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Research Article

Eco-friendly valorization of fruit peels: Physicochemical and functional characterization for feed industry applications

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Abstract

The fruit processing industry generates large amounts of fruit peels as waste. These peels, however, are rich in bioactive compounds like flavonoids and phenolics, with excellent antioxidant properties. Utilizing them as feed ingredients provides an eco-friendly waste management solution and adds value to the processing chain. This study aimed to characterize the physicochemical (e.g., pH, ash, moisture content, crude lipid, crude fibre, carbohydrates content) and functional properties (e.g., bulk density, tap density, flowability, porosity, water and oil absorption capacities, foaming capacity, stability, and least gelation concentration) of selected fruit peels such as *Carica papaya*, *Ananas comosus*, *Musa acuminata*, and *Punica granatum*. The findings highlight the potential of the selected fruit peels as valuable feed ingredients. The low bulk density and tap density in *M. acuminata* peels ($0.29 \pm 0.01 \text{ g. cm}^{-3}$ and $0.31 \pm 0.01 \text{ g. cm}^{-3}$, respectively) helps in enhanced palatability. *M. acuminata* peels also showed excellent water and oil absorption ($5.30 \pm 0.10 \text{ mL. g}^{-1}$ and $1.57 \pm 0.05 \text{ mL. g}^{-1}$) and porosity (71.15 ± 2.22), indicating their role as effective food hydrocolloids, improving digestibility and binding properties. Notably, *P. granatum*, *C. papaya* and *A. comosus* peels also demonstrated strong performance across all selected parameters, suggesting their utility in the feed industry. While the ash content was notably high in *M. acuminata* peels, all fruit peels exhibited high fibre content, which is beneficial for digestive health and gut functionality in livestock. These properties contribute to better feed stability, energy retention, and eco-friendly production, promoting sustainable waste valorization practices.

Keywords

Fruit peel, bioactive compounds, waste management, physicochemical properties, functional properties

Abbreviations

pH – the negative log of the hydrogen ion concentration

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Introduction

The feed or food business is a multimillion-dollar global sector that is essential to animal and human nutrition (Boyd 2020). To accomplish bio-secure, eco-nutritional, high-quality products with increased shelf life, a multifaceted approach is evolving for selecting and sourcing feed ingredients in the feed industry worldwide (Shurson et al. 2021). Crude protein (CP), crude fat, and crude fibre concentration have historically been the main factors considered when choosing feed ingredients, which provide minimal information about the nutritional and final quality of the product (Coffey et al. 2016), the physicochemical properties of the food ingredients are majorly involved in determining the final product quality. Furthermore, the latter plays a major role in the design and quality control phases during food processing (Martínez and Carballo 2021). Therefore, assessing the functional and physicochemical properties of the feed ingredient is highly recommended to ensure the quality and stability of the end product.

Fruit peels are an emerging source of new ingredients in the food processing industry due to their high nutritional value (Willett et al. 2019). Utilization of these fruit peels in the food industry would also help in waste management since the food industry generates huge amounts of fruit by-products, especially fruit peels, as waste throughout the year (Ain et al. 2020). Improper disposal of these wastes is a global concern that needs to be addressed to ensure a reduction in greenhouse gas emissions, improve the health of the population, and enhance food security (Gbenga-Fabusiwa et al. 2022). Among the food waste generated, fruit and vegetable wastage are the highest, accounting for approximately 46 %, of which fruit peel accounts for 15-60% (Zhang et al. 2020). Considering the seriousness of this issue, the 2030 agenda for sustainable development (Goal 12.3) was proposed in the year 2015 by the UN to provide sustainable diets and to reduce the overall global food waste by 2030. However, the latest progress report of the agenda (2022) pointed out a deteriorating rate in the progress, suggesting the urgent need to find innovative and sustainable ways to recycle the waste generated (Sachs et al. 2022).

Perennial fruits like *Punica granatum* (Pomegranate), *Musa acuminata* (Cavendish Banana), *Carica papaya* (Papaya), and *Ananas*

comosus (Pineapple) produce a significant amount of waste since peels, constituting a major portion of these fruits, approximately 26-30% in *P. granatum*, 36.60% in *M. acuminata*, 20-25% in *C. papaya*, and 29-40% in *A. comosus* (Willett et al. 2019). Proper utilization of these fruit peels would be a promising solution to reducing global waste production. Studies have proven that fruit peels can be an excellent and promising source of prebiotics and bioactive compounds that are beneficial for the feed industry (Zahid et al. 2021). In addition to this, our previous studies have shown that fruit peels can help in effective nutrient utilization when supplemented in feed (Gopalraaj et al. 2022; Gopalraaj and Velayudhannair 2024a), and have exceptionally good protease activity that could enhance the protein digestibility and nutrient utilization (Gopalraaj and Velayudhannair 2023; Gopalraaj and Velayudhannair 2024b). Considering the nutritional aspects of the fruit peels, they could be an excellent feed ingredient in the feed industry.

Though studies have been conducted to understand their potential application as a feed supplement in the animal feed industry (Diarra 2018; Gopalraaj et al. 2022; Sugiharto 2023; Gopalraaj and Velayudhannair 2024a), research focusing on their functional properties remains limited. Therefore, it is essential to characterize the physicochemical and functional properties of the selected fruit peels, such as moisture content, ash content, pH, Bulk density (BD), Tap density (TaD), Hausner ratio, Carr index, Flowability, True density (TD), Porosity, Water absorption Capacity (WAC), Oil absorption Capacity (OAC), Foaming capacity (FC), Foaming Stability (FS), and Least gelation concentration (LGC) to understand their application in feed industry (Bakshi and Ananthanarayan 2022). This study aimed to compare the functional and physicochemical properties to understand the possibility and suitability of the selected fruit peels, namely, *P. granatum*, *M. acuminata*, *C. papaya*, and *A. comosus* as a natural food ingredient in the feed industry. Hence, this study provides novel insights into these critical functional properties, which are essential for optimizing feed formulation, improving storage and handling efficiency, and enhancing the nutritional and functional quality of feed products, thereby ensuring cost-effective,

sustainable, and nutritionally efficient feed solutions.

Materials and Methods

Collection and Preparation of fruit peel powder.

Fresh fruits of *C. papaya*, *A. comosus*, *M. acuminata*, and *P. granatum* were sourced from the local market. The fruits were thoroughly washed with fresh water and peeled using a ceramic knife. The obtained peels were dried at 40-45°C separately in a thermostatic hot air oven (Beston-BHO-02UD, India) for 7 days. After complete drying, the peels were ground to a fine powder using a blender, sieved, and stored at 4°C in an airtight container for further analysis. Properly sealed containers limit the interaction with external air and water vapor, while 4°C is a common temperature to reduce the risk of mold and subsequent digestive disorders, thereby extending the shelf life of the dried material (Miranda et al. 2019).

Assessing the physicochemical properties of peel powder. Moisture content, ash content, pH, crude fibre, crude lipid and carbohydrate content are crucial analytical values in understanding the quality of the ingredient and its application in the feed industry (Jalal et al. 2018). The moisture content was analysed using a moisture analyser (Shimadzu-MOC63u, Japan). Ash is considered the total inorganic content of the sample and provides vital information on the nutritional value of the sample (Ismail 2017). The Ash content of the fruit peel samples was analysed by heating the samples at 550°C for 2 h in a muffle furnace (Ismail 2017). The pH value of the selected fruit peels was determined by shaking 1 g of the fruit peel sample in 10 ml distilled water, allowed to stand for 30 min. and pH was measured using a pH meter (AnaMatrix Lmph-10, India) (Dias et al. 2020). Crude fibre and lipid, and carbohydrate content were analysed according to Anjum and Sundaram (2022) and Ludwig and Goldberg (1956), respectively.

Assessing the functional properties. The powder of all the above fruit peels was subjected to analyse various functional properties such as bulk density (BD), tap density (TD), true density (TrD), porosity (PO) (Bakshi and Ananthanarayan 2022), Hausner ratio (HR), Carr index (CI), Flowability (FL) (Tze et al. 2012), water holding capacity (WHC), oil holding capacity (OHC) (Jalal et al. 2018), foaming capacity (FC), foaming stability (FS), and least gelation concentration (LGC) (Dias et al. 2020) using the following formulae:

$$\text{Bulk density (g. cm}^{-3}\text{)} = \frac{\text{Weight of peel powder (g)}}{\text{Powder volume (cm}^3\text{)}}$$

$$\text{Tap density (g. cm}^{-3}\text{)} = \frac{\text{Weight of peel powder (g)}}{\text{Final tapped volume (cm}^3\text{)}}$$

$$\text{Hausner's Ratio (HR)} = \frac{\text{Tap density}}{\text{Bulk density}}$$

$$\text{Carr Index (CI)} = \frac{\text{Tap density} - \text{Bulk density}}{\text{Tap density}} \times 100$$

$$\begin{aligned} \text{True Density (g. mL}^{-1}\text{)} \\ &= \frac{\text{Weight of peel powder (g)}}{\text{Rise in Toluene Volume (mL)}} \end{aligned}$$

$$\text{Porosity} = 1 - \frac{\text{Bulk density}}{\text{True density}} \times 100$$

$$\begin{aligned} \text{Water absorption capacity (mL. g}^{-1}\text{)} \\ &= \frac{\text{Weight of wet peel powder (g)}}{\text{Initial weight of peel powder (g)}} \end{aligned}$$

$$\begin{aligned} \text{Oil absorption capacity (mL. g}^{-1}\text{)} \\ &= \frac{\text{V1 (mL)} - \text{V2 (mL)}}{\text{W (g)}} \end{aligned}$$

Where,

V1- Volume of oil before centrifugation,

V2- Volume of oil after centrifugation,

W- Weight of peel powder

$$\text{Foaming capacity (\%)} = \frac{\text{V1 (mL)} - \text{V2 (mL)}}{\text{W (g)}} \times 100$$

Where,

V1- Volume of foam after whipping,

V2- Volume of foam before whipping,

W- Weight of peel powder

$$\text{Foaming stability (\%)} = \frac{\text{V1 (mL)} - \text{V2 (mL)}}{\text{W (g)}} \times 100$$

Where,

V1- Foam volume after one hour of whipping,

V2- Volume of foam before whipping,

W- Weight of peel powder

Statistical analysis. All the obtained data were expressed as mean $\pm$ standard deviation (SD). The statistical analysis was done using one-way ANOVA, SPSS Software, version 24, with a significance level of p-value < 0.05.

Results and Discussion

Physicochemical properties. The physicochemical properties of the peel powders can help in understanding their applications in various sectors of the food industry (Bakshi and Ananthanarayan 2022). The physicochemical properties of the selected fruit peels are presented in Table 1. The moisture content in the fruit peels ranged from 5.05 to 9.71%. *M. acuminata* registered high moisture content followed by *P. granatum* ($8.72 \pm 0.01\%$), *C. papaya* ($5.71 \pm 0.01\%$), and the least *A. comosus* peel. These registered values are at safe levels since moisture content below 10% is ideal for making microbiologically safe food powder (Tze et al. 2012). The ash content ranged from $18.00 \pm 0.50\%$ (*M. acuminata* peel) to $2.67 \pm 0.29\%$ (*A. comosus* peel). Ash content analysis plays an important role in estimating the energy contents in animal diets and gives an indirect estimate of total organic matter, non-fibre carbohydrates, and nitrogen-free extract (Thiex et al. 2012). *M. acuminata* peel showed significantly higher levels of ash content, which is comparable to the results obtained by Zahid et al. (2021). Since ash provides various types of minerals, the selected fruit peels can be incorporated during feed formulation for health benefits. High ash content reduces the energy and protein nutritional value of the feed, hence, *M. acuminata* peel can be blended with low-ash ingredients to balance the overall ash content in the final feed or can be used at a lower inclusion rate. However, studies have shown that dietary inclusion levels up to 17.5% were not detrimental to Atlantic Salmon (Shearer et al. 1992). Additionally, it was observed that all the fruit peels showed acidic pH ranging from 4.19 ± 0.02 (*C. papaya* peel) to 5.77 ± 0.03 (*M. acuminata* peel), which was in accordance with the previous findings (Dias et al. 2020; Anjum and Sundaram 2022; Muhammad et al. 2023). The pH values give information on the risk of product deterioration. Low values of pH indicate that the product deterioration is minimal (Jalal et al. 2018). Crude lipid analysis revealed that fruit peels of *M. acuminata* showed comparatively high levels of crude lipid ($1.29 \pm 0.19\%$) compared to the other fruit peels, possibly due to the high levels of polyunsaturated fatty acids, mainly linoleic acid and α -linolenic acid reported in *M. acuminata* peels (Anjum and Sundaram 2022). However, the overall crude lipid content is relatively low, indicating that

fruit peels are not a significant source of fats. Crude fibre and carbohydrate content of the fruit peels were analysed, and it was found to be in high levels in *M. acuminata* ($36.01 \pm 0.19\%$ and $402.03 \pm 0.74\%$ respectively) and *C. papaya* ($37.91 \pm 0.90\%$ and $131.71 \pm 0.64\%$ respectively). The content of crude fibre was found to be inversely proportional to the carbohydrate content, which was consistent with the findings of Hasanah et al. (2017). The high crude fibre content in the selected fruit peels makes them a rich source of indigestible or partially digestible materials, which is essential for animals like ruminants that rely on fibre fermentation in the rumen for energy. The crude lipid and crude fibre levels in fruit peels of *C. papaya*, *A. comosus*, *M. acuminata*, *P. granatum* were found to be consistent with the findings of Tze et al. (2012), Dias et al. (2020), Anjum and Sundaram (2022), and Muhammad et al. (2023) respectively.

Functional properties. Functional properties are fundamental in understanding the quality, nutritional value, and acceptability of a food product. The functional properties are determined by the chemical, organoleptic, and physical properties of the food (Chandra and Samsheer 2013). This study would provide useful information to the feed industry on the incorporation of fruit peels during feed formulation to produce natural, cheap, and high-quality functional foods. Bulk and tap densities are physical properties that characterise and define the volume occupied by the solid, which majorly depends on the internal porosity, particle size, and their special arrangement in the container (Ezzat et al. 2020). 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 (Farid et al. 2022). The fruit peels showed low bulk density ranging from $0.29 \pm 0.01 \text{ g. cm}^{-3}$ (*M. acuminata* and *A. comosus* peel) to $0.43 \pm 0.03 \text{ g. cm}^{-3}$ (*C. papaya* peel) and low tap density ranging from $0.31 \pm 0.01 \text{ g. cm}^{-3}$ (*M. acuminata* peel) to $0.81 \pm 0.02 \text{ g. cm}^{-3}$ (*C. papaya* and *A. comosus* peel) (Fig.1). Low bulk density ingredients have improved palatability and are easy to handle, hence, the selected fruit peels can blend with denser components in feed formulations, promoting a uniform mix (Farid et al. 2022). True density is equivalent to the actual density of a solid and does not take into account the spaces between particles (Smita et al. 2019). The fruit peels showed

high true density values ranging from 1.10 ± 0.1 g.mL⁻¹ (*M. acuminata* peel) to 1.56 ± 0.06 g.mL⁻¹ (*P. granatum* peel) (Table 2). Higher true densities allow more materials to be packed, reducing storage space and transportation costs. It was observed that the TD, TrD, BD values in *C. papaya*, *A. comosus*, *P. granatum*, and *M. acuminata* were found to be consistent with the findings of Tze et al. (2012), Dias et al. (2020), Patel et al. (2018), and Mohd

Dom et al. (2021) respectively. Hence, the selected fruit peels have a combination of low bulk density and high true density, making it an ideal choice as a feed ingredient. The porosity of the peel powder is the volume percentage of air or void in the sample (Smita et al. 2019). The fruit peels showed moderate to high porosity ranging from 34.58 ± 1.63 (*A. comosus* peel) to 71.15 ± 2.22 (*M. acuminata* peel) (Table 2).

Table 1. Physicochemical properties of the fruit peel powder.

Physiochemical properties	Fruit peel samples			
	<i>C. papaya</i>	<i>A. comosus</i>	<i>M. acuminata</i>	<i>P. granatum</i>
pH	4.19 ± 0.02^c	4.47 ± 0.06^b	5.77 ± 0.03^a	4.23 ± 0.11^c
Moisture content, %	5.71 ± 0.01^c	5.05 ± 0.01^d	9.71 ± 0.01^a	8.72 ± 0.01^b
Ash content, %	6.83 ± 0.29^b	4.33 ± 0.29^c	18.00 ± 0.50^a	2.67 ± 0.29^d
Crude fibre, %	37.91 ± 0.90^a	12.10 ± 0.01^d	36.01 ± 0.19^b	17.26 ± 0.19^c
Crude lipid,	1.19 ± 0.19^a	0.92 ± 0.02^b	1.29 ± 0.11^a	0.80 ± 0.10^b
Carbohydrates, $\mu\text{g. mg}^{-1}$	131.71 ± 0.64^b	89.32 ± 0.99^d	402.03 ± 0.74^a	65.10 ± 0.98^c

*All values are expressed as mean $\pm$ standard deviation (n = 5). ^{a, b, c, d} - indices showing significant differences (p < 0.05) between the mean values in the rows (ANOVA and Duncan's test).

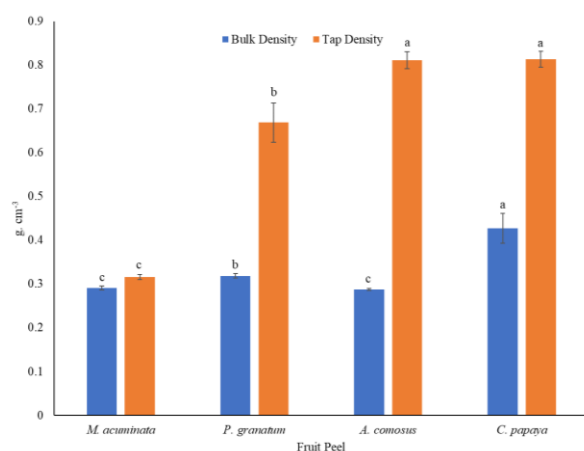


Figure 1. Bulk density and tap density in *C. papaya*, *A. comosus*, *M. acuminata*, *P. granatum*.

*All values are expressed as mean $\pm$ standard deviation (n = 3). ^{a, b, c} - indices showing significant differences (p < 0.05) between the mean values in the rows (ANOVA and Duncan's test)

Shrinkage and altered shape of the food materials caused due to low porosity can negatively impact the feeding behaviour in animals (Mayor and Sereno 2004). Additionally, high porosity in these fruit peels improves the water and oil absorption

capacity, which enhances the palatability and hydration of the feed. Porous food also shows increased crispiness and breaks down faster during digestion, making nutrients more bioavailable for the animal (Joardder et al. 2016). Hence, our studies show that all the selected fruit peels have good porosity that can help in enhanced absorption and improved digestibility and are easier to handle during transportation and storage.

Understanding the flow properties of the powder is very important to determine the handling, measuring, and transportation during the production process (Ezzat et al. 2020). Flowability increases with an increase in moisture content due to increased powder cohesion. The flowability of powder and cohesiveness can be evaluated by Hausner's ratio (HR) and Carr index (CI), which showed that *M. acuminata* peels exhibited excellent flowability (Table 2). This can be justified by the fact that *M. acuminata* peel showed the lowest bulk density. Low bulk density is an indication of excellent flowability with minimum caking behaviour (Farid et al. 2022). HR value of 1.4 or above and CI value above 25% suggest that the powder is less fluidised and has poor flowability

(Bakshi and Ananthanarayan 2022). Our studies show that *M. acuminata* and *C. papaya* peel have excellent flowability (Table 2), which was consistent with the findings of Mohd Dom et al. (2021), and Tze et al. (2012), indicating their role in enhancing the final product quality, and the overall

success of food processing and handling operations. Though limited studies have examined the flow properties of *M. acuminata* and *C. papaya* peel (Mohd Dom et al. 2021; Tze et al. 2012), there are no findings reported on the flow properties of *P. granatum* and *A. comosus* fruit peels.

Table 2. Functional properties of the fruit peel powder.

Functional properties	Fruit peel samples			
	<i>C. papaya</i>	<i>A. comosus</i>	<i>M. acuminata</i>	<i>P. granatum</i>
Hausner's Ratio	1.91±0.15 ^b	2.82±0.04 ^a	1.08±0.01 ^c	2.10±0.11 ^b
Carr index, %	47.44±4.43 ^b	64.60±0.54 ^a	7.94±1.31 ^c	52.25±2.62 ^b
Flowability	Poor	Poor	Excellent	Poor
True Density, g. mL ⁻¹	1.25±0.01 ^b	1.24±0.01 ^b	1.10±0.1 ^c	1.56±0.06 ^a
Porosity	34.76±1.34 ^c	34.58±1.63 ^c	71.15±2.22 ^a	57.28±3.17 ^b
Least Gelation Concentration, %	10.00±0.00 ^a	9.00±0.00 ^b	4.00±0.00 ^d	5.00±0.00 ^c

*All values are expressed as mean ± standard deviation (n = 5). ^{a, b, c}- indices showing significant differences (p < 0.05) between the mean values in the rows (ANOVA and Duncan's test).

The water-holding capacity (WHC) and oil-holding capacity (OHC) were found to be significantly higher (p < 0.05) in *M. acuminata* peels compared to the other selected fruit peels (Fig. 2). Both WHC and OHC has an important role in the final food product quality (Felli et al. 2018). This increase in WHC ($5.30 \pm 0.10 \text{ mL.g}^{-1}$) in *M. acuminata* peel could be attributed to the fact that water molecules reside in the empty spaces of the fibres since *M. acuminata* peels are rich sources of crude fibre (Akram et al. 2022). High WHC indicates the ability of the powder to hold the water molecules, thereby leading to a satiety effect and increased fecal bolus, ultimately resulting in decreased fat, glucose, and cholesterol absorption in animals (Dias et al. 2020). Lipophilic tendency (OHC) was found to be in moderate levels in *M. acuminata* peel ($1.57 \pm 0.05 \text{ mL.g}^{-1}$), suggesting increased hydrophobic interaction sites, indicating their potential value in energy contribution, palatability, and as a binding agent (Dias et al. 2020). The WHC and OHC in fruit peels of *A. comosus* and *C. papaya* showed slightly lower values when compared to the findings reported by Dias et al. (2020) and Joshi and Dobhal (2023), while the results of *M. acuminata* and *P. granatum* were found to be consistent with the findings of Mohd Dom et al. (2021) and Sarkar et al. (2024).

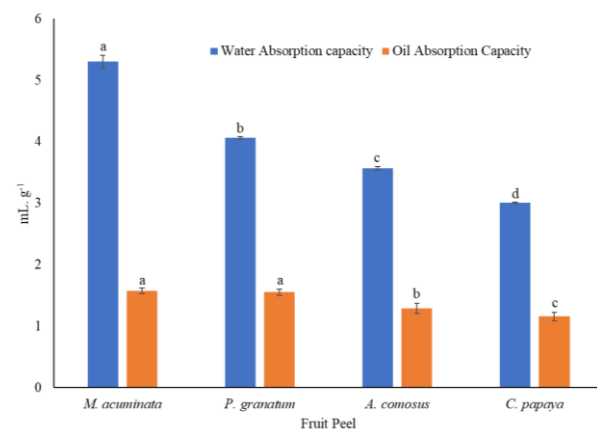


Figure 2. Water absorption capacity and oil absorption capacity in *C. papaya*, *A. comosus*, *M. acuminata*, *P. granatum*.

*All values are expressed as mean ± standard deviation (n = 3). ^{a, b, c}- indices showing significant differences (p < 0.05) between the mean values in the rows (ANOVA and Duncan's test)

The water-holding capacity (WHC) and oil-holding capacity (OHC) of the fruit peels are significant indicators of their functionality in feed formulations. High WHC enhances hydration, gut health, and digestibility, while moderate OHC levels support energy density and fat-soluble nutrient retention, making fruit peels versatile

ingredients for balancing energy and fiber in animal feed (Adebowale et al. 2005).

The foaming property of a powder plays an important role as it can act as a foaming agent during the feed processing (Wilson et al. 2012). The drying time is less in foamed powders compared to the other drying techniques due to the large surface area and open porous structure, which helps accelerate the removal of moisture. Therefore, foamed powders provide superior quality end products compared to the products obtained by conventional drying techniques (Wilson et al. 2012). Our results showed a good foaming property in all the fruit peels (Fig. 3) ranging from $9.33 \pm 0.57\%$ (*M. acuminata* peel) to $91.66 \pm 2.89\%$ (*C. papaya* peel) and can act as a foaming agent in food processing.

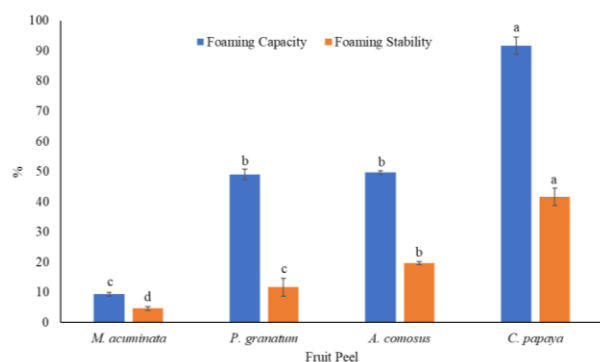


Figure 3. Foaming capacity and foaming stability in *C. papaya*, *A. comosus*, *M. acuminata*, *P. granatum*.

*All values are expressed as mean $\pm$ standard deviation (n = 3). a, b, c, d - indices showing significant differences (p < 0.05) between the mean values in the rows (ANOVA and Duncan's test)

Our results reported higher foaming capacity in *A. comosus* when compared to the findings reported by Dias et al. (2020). However, very few or no studies have been conducted to understand the foaming capacity in the selected fruit peels. The selected fruit peels have the potential to enhance feed texture and palatability, binding and stability in formulations, and the ability to encapsulate nutrients or additives, protecting them from oxidation and improving their stability during storage and digestion (Kargarzadeh et al. 2018).

Least gelation properties are largely affected by the presence of fibre, polysaccharide, and pectin content (Dias et al. 2020). Gelation properties are

interrelated to WHC (Adebowale et al. 2005), hence, this explains the fact that *M. acuminata* peels showed a high gelation property ($4 \pm 0.00\%$). Increased fibre content also plays a major role in gelation properties (Akram et al. 2022). The peel powders with the lowest gelation concentrations can serve as gelling agents (Adebowale et al. 2005) which help bind ingredients together in pelleted or extruded feed ensuring structural integrity and reducing feed wastage during handling and consumption. No studies have been done to understand the gelation property in the selected fruit peels.

Conclusions

Fruit peels possess a diverse set of functional properties that make them valuable ingredients in the animal feed industry. Their moisture content and pH influence feed stability and microbial resistance, ensuring longer shelf life and safer consumption. The ash content contributes essential minerals, vital for livestock nutrition, while the bulk and tap densities enhance storage and transport efficiency. The fiber content enhances gut health and promotes proper digestion, while carbohydrates provide an accessible source of energy, and lipids contribute to the overall energy density of the feed, supporting growth and physiological functions. Water and oil absorption capacities improve hydration, digestibility, and energy density, making them versatile for formulating feeds for various species. Additionally, the foaming properties contribute to feed texture and stability, enhancing palatability and homogeneity. The lowest gelation concentration demonstrates their potential as natural binders, reducing reliance on synthetic additives while improving structural integrity in pelleted and extruded feeds. Overall, the integration of fruit peels in animal feed not only leverages their nutritional and functional benefits but also aligns with sustainability goals by valorising agricultural waste, making them a cost-effective and eco-friendly solution for modern husbandry practices. Overall, the findings highlight the potential of these fruit peels as valuable feed ingredients with desirable physicochemical and functional properties for the feed industry. Given their successful application in existing research focused on aquaculture and poultry supplementation, the processing methods described in this study are reliable and applicable.

However, while these materials are generally safe for feed use, if they were to be utilized in human food products, they would require stricter controls under HACCP to meet safety standards. Further research and correlation analyses would continue to provide deeper insights into their functional properties and broader applications.

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