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Original article

Predictive models for estimating the sugar content and organic acids in processed mangoes based on the initial content

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Summary The quality of processed products can be adversely affected by uncontrollable batches of mangoes, which exhibit heterogeneous characteristics. This study aimed to establish predictive models for sugar and organic acid contents (dependent variables) in processed products using the initial compositions of fresh mangoes. Three mango cultivars (cv. 'Kent', cv. 'Keo Romeat', and cv. 'Keo Chen') were classified as low-density and high-density groups. Each group of mangoes at the green-mature, mid-ripe, and ripe stages was processed into pasteurised purees, dried slices, and mango chips. Prediction models were established using a mix of simple linear regression (SLR) based on the initial content and Analysis of Variance (ANOVA) to identify the impact of qualitative variables (ripening stage, cultivar-density, and processing technique). In processed mangoes, 13% sucrose content was estimated to accumulate with the three qualitative variables, whereas glucose and fructose contents decreased from their initial levels by 10% and 7%, respectively. Processing techniques can predict the ratio of sugars/acids (S/A) in processed products, regardless of the ripening stage or cultivar-density. Similar to S/A, citric acid and malic acid contents in mango products were significantly increased by processing techniques. The initial content and processes were insufficient to predict the final contents of the same parameters in processed mangoes; therefore, some models need to include the effects of ripening stage and cultivar-density to improve the prediction. These relevant explanatory variables contributed significantly to the development of the models, resulting the accuracy of predictive models with normalised root mean square errors (NRMSEs) lower than 10%, except for malic acid (14.04%). In conclusion, it is feasible to estimate the sugar and acidity levels in processed mangoes, offering promising possibilities for ensuring consistent quality of mango-based products.

Keywords Fructose, glucose, hot-air drying, malic acid, mango cultivar, pasteurisation, quality prediction, ripening stage, sucrose, vacuum frying.

Introduction

Mango is a popular tropical fruit known for its sweet taste, flavour, and nutritional benefits. To prolong the availability of mango products beyond their short seasonal harvest, various processing techniques such as pasteurisation, hot-air drying, and vacuum frying have been utilised (Bonneau *et al.*, 2016; Soto *et al.*, 2021; Wongkaew *et al.*, 2021). The demand for processed mango products, such as purees, dried slices, and vacuum-fried chips, has increased owing to increasing consumer interest in health awareness and convenience in food usage (Owino & Ambuko, 2021). This growing demand also underscores the importance of reliable methods for evaluating mango quality in terms of sweetness and acidity, which are key factors that influence consumer preferences.

Processing techniques could induce changes in the physicochemical properties of mangoes, including their sugar and acidity content (Mitrović *et al.*, 2019). For example, pasteurisation of mango puree leads to decreased sugar content and increased acidity because organic acids are denatured and released during heating (Makroo *et al.*, 2019). Consequently, the sensory qualities and nutritional composition of pasteurised products were affected (Jayathunge *et al.*, 2019). Prolonged exposure to lower temperatures and air velocities during oven drying was associated with degradation of amylase and invertase activity, which may be attributed to longer exposure to heat or oxidation, product

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accumulation, and other physicochemical alterations in dried mangoes (Mukhtar *et al.*, 2021; Ampah *et al.*, 2022). Drying temperatures (70 °C and 90 °C) affected the sugar content of the dried plum fruits of the investigated cultivars. However, the intensity of the changes, including the loss of total sugars and sucrose content and an increase in inverted sugars, was conditioned by varietal characteristics (Mitrović *et al.*, 2019). Vacuum frying is an innovative processing technique that has been used to produce healthy snacks with minimal or no acrylamide formation, to preserve nutrients, and to enhance organoleptic attributes (Ayustaningwarno *et al.*, 2018; Zhang *et al.*, 2020; Wang *et al.*, 2021). Ayustaningwarno *et al.* (2020a) found that the fat content of vacuum-fried ripe mangoes was higher than that of unripe mangoes, whereas the total ascorbic acid content of the products of unripe mangoes remained higher. Although the impact of vacuum frying on the sugar and acidity profiles of mangoes has not been extensively studied, available literature suggests that this processing technique could limit the degradation of the final product (Sosa-Morales *et al.*, 2022; Manzoor *et al.*, 2023).

Even though manufacturers can control operational processes, it may be challenging to oversee the quality of raw materials. The heterogeneity of batches at harvesting can affect the entire processing chain, often leading to approximate quality management based on average batch quality. For instance, the quality of the received fruit can vary due to a multitude of factors, such as varietal supply (a mix of varieties within a batch), climatic conditions (measurable through fruit density), and fruit ripening stages (ranging from green mature to ripe stages). It is challenging to obtain a comprehensive view of how the initial content and processing conditions affect the sugar and acid composition of processed mangoes, and whether the final composition can be predicted from the initial content and type of process.

This study aimed to investigate the feasibility of developing predictive models that use the initial sugar and organic acid levels in fresh mangoes to estimate the same attributes in mango puree, dried mango, and vacuum-fried chips. The findings of this study could provide objective methods for optimising mango fruits for each processing technique, improve the quality consistency of mango products, enable more efficient quality control, and contribute to the mango industry by reducing waste and processing costs.

Materials and methods

Fruit sampling

Three mango cultivars were selected, cv. Kent ('K') from the Republic of Peru and two Cambodian varieties: cv. Keo Romeat ('KRM'), and cv. Keo Chen ('KC'). The fruits were collected at the pre-climacteric green-mature stage to ensure sufficient shelf life for air transportation (for Cambodian cultivars) and cold shipping (for 'K') to the CIRAD laboratory in Montpellier, France.

Density measurements were performed using Archimedes' method (Joas *et al.*, 2009; Hor *et al.*, 2020). The 'KC' was equivalent to a high-density group ('KC-HD'), while the 'KRM' corresponded to the low-density group ('KRM-LD'). Only 'K' mangoes were classified into low-density ('K-LD') and high-density ('K-HD') groups. The density distributions within each group were presented in Table 1.

For each batch of mangoes from different cultivar-density, one-third of the green-mature mangoes (G) were placed in an enclosure at ambient temperature for 24 h before processing. The remaining mangoes were ripened using ethylene induction (100 ppm) and stored in a climacteric chamber at 20 °C with 80% humidity for the mid-ripe (M: 8 days) and ripe (R: 11 days) stages (Nambi *et al.*, 2015). Due to unexpected logistical challenges in obtaining 'KC-HD' mangoes from Cambodia, only two ripening stages (M and R) were examined. Eleven uniform batches of mangoes from three different cultivars and two density groups were used for processing (Fig. 1).

Preparation of mango pulp

The mango cheeks were sliced into 2 mm (one cheek) and 4 mm (the other cheek) thickness using a stainless-steel slicer (Rallongé anodisé, Micra 220, Roussey, France) and subsequently shaped into 40.0 mm diameter discs using a circular cutter. Half of the mango slices with 2 mm thickness were randomly subjected to rapid freezing in liquid nitrogen. The other half was used for vacuum frying. Mango slices of 4 mm thickness were designated for drying and pasteurisation.

Table 1 Distribution of the density ($g \cdot mL^{-1}$) in mangoes from different cultivars for each ripening stage

Density	Mango cultivar	Mango batch (cultivar-density)	Green-mature stage (G)	Mid-ripe stage (M)	Ripe stage (R)
Low (LD)	Keo Romeat (KRM)	KRM-LD	0.975 ± 0.006	0.975 ± 0.006	0.977 ± 0.007
	Kent (K)	K-LD	0.977 ± 0.008	0.978 ± 0.007	0.979 ± 0.007
High (HD)		K-HD	1.016 ± 0.004	1.017 ± 0.005	1.017 ± 0.005
	Keo Chen (KC)	KC-HD		1.026 ± 0.009	1.027 ± 0.010

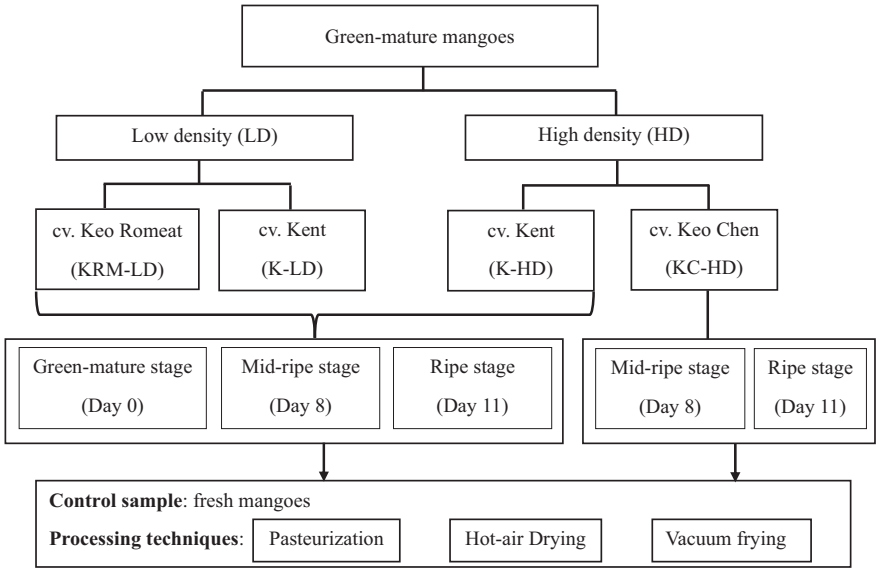

Figure 1 Experimental layout from mango batches (cultivar-density) to processing techniques.

Processing technique

Three processing techniques, including pasteurisation, hot-air drying, and vacuum frying were used in this study. The mango slices were dried in the pilot unit of a hot-air dryer (UTA dryer, Villeneuve-sur-Lot, France) at 60 °C for 150 min at 40% RH. For pasteurisation, approximately 100 g of the blended mango was placed in steamer glass (200 mL) and connected to a heating immersion circulator (Fisher Bioblack Scientific, France). The puree was heated using a hot-water circulation system until it reached 85 °C and was maintained for 5 min (total heating time of 16 min). After heating, each batch was transferred immediately to a glass jar and cooled in an ice bath. The vacuum frying conditions used in this study were previously developed within the framework of CIRAD (Soto *et al*., 2020). Fifty-five litres of sunflower oil was heated to 100 °C. The mango slices were placed on each tray in a basket of fryers (Auriol, Marmande, France) with the operation commencing at a pressure of 25 kPa. Subsequently, the basket was submerged in oil for 7 min and centrifuged for 3 min. The mango chips were then removed from the fryer, cooled to ambient temperature, and dried using paper towels to remove the excess surface oil. All samples were stored in a glass jar at −20 °C for further analysis.

Physicochemical properties of fresh and processed mangoes

The firmness and colour of the mango pulp were measured using a texture analyser (Model TA. XT. plus, Stable Micro Systems, UK) and a Minolta Chroma Meter CR 400 (Konica Minolta, Osaka, Japan), following the method described by Hor *et al*. (2020). The maximum force recorded during the measurement was used to indicate firmness (N), and the colour was described by the hue angle value (hue, in °). Fifteen fruits of each mango batch were used for experiment. Firmness was measured in duplicate at the equatorial region of each fruit, whereas pulp colour was determined three times on each cheek at the stem end, back, and nak region. Dry matter content (DM, %) was determined in triplicate by using the AOAC procedure (method 934.06/37.1.10) (AOAC, 2000).

Chemical analyses were conducted on fresh mangoes and processed products to determine their sugar (sucrose, glucose, and fructose) and organic acids (citric and malic acids) contents. The total soluble sugar and organic acid contents were analysed using standards from Sigma Aldrich (St. Louis, MO, USA). Samples were prepared according to the method described by Soto *et al*. (2020) with some modifications. Vacuum-fried mangoes were defatted with petroleum ether before extraction of sugar and organic acids. The soluble sugars and organic acids were extracted by weighting 0.5 g DM of the sample, mixed with 10 mL of ethanol (80%, v/v), and warmed in a water bath (WTB6, Memmert GmbH, Germany) at 70 °C for 30 min. After centrifugation at 10 000 × ***g*** for 10 min at 10 °C, the extraction was repeated twice as previously described. The mixed supernatant was pooled and filtered through a 0.45 μm syringe filter (Whatman, Germany) before HPLC injection. One microlitre of the sample was analysed using HPLC

(Agilent Technologies 1260 Infinity) equipped with a Shodex sugar SH1011 column (Shodex, Japan), a UV detector set at 210 nm for organic acids, and a refractometric detector 1260 at 50 °C for sugar (Agilent Technologies, USA). Elution was carried out at 40 °C, 0.7 mL·min^{-1} flow rate of 0.01% H_2SO_4, and analysed for 20 min for each sample.

Individual sugars and organic acids were identified by comparing the retention times with reference compounds (HPLC-grade sucrose, glucose, fructose, citric acid, and malic acid) (Fig. 2). Quantification was achieved by calculation of the peak areas, using the equation from calibration curves of standards (Table 2). A stock solution of each soluble sugar (10 g·L^{-1}) was diluted for preparing standards (0.3125, 0.625, 1.25, 2.5, 5, and 10 g·L^{-1}). Each organic acids were prepared for stock solution (1 g·L^{-1}) and then diluted to six concentrations for standards (0.03125,

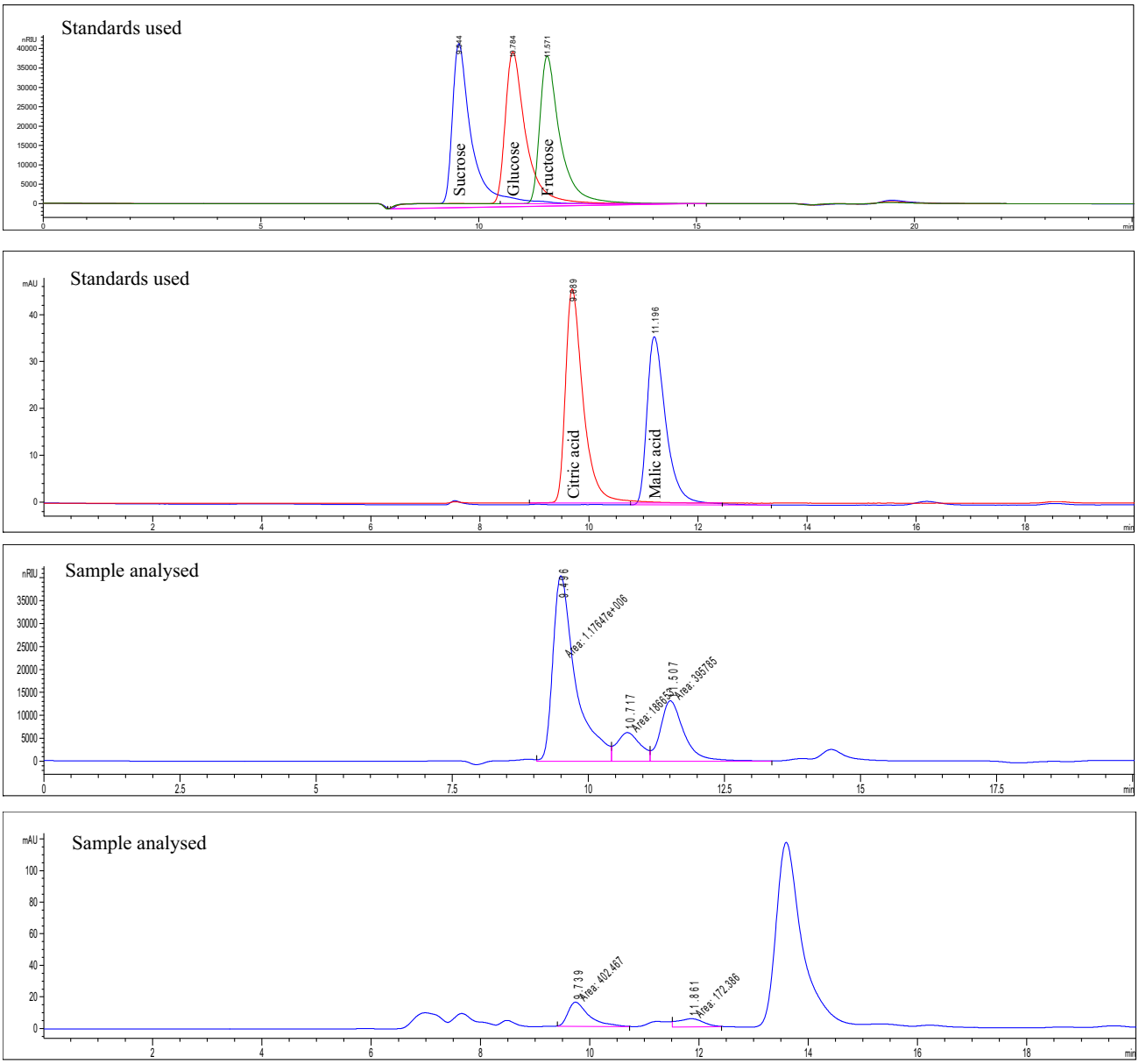

Figure 2 HPLC separation of sugars, organic acids from standards used, and sample analysed. For compounds associated with the HPLC set-up, see Table 2.

Table 2 Linear range of calibration curve, R^2, LOD, LOQ, and % relative SD of all the compounds associated with HPLC set-up

Compound	Equation from the calibration curve	Linear range ($g \cdot kg^{-1}$)	R^2	LOD ($g \cdot kg^{-1}$)	LOQ ($g \cdot kg^{-1}$)	RSD ($n = 3$) (%)
Sucrose	$y = 8.0798E{-}06 * Area$	18.8–600	>0.99	2.4	8.1	4.5
Glucose	$y = 7.7561E{-}06 * Area$	18.8–600	>0.99	2.2	7.4	4.1
Fructose	$y = 8.0580E{-}06 * Area$	18.8–600	>0.99	1.7	5.6	2.9
Citric acid	$y = 9.6157E{-}04 * Area$	1.9–60	>0.99	0.2	0.7	0.9
Malic acid	$y = 1.1453E{-}03 * Area$	1.9–60	>0.99	0.3	1.0	1.4

0.0625, 0.125, 0.25, 0.5, and 1 $g \cdot L^{-1}$). The calibration curves were plotted linearly with the intercept of zero. The total sugar (TS) content is the sum of the individual soluble sugars (Glu + Suc + Fruc) (Lee *et al.*, 2021). This individual soluble sugar was used for further calculation of sucrose to hexose ratio ($S/H = \frac{Suc}{Glu + Fru}$) and sugars to acids ratio ($TS/A = \frac{Suc + Glu + Fru}{Citric + Malic\ acids}$).

All results for mango products were expressed as dry matter (DM) and the contents in vacuum-fried mangoes were expressed as $g \cdot 100\ g^{-1}$ non-fat dry matter (NF-DM). All chemical analyses were performed in triplicates.

Data analysis and model development

Data analysis was performed using the XLSTAT software (Lumivero, Version 2023.1.6, Addinsoft, Paris, France).

First, a linear model was constructed using the simple linear regression (SLR). This model was built to predict the content of the dependent variables (Y_i: total sugar, sucrose, glucose, fructose, sucrose/hexose, citric acid, malic acid, and sugars/acids) in processed mangoes, based on their initial content in fresh fruits (X_i: quantitative variable). Given that when the concentration of sugars and acids in fruits are close to zero, they are also close to zero in the processed products. The potential models were set at a fixed intercept of zero with a 95% confidence interval, and were written as follows:

$$Y_i = a_i X_i, \tag{1}$$

where a_i is the regression coefficient of component i.

Additionally, the model was improved by adding the effect of qualitative variables (RS: ripening stage, C: mango cultivar-density, and P: processing technique) to the residuals of each dependent variable. An analysis of variance (ANOVA) with a pairwise comparison of Tukey (HSD) test at a level of 5% was performed to identify a significant impact and define the constant of each significant factor (α_{RS}, β_C, and δ_P) for each dependent variable.

Finally, a predictive model for each dependent variable (2) was developed using a combination of linear eq. (1) and the constants of the significant qualitative variables from the residual:

$$Y_i = a_i X_i + \alpha_{RS} + \beta_C + \delta_P \tag{2}$$

The coefficient of determination (R^2), root mean square error (RMSE), and normalised root mean square error (NRMSE) were calculated and used to evaluate the performance of the proposed model.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (Y_{i,P} - Y_{i,O})^2}$$

where $Y_{i,P}$ is the predicted value, $Y_{i,O}$ is the observed value obtained from experimental analysis, and N is the number of observations.

The advantage of RMSE was that it expressed the error in the same units as the variable, providing more insight into the effectiveness of the model. The lower the RMSE, the more accurate was the prediction.

$$NRMSE = \frac{RMSE}{Y_{i,O_{max}} - Y_{i,O_{min}}} \times 100\%$$

where $Y_{i,O_{max}}$, $Y_{i,O_{min}}$ are the maximum and minimum observed values obtained from experimental analysis.

Normalised root mean square error provides a standardised way to evaluate model performance across different datasets.

Results

Physicochemical composition of fresh mangoes varied with the ripening stages and cultivar-density

The variability in the physicochemical characteristics of fresh mangoes from the three different cultivars at the two densities and the three ripening stages was presented in Table 3. The most significant change observed during ripening was the loss of firmness. Cambodian mangoes were softer than 'K' mangoes by approximately 2 N at the same ripening stage. The hue angle of the fruit pulp gradually decreased as ripening progressed, indicating an increase in the β-carotene content, as confirmed in a previous study by Hor *et al.* (2020). High-density mangoes ('KC-HD' and 'K-HD') presented hue angle 5^0 lower than the low-density mangoes ('KRM-LD' and 'K-LD'), suggesting that these

Table 3 Physicochemical characteristic of fresh fruits from different ripening stages and mango cultivar-density

Mango fruits												
Cultivar-density	Ripening stages	Firmness (N)	Pulp colour (^{0}, Hue)	Dry matter (%)	Total sugar content	Sucrose content	Glucose content	Fructose content	Sucrose/ fructose + glucose	Citric acid	Malic acid
Keo Romeat (KRM-LD)	G	27.0 ± 3.5	94.1 ± 2.4	14.9 ± 0.0	50.75 ± 0.30	18.98 ± 0.23	10.03 ± 0.02	21.73 ± 0.13	0.60 ± 0.01	7.83 ± 0.22	1.20 ± 0.03
	M	5.8 ± 1.0	84.1 ± 1.5	14.0 ± 0.03	83.27 ± 0.36	46.87 ± 0.17	9.08 ± 0.07	27.31 ± 0.21	1.29 ± 0.01	3.97 ± 0.01	1.09 ± 0.03
	R	4.7 ± 0.4	81.6 ± 1.4	15.8 ± 0.0	88.67 ± 1.03	54.95 ± 0.61	4.25 ± 0.03	29.47 ± 0.44	1.63 ± 0.00	1.74 ± 0.14	1.13 ± 0.01
Kent-low density (K-LD)	G	27.6 ± 2.9	95.6 ± 2.1	15.5 ± 0.01	73.64 ± 0.96	32.35 ± 0.72	13.47 ± 0.10	27.83 ± 0.14	0.78 ± 0.01	6.69 ± 0.03	1.80 ± 0.01
	M	9.7 ± 1.4	92.1 ± 1.7	14.2 ± 0.02	82.22 ± 0.67	31.63 ± 0.43	15.39 ± 0.05	35.21 ± 0.22	0.63 ± 0.01	6.55 ± 0.06	2.14 ± 0.06
	R	7.6 ± 0.7	90.2 ± 1.3	15.1 ± 0.03	82.02 ± 0.58	20.50 ± 0.14	19.24 ± 0.14	42.29 ± 0.68	0.33 ± 0.00	4.79 ± 0.02	2.33 ± 0.03
Kent-high density (K-HD)	G	26.5 ± 2.6	88.7 ± 2.4	20.1 ± 0.06	73.60 ± 0.15	39.77 ± 0.04	9.75 ± 0.06	24.07 ± 0.05	1.18 ± 0.00	4.96 ± 0.08	1.59 ± 0.05
	M	8.6 ± 0.6	86.1 ± 1.9	18.7 ± 0.07	79.18 ± 0.59	36.82 ± 0.36	11.11 ± 0.06	31.24 ± 0.22	0.87 ± 0.01	4.99 ± 0.06	2.00 ± 0.02
	R	6.5 ± 0.4	85.5 ± 1.6	19.8 ± 0.05	75.56 ± 0.70	23.86 ± 0.20	14.84 ± 0.15	36.86 ± 0.39	0.46 ± 0.00	4.17 ± 0.07	2.27 ± 0.07
Keo Chen (KC-HD)	M	5.4 ± 0.5	88.0 ± 1.2	23.2 ± 0.12	64.04 ± 0.36	38.80 ± 0.23	8.01 ± 0.05	17.21 ± 0.09	1.54 ± 0.00	2.86 ± 0.01	0.93 ± 0.03
	R	4.7 ± 0.5	85.9 ± 1.0	23.2 ± 0.04	80.94 ± 0.41	52.54 ± 0.30	8.43 ± 0.08	19.97 ± 0.08	1.85 ± 0.01	2.43 ± 0.04	1.01 ± 0.02

The content of each sugar and organic acid was expressed as g·100 g^{-1} DM.
G, green-mature stage; M, mid-ripe stage; R, ripe stage.

mangoes also had a higher yellow-orange pulp colour and β-carotene content. Dry matter content showed a slight change as ripening progressed (min = 0.9%, max = 1.8%). Low-density mangoes contained dry matter in the range of 14.0–15.8 g·100 g^{-1} DM, whereas high-density mangoes had a higher amount, ranging from 18.7 to 23.2 g·100 g^{-1} DM (almost 5% higher). The highest dry matter content was found in 'KC-HD' mango (23.2 g·100 g^{-1} DM), while the lowest was in '-KRM-LD' mango (14.0 g·100 g^{-1} DM).

The ripening progress in Cambodian mangoes ('KC-HD' and 'KRM-LD') resulted in a more significant increase in total sugar content than 'K' mangoes. This was mainly due to an increase in sucrose and fructose content. At the ripe stage, 'KRM-LD' mangoes exhibited the highest total sugar content (88.67 g·100 g^{-1} DM), which explains why they are the most popular in Cambodia. The total sugars in 'K' mangoes only slightly increased from the green-mature to the mid-ripe stage, whereas sucrose levels decreased significantly as the fruit ripened (approximately −40%). The levels of glucose and fructose significantly rose as the 'K' mangoes ripened, leading to a decrease in the sucrose/hexose (S/H) ratio. This result differs from that observed for Cambodian mangoes.

The citric acid content decreased as the mangoes ripened, with a more significant decrease observed in low-density batches ('KRM-LD' and 'K-LD'). The malic acid content slightly increased in 'K' mangoes and remained stable in Cambodian mangoes during ripening. Cambodian mangoes also had lower organic acid contents (approximately 2 times less than 'K') at the mid-ripe and ripe stages.

Predictive sugars and organic acids content in processed mangoes according to the initial content and processing techniques

All results were expressed as dry matter (DM) content to ensure a fair comparison between processed mangoes (data not shown). The dry matter contents of fresh fruits and pasteurised puree exhibited a strong correlation ($R^2 = 0.998$), confirming that the dry matter content remained unchanged during pasteurisation. The dry matter content of dried products was approximately 84.1 ± 2.0%, consistent with expectations for dried slices (Bonneau *et al.*, 2016). The fried chips had a dry matter content of approximately 86 ± 5.0%, similar to that reported by Soto *et al.* (2020).

Table 4 presents the descriptive statistics of the relationship between the initial content of the variables in fresh fruits and the final content in processed mangoes. The effects of the ripening stage (RS), mango cultivar-density (C), and processing technique (P) on the residuals of each dependent variable (total sugar, sucrose, glucose, fructose, sucrose/hexose, citric acid,

Table 4 Descriptive statistics of relation between initial content of variables (total sugar, sucrose, glucose, fructose, citric acid, malic acid and the ratio of sucrose/hexose, sugars/acids) in fresh fruits and processed mangoes, using the SLR

Dependent variables	R^2	Estimated regression coefficients (*a*)	Lower bound	Upper bound
Total sugar	0.75	1.046	1.020	1.072
Sucrose	0.72	1.127	1.059	1.194
Glucose	0.72	0.895	0.837	0.953
Fructose	0.86	0.935	0.903	0.966
Sucrose/hexose	0.87	1.153	1.086	1.219
Citric acid	0.91	1.042	0.999	1.085
Malic acid	0.10	1.007	0.835	1.179
Sugars/acids	0.85	1.017	0.952	1.082

malic acid, and sugar/acid ratio) in the processed mangoes were shown in Table 5. The predictive equation relating the chemical attributes of fresh mangoes to the processed product properties was illustrated in Table 6.

Total sugar content

The correlation between the initial total sugar content in fruits and the final content in processed products yielded an R^2 value of 0.75 (Table 4), indicating that the initial sugar content in fresh fruits contributed to 75% of the variability in the total sugar content of the processed products. The estimated regression coefficient of total sugar was 1.046 ± 0.026, suggesting that the total sugar content increased by 4% after processing, regardless of the technique used (pasteurisation, hot-air drying, and vacuum frying). Significant effects of mango cultivar-density ($P < 0.05$) and processing technique ($P < 0.001$) on residual sugar content were observed (Table 5), underscoring their crucial role in the development of a predictive model for total sugar content in processed products (Table 6). Notably, products of 'K' mangoes ('K-LD': +1.06 g·100 g^{-1} DM and 'K-HD': +3.30 g·100 g^{-1} DM) contained higher total sugar content than Cambodian mangoes ('KC-HD': −0.91 g·100 g^{-1} DM and 'KRM-LD': −2.81 g·100 g^{-1} DM). Pasteurisation led to a significant decrease of 4.52 g·100 g^{-1} DM, while hot-air drying and vacuum frying resulted in an accumulation of sugar content of 0.74 g·100 g^{-1} DM and 4.25 g·100 g^{-1} NF-DM, respectively. The results illustrated in Fig. 3a underscore the reliability of the predictive model ($R^2 = 0.91$). Furthermore, the RMSE indicated a good predictive performance with an average error rate of 3.47 g·100 g^{-1} DM, and the NRMSE of 8.07%.

Soluble sugars content and the ratio of sucrose-to-hexose

Similar to the total sugars, the sucrose content and sucrose/hexose ratio in the processed products were estimated to increase after processing. The sucrose content increased by a coefficient of 1.127 ± 0.068 compared with the initial content ($R^2 = 0.72$) (Table 4). This demonstrated that the sucrose content increased by approximately 13%. In contrast, the amounts of glucose and fructose in processed mangoes decreased by 10% (*a*-value = 0.895 ± 0.058) and 7% (*a*-value = 0.935 ± 0.0.32), respectively, compared to those in fresh fruits. Therefore, this resulted in an increase in sucrose and a decrease in glucose and fructose (+Suc, −Glu, and −Fru content), which logically led to an increase in the ratio of sucrose/-hexose between the fresh and processed products, with an average coefficient of 1.153 ± 0.067 ($R^2 = 0.87$).

Analysis of variance revealed the impact of three explanatory variables (ripening stage, mango cultivar-density, and processing technique) only on the residual of sucrose. This indicates that sucrose content in mangoes could be manipulated through cultivar-density selection, an optimised ripening stage, and processing. The ripening stage and cultivar-density affected the residual glucose and sucrose/hexose ratio, whereas processing did not affect these traits (Table 5). The ripening stage had a more significant impact on the glucose content, fructose content, and sucrose/hexose ratio ($P < 0.001$) than on sucrose content ($P < 0.05$). Meanwhile, mango cultivar-density was the most influential

Table 5 Effect of mango ripening stages, cultivar-density, and processing techniques on the residual of dependent variables using ANOVA

***F*-value and significance**[a]								
Factors	**Total sugar**	**Sucrose**	**Glucose**	**Fructose**	**Sucrose/hexose**	**Citric acid**	**Malic acid**	**Sugars/acids**
RS	1ns	5*	21***	19***	14***	3*	2ns	0.06ns
C	4*	13***	4*	2ns	12***	4*	7**	1ns
P	15***	5*	0.7ns	5*	2ns	7**	65***	12***

C, mango cultivars-density; ns, not significant; P, processing techniques; RS, ripening stages.
[a]***P-value <0.001; **P-value <0.01; *P-value <0.05.

Table 6 Predictive equations of dependent variables using linear regression and the significant factors presented in Table 5

Dependent variables	Equation of the model	α_{RS}	β_C	δ_P
Total sugar (TS)	1.046 * TS $_{Fruits}$ + β_C + δ_P		KRM-LD: −2.81 K-LD: 1.06 K-HD: 3.30 KC-HD: −0.91	Past = −4.52 *D* = 0.74 VF[a] = 4.25
Sucrose	1.127 * Sucrose $_{Fruits}$ + α_{RS} + β_C + δ_P	G: −2.56 M: 0.91 R: 3.92	KRM-LD: −4.66 K-LD: 5.41 K-HD: 5.71 KC-HD: −3.42	Past = −2.59 *D* = 1.47 VF[a] = 3.40
Glucose	0.895 * Glucose $_{Fruits}$ + α_{RS} + β_C	G: 2.40 M: 0.29 R: −1.19	KRM-LD: 1.44 K-LD: 0.12 K-HD: −0.36 KC-HD: 0.80	
Fructose	0.935 * Fructose $_{Fruits}$ + α_{RS} + δ_P	G: 2.94 M: 0.49 R: −1.66		Past = −0.55 *D* = 0.63 VF[a] = 1.69
Sucrose/hexose (S/H)	1.153 * S/H $_{Fruits}$ + α_{RS} + β_C	G: −0.13 M: 0.05 R: 0.17	KRM-LD: −0.16 K-LD: 0.13 K-HD: 0.15 KC-HD: −0.002	
Citric acid (CA)	1.042 * CA $_{Fruits}$ + α_{RS} + β_C + δ_P	G: 0.25 M: −0.25 R: −0.07	KRM-LD: 0.34 K-LD: −0.34 K-HD: 0.04 KC-HD: −0.13	Past = −0.37 *D* = −0.04 VF[a] = 0.33
Malic acid (MA)	1.007 * MA $_{Fruits}$ + β_C + δ_P		KRM-LD: 0.27 K-LD: −0.25 K-HD: −0.03 KC-HD: 0.55	Past: −0.12 *D*: −0.54 VF[a]: 1.07
Sugars/Acids (TS/A)	1.017 * TS/A $_{Fruits}$ + δ_P			Past: 0.47 *D*: 2.26 VF: −2.47

The content of each sugar and organic acid were expressed as g·100 g^{-1} DM.
C, mango cultivars; D, hot-air drying; G, green-mature stage; M, mid-ripe stage; P, processing techniques; Past, pasteurisation; R, ripe stage; RS, ripening stages; VF, vacuum frying.
[a]The contents of each sugar and organic acid in vacuum-fried mangoes were expressed as g·100 g^{-1} non-fat dry matter, NF-DM.

factor affecting sucrose content and sucrose/hexose ratio ($P < 0.001$). The products at the ripe stage showed an increase of sucrose content and sucrose/hexose ratio (respectively sucrose = +3.92 g·100 g^{-1} DM, sucrose/hexose = +0.17) and for 'K' mangoes (respectively sucrose = +5.56 g·100 g^{-1} DM, sucrose/hexose = +0.14) (Table 6). In addition, vacuum frying significantly accumulated the sucrose content by 3.40 g·100 g^{-1} DM, which was higher than that of the other processing techniques. As illustrated in Fig. 3b,e, the model performance improved after adding the effect of relevant explanatory variables to the regression model for sucrose content ($R^2 = 0.94$, RMSE = 4.15 g·100 g^{-1} DM, NRMSE = 9.93%) and the sucrose/hexose ratio ($R^2 = 0.96$, RMSE = 0.12, NRMSE = 6.31%). Conversely, the greatest decrease in glucose and fructose was observed in the products at the ripe stage (Glu = −1.19 g·100 g^{-1} DM, Fru = −1.66 g·100 g^{-1} DM) (Table 6). After processing, Cambodian mangoes had a higher increase in glucose content (+0.80 and +1.44 g·100 g^{-1} DM) for 'KC-HD' and 'KRM-LD', respectively. The model performance was improved after adding the effect of each variable to the model regression for glucose content ($R^2 = 0.89$, RMSE = 1.21 g·100 g^{-1} DM, NRMSE = 8.91%) and fructose content ($R^2 = 0.94$, RMSE = 1.71 g·100 g^{-1} DM, NRMSE = 7.98%) (Fig. 3c,d).

Primary organic acids content and the ratio of sugars/acids

After processing, the estimated coefficients of citric acid (CA) content (1.042 ± 0.043) and sugars/acids ratio (S/A: 1.017 ± 0.065) changed slightly (Table 4). This indicated that the CA content and ratio increased slightly in the processed mangoes. The relationship of

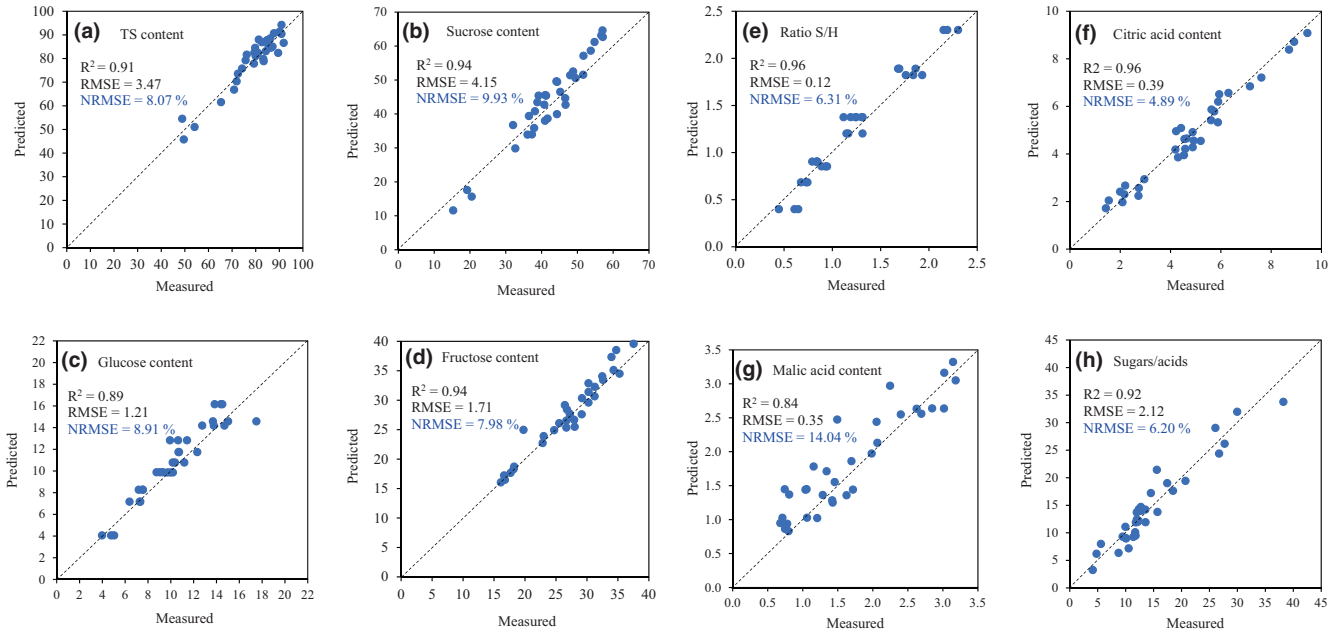

Figure 3 Comparison between the experimental and predictive content in processed mangoes. (a) total sugar, (b) Sucrose, (c) Glucose, (d) Fructose, (e) Sucrose/hexose, (f) Citric acid, (g) Malic acid, and (h) Sugars/acids.

malic acid (MA) content between fresh and processed products revealed a marked variation with a coefficient of 1.007 ± 0.172 and $R^2 = 0.10$.

According to the F-value (Table 5), the processing techniques were the most influential factors affecting the residual CA content ($P < 0.01$), MA content ($P < 0.001$), and S/A ratio ($P < 0.001$) in mango products. The prediction of CA in processed mangoes increased with ripening stage. Table 6 demonstrated the greatest impact of pasteurisation and hot-air drying on the predicted MA content in processed products, a decrease of 0.12 and 0.54 g·100 g^{-1} DM, respectively, from the initial content. Vacuum frying significantly increased the MA content in mango products (+1.07 g·100 g^{-1} NF-DM). The highest content was found in the vacuum-fried mangoes of 'KC-HD', followed by the products of 'KRM-LD', 'K-HD', and 'K-LD'. It was clear from Fig. 3g that the model performance (RMSE = 0.35 g·100 g^{-1} DM, NRMSE = 14.04%) was strongly affected by processing techniques and cultivar-density as the coefficient of determination (R^2) was changed from 0.10 to 0.84 after adding the effect of significant factors. Regardless of the ripening stage or mango cultivar-density, the S/A ratios of the puree and dried products were higher than those of fresh fruits by 0.47 and 2.26, respectively. Vacuum frying resulted in the greatest reduction (−2.47) in the S/A ratio of all mango chips.

Discussion

The primary objective of this study was to build models for predicting the soluble sugar and organic acid contents of processed mangoes, considering both the initial composition of the fruit and processing techniques (pasteurisation, drying, and vacuum frying). To the best of our knowledge, this is the first time such models have been proposed. Existing models are generally built to control the final quality of products by varying heat-treatment parameters (Ayustaningwarno *et al.*, 2020b; Soto *et al.*, 2021; Hu *et al.*, 2022). Only Korbel *et al.* (2013) proposed a model for the formation of Maillard reaction products on dried mangoes by varying the water activity of the initial products and drying time. The coefficients of determination above 0.90 for sugars and organic acids (except for malic acid with an R^2 of 0.84) and low RMSEs indicate good model performance. For example, it is possible to predict the final total soluble sugar content of processed mangoes with an accuracy of 3.5 g·100 g^{-1} DM from their initial total sugar content, ripening stage, cultivar-density, and the processing method used.

To ensure robustness of our model, the strategy chose a great variation of fruits which was characterised by different maturity stages (indicated by fruit density), ripening stages (from green-mature to ripe), and varieties origin (Peru 'Kent') and Cambodia ('Keo Chen' and 'Keo Romeat' cultivars). As expected, the

initial sugar and acid contents of the fruits were the predominant variables in these models, explaining at least 72% (except for malic acid: 10%) of the variability in the final sugar and acid content. Processing technique was the second most crucial factor. Differences in total sugars of approximately 9 g·100 g^{-1} DM were observed between pasteurised mango purees and vacuum-fried chips from the same fruit batch. Notably, the cultivar-density and ripening stage were significant factors in the development of these models. Differences in sucrose levels of almost 10 g·100 g^{-1} DM were observed between processed products from 'Kent' and 'Keo Romeat' and 7 g·100 g^{-1} DM between processed products from green-mature and ripe mangoes. This indicates that the sucrose content of mangoes was not the only factor to be considered in the initial composition of these fruits.

The purpose of these models is not only to forecast the final sugar and acid contents but also to elucidate the individual impacts of the explanatory variables (RS, C, and P) and identify the primary factors that affect the dependent variables (sugar and organic acid contents). Further validation of these models using new fruit samples from the same cultivar is proposed in the next stage. The generalisability of these models requires the exploration of new parameters that must be integrated. For example, the "cultivars-densities" or "ripening stage" factors could be translated into co-variables (starch content, firmness, enzymatic activity, etc.) that could contribute to and improve existing models.

Predictive models of individual soluble sugars (sucrose, glucose, and fructose) showed that processing had different effects on the final contents of these sugars in the processed products. The sucrose content increased by an average of 13% during processing, whereas the glucose and fructose contents decreased by 10% and 7%, respectively. Taking a deeper look at the model parameters, sucrose levels increased by 20% for mangoes processed into vacuum-fried chips, 15% for dried slices, and 8% for pasteurised purees. In the case of fructose, a decrease was observed during pasteurisation and hot-air drying. The increase in sucrose during vacuum frying has already been observed in papaya by Soto *et al.* (2021). Although the sucrose levels in red-fleshed papaya fruits (*Carica papaya* L.) were insignificant, 15% sucrose was formed during vacuum frying at 100 °C for 14 min. Conversely, the glucose and fructose contents decreased during these processes. Soto *et al.* (2021) proposed two hypotheses for sucrose formation during the vacuum frying of papaya fruit. This formation could be explained either by a condensation reaction between glucose and fructose, leading to sucrose synthesis, or by thermal degradation of the cell wall and middle lamella, which could lead to sucrose release during frying. To our knowledge, no new information in literature supports this hypothesis. Nevertheless, the formation of disaccharides by condensation reactions requires high temperatures of over 100 °C, preferably at temperatures close to or above the melting point of the saccharides (Shah *et al.*, 2004). In our study, the stoichiometry of the condensation reaction was not fully applied (+13% sucrose, −10% glucose, and −7% fructose), leading to a slight increase in total soluble sugars (+4%) in the processed products. This could support the second hypothesis to the detriment of condensation supposition. However, sucrose formation was found to a lesser extent in dried and pasteurised mango purees. The temperatures used for these two processes (60 °C for drying and 85 °C for pasteurisation) did not support the condensation hypothesis, which requires higher temperatures. Further studies using other matrices and heat treatments are required to confirm these findings.

The predictive models for citric and malic acids demonstrated that vacuum frying increased acid formation by over 30%, especially for malic acid. A previous study found an increase (5–10%) in the sum of malic acid and quinic acid after quince fruit processing into jam (Silva *et al.*, 2004). In addition, higher organic acid production in pasteurised juice (72 °C, 15 s) was associated with the degradation of carbohydrates and other phenolic compounds (Tembo *et al.*, 2017). Zhou *et al.* (2021) identified an increase in citric and malic acid contents in peaches after hot-air treatment, as a consequence of higher gene expression of citrate synthase and malate dehydrogenase.

The models showed that considering the initial sugar and acid content and processes was insufficient for predicting the final content of the same compounds. To improve the prediction, some models must include the ripening stage and cultivar-density. This implies that other parameters associated with either the ripening stage or cultivar-density should be considered. The relative gene expression of sugar-related enzymes (acid invertase, neutral invertase, sucrose synthase, sucrose phosphate synthase), citrate-related enzymes (phosphoenolpyruvate carboxylase, citrate synthase, aconitase, and isocitrate dehydrogenase), malate-related enzymes (malate dehydrogenase and malic enzyme), and the activity of catalase and polyphenol oxidase (PPO) should be considered, as the regulation of these enzymes changes the sugar and organic acid content after heat treatment (Chen *et al.*, 2012; Lin *et al.*, 2016; Mukhtar *et al.*, 2020, 2022; Zhou *et al.*, 2021).

Conclusions

This study successfully established a predictive model to estimate the sugar and organic acid contents in processed mangoes based on their initial composition and processing techniques. These findings demonstrated that sucrose levels tended to increase, while glucose

and fructose levels decreased during processing. This model highlights the significant impact of different processing methods, such as pasteurisation, hot-air drying, and vacuum frying, on the quality of the final products. Furthermore, this study emphasises the importance of considering variables such as ripening stage and cultivar-density to improve prediction accuracy. Future research should focus on validating these models across different mango varieties and processing conditions to enhance their applicability and reliability in the mango-processing industry.

This comprehensive approach can help optimise raw material selection and processing methods, ensure consistent quality, and reduce waste and processing costs in mango product manufacturing.

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Author contributions

Lyda Chin: Writing – original draft; methodology; validation; visualization; formal analysis; investigation; conceptualization. **Adrien Servent:** Writing – review and editing; validation; methodology; formal analysis. **Sivmey Hor:** Conceptualization; investigation; writing – review and editing; project administration. **Hasika Mith:** Conceptualization; investigation; funding acquisition; writing – review and editing; project administration; supervision. **Christophe Bugaud:** Conceptualization; investigation; funding acquisition; methodology; validation; visualization; writing – review and editing; formal analysis; project administration; supervision; data curation; resources; software.

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical approval

Ethical approval was not required for this study.

Peer review

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Data availability statement

The data supporting the findings of this study are available from the authors upon request.

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