder across six sensory descriptors.

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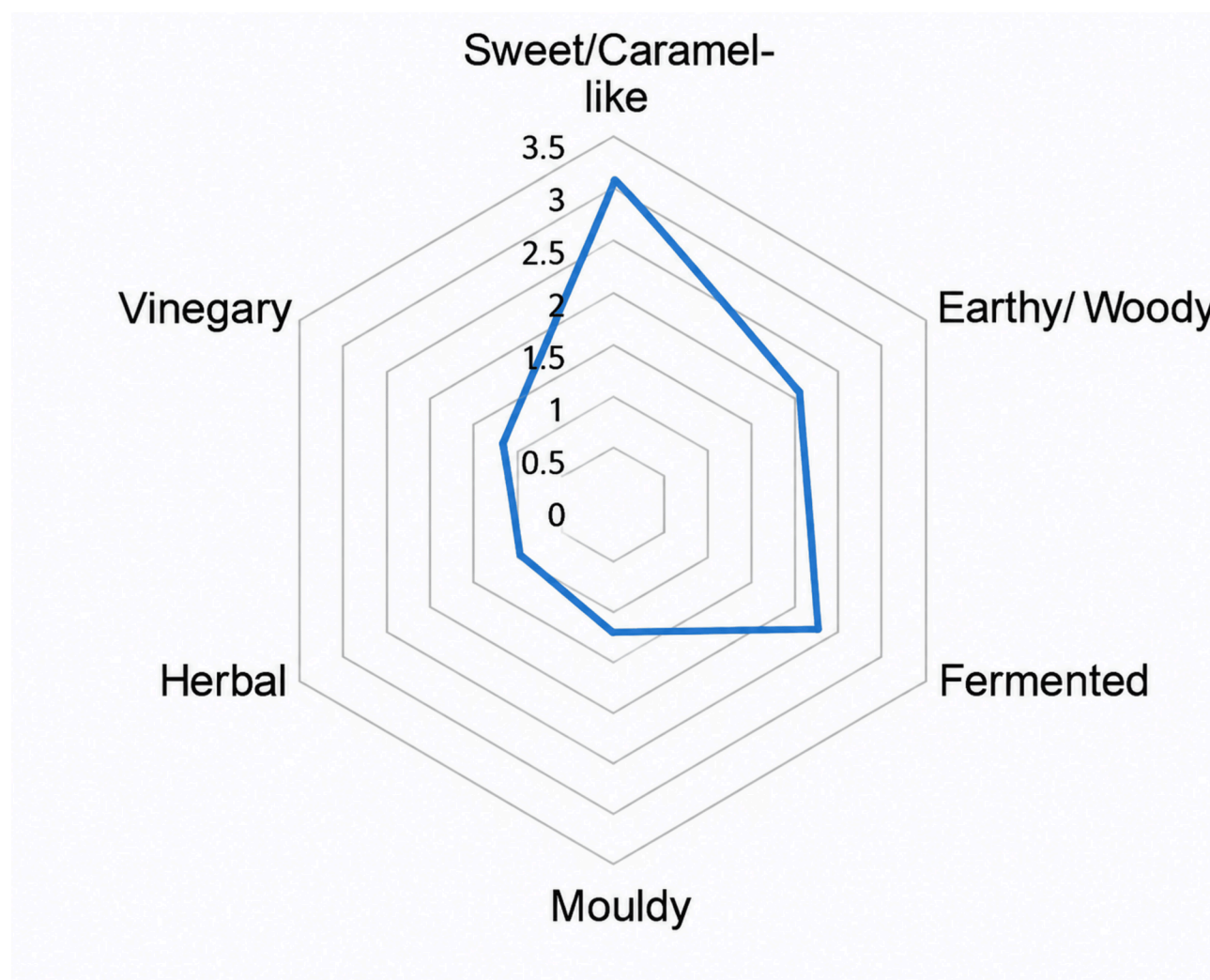


FIGURE 3: Aroma profile of *U. kirkiana* fruit pomace powder

The most prominent aroma detected in *U. kirkiana* fruit pomace powder was a sweet aroma, with a mean score of 3.25, indicating a moderately strong and pleasant sweetness. This is likely derived from residual sugars or sugar alcohols in the pomace. This aroma could enhance feed palatability for some livestock species, such as poultry, pigs, and cattle. The earthy/woody aroma scored 2.10, a mild but detectable note expected from the fruit's fibrous cell wall material. The fermented aroma scored 2.25, suggesting a slight, but not overpowering, fermented character, possibly resulting from natural post-harvest fermentation before drying. The remaining aromas were very weak (scores ≤ 1.21): mouldy (1.21), herbal (1.00), and vinegary (1.21). These low scores indicate that the pomace powder was free from spoilage odours, off-notes, or unpleasant acidic or medicinal smells.

The aroma of the feed is the first stimulus perceived by animals when exposed to the diet, whereas taste is perceived only after the animal has begun to consume the feed [101]. Aroma affects feed intake and feed preferences, especially in pigs and calves [20]. Franz et al. [73] added that feed aroma, along with essential oils, improves appetite and modulates the bacterial flora, and can induce growth-promoting responses such as increased feed intake, weight gain, and improved feed conversion ratio. Several preference tests showed a clear preference of pigs and cattle for feed with a sweet aroma, especially during the post-weaning period [20]. Notably, pigs have a large number of functional olfactory receptor genes compared with other mammalian species [19].

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The aroma profile could be due to geranyl- α -terpinene, a flavour compound detected by GC-MS in the pomace powder extract, as discussed earlier. However, the present findings are based on a single batch of *U. kirkiana* pomace collected from one location and during one season, and therefore may not represent variation in aroma characteristics across different locations, harvest seasons, or batches. Overall, the aroma profile suggests that *U. kirkiana* pomace may be palatable to livestock species, although formal palatability trials are required to confirm this.

Conclusions

The chemical, phytochemical, functional, and aroma properties of *U. kirkiana* fruit pomace could make it a suitable livestock feed ingredient for both ruminant and non-ruminant animals. The pomace exhibits promising preliminary attributes that justify continued research attention. However, essential studies, including multi-batch sampling to establish representative compositional ranges, absolute quantification of key bioactive compounds using validated standards, in vitro digestibility assays, controlled in vivo feeding trials across target species, and pilot-scale processing validation, must be conducted before any practical application in livestock nutrition can be considered. Until such studies are undertaken, *U. kirkiana* pomace should be regarded as a candidate material for further investigation rather than a validated feed ingredient, and no practical feeding recommendations can be advanced based on the present data.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Pride Hodzi, Xavier Poshiwa, Tonderai Mutibvu, Godfrey B. Nyamushamba, Soul Washaya

Acquisition, analysis, or interpretation of data: Pride Hodzi

Drafting of the manuscript: Pride Hodzi

Critical review of the manuscript for important intellectual content: Xavier Poshiwa, Tonderai Mutibvu, Godfrey B. Nyamushamba, Soul Washaya

Supervision: Tonderai Mutibvu, Godfrey B. Nyamushamba, Soul Washaya

Disclosures

Plant subjects: All authors have confirmed that this study did not involve any herbarium specimen.

Human subjects: Consent was obtained or waived by all participants in this study.

Animal subjects: All authors have confirmed that this study did not involve animal subjects or tissue.

Conflicts of interest: In compliance with [the ICMJE uniform disclosure form](#), all authors declare the following:

- **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work.
- **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work.
- **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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Data Availability Statements

The datasets (and/or code) supporting this study are available from the corresponding author upon reasonable request. All data generated or analyzed during this study are included in this published article and/or its appendices.

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