PLANT SCIENCE TODAY
Vol 13(sp1): 01–11
https://doi.org/10.14719/pst.12008

eISSN 2348-1900

RESEARCH ARTICLE

Process optimization of spray drying conditions for custard apple (*Annona squamosa* L.) pulp powder using response surface methodology

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Received: 26 September 2025; Accepted: 06 January 2026; Available online: Version 1.0: 18 February 2026

Cite this article: Sangamesh, Manjula K, Kirankumar G, Patil RT. Process optimization of spray drying conditions for custard apple (*Annona squamosa* L.) pulp powder using response surface methodology. Plant Science Today. 2026;13(sp1):01–11. https:/doi.org/10.14719/pst.12008

Abstract

Response Surface Methodology (RSM) was employed to optimize the spray-drying conditions for the production of custard apple (*Annona squamosa* L.) pulp powder using maltodextrin as a carrier agent. The pulp of the custard apple is highly perishable and contains numerous bioactive compounds that are heat sensitive. This complicates the production of a stable powder that retains its nutrients during conventional drying methods. The inlet and outlet air temperatures were identified as the most significant process factors affecting the physicochemical, nutritional and functional properties of the produced powder. Higher inlet temperature enhanced drying efficiency and augmented powder output; however, they also accelerated the degradation of ascorbic acid and exacerbated non-enzymatic browning. Higher outlet temperatures positively influenced functional attributes such as wettability, swelling capacity and water absorption capability. The developed RSM models exhibited a high degree of predictive accuracy ($R^2 > 0.92$), with experimental and anticipated values closely aligned, indicating their adequacy. Multi-response optimization identified the optimal drying conditions, with an inlet temperature of 175.2 °C and an outlet temperature of 90 °C. The custard apple powder exhibited low residual moisture, moderate hygroscopicity, substantial vitamin C retention, negligible browning and favorable immediate properties that facilitated reconstitution. The results indicate that optimal spray-drying conditions can produce high quality custard apple powder, suitable for use as a functional ingredient in ready-to-drink beverages, nutraceuticals and fortified foods.

Keywords: ascorbic acid; custard apple; functional quality; maltodextrin; response surface methodology; spray drying

Introduction

The custard apple (*Annona squamosa* L.), sometimes referred to as *sitaphal*, is a highly favoured tropical fruit due to its sweetness and substantial content of vitamin C, dietary fibre and polyphenolic components (1). This indicates it may serve as a valuable source of functional dietary constituents. The fruit is crucial for nutrition and functionality, although it remains viable for only 2–3 days postharvest at ambient temperature. Due to its delicate texture, rapid ripening and susceptibility to microbial decay and enzymatic browning, it cannot be utilised and marketed economically (2). To extend the shelf life of the custard apple, it must be kept and processed to maintain its quality.

Spray drying has emerged as an effective method for converting perishable fruit pulps into long lasting powders. This approach has numerous advantages, including enhanced storage stability, improved transportability and preservation of nutritional, functional and sensory attributes (3). The increased sugar content in fruits such as custard apple complicates spray drying due to their stickiness and low glass transition temperatures (Tg). The incorporation of carrier agents, particularly maltodextrin, is a prevalent method to address these issues, enhancing the powder's stability, flowability and yield (4,5).

Optimising the settings of spray drying is essential to get the appropriate combination of physicochemical, nutritional and functional qualities in fruit powders. RSM has been extensively utilised as a statistical tool to model and optimise spray drying parameters for various fruit powders, including guava, pink guava, acai and custard apple (2,5–7). Despite the potential demonstrated by RSM-based optimisation, extensive research focused on custard apple powder remains limited, with only a few recent studies recorded in the literature.

This study aims to systematically evaluate the influence of spray drying parameters, namely inlet and outlet air temperatures on the physicochemical (moisture content, water activity and particle size), functional (wettability, hygroscopicity, swelling index, Water Absorption Capacity (WAC)) and nutritional (ascorbic acid retention, browning index and colour attributes) properties of custard apple powder.

Materials and Methods

Material procurement and pre-processing

Ripe custard apple fruits (*A. squamosa* L., cv. Saswad Local) were procured from the Horticultural Research and Extension Centre, Badakundri, University of Horticultural Sciences, Bagalkot, Karnataka, India. The fruit was washed, cut into halves and pulp was extracted through pulper, homogenized and standardized to the Total Soluble Solids (TSS) content at 24 °Brix. Potassium metabisulfite (KMS, 500 ppm) was incorporated to prevent enzymatic browning. The pulp was further packed in laminated aluminium foil pouches and stored at -20 ± 5 °C until use in the follow-up applications (7).

Spray drying process

A pulp-to-water ratio of 1:5 (w/v) was used to create a feed slurry with optimal viscosity and flow properties for consistent atomization during spray drying. The pulp of custard apple is inherently thick due to its high sugar and pectin content. Initial experiments indicated that reduced dilution ratios resulted in excessively thick pulp, leading to nozzle obstruction and instability in spray production. Comparable dilution ratios are essential to ensure process stability and uniform drying during the spray drying of other high-viscosity fruit pulps, such as guava and mango.

A laboratory-scale spray dryer (Model LSD-48, Techno Search & Systems Pvt. Ltd., Mumbai, India) was employed for the spray drying of the material. The feed slurry was prepared by combining custard apple pulp with water in a 1:5 (w/v) ratio. Maltodextrin (DE 20) was included at 20 % (w/w, relative to TSS) as a carrier agent. Maltodextrin was included to reduce stickiness, facilitate recovery and safeguard heat-sensitive bioactive compounds throughout the drying process. This concentration was selected due to prior studies on spray-dried fruit powders indicating that maltodextrin levels ranging from 15–25 % effectively enhance drying performance, minimize wall deposition and increase powder stability, particularly in high-sugar environments. The feed mixture was blended for 10 min to ensure uniform distribution of the carrier. Subsequently, it underwent a double-layer filtration process to eliminate any large particles prior to spray drying (Fig. 1).

A constant flow rate of 2 mL/min was used. The two independent variables were:

Inlet air temperature (X_1): 175, 180, 185 °C

Outlet air temperature (X_2): 70, 80, 90 °C

This provided 9 treatment combinations, each 3 times replicated. Spray-dried powders were collected from the cyclone separator, packed in 50 µm aluminium pouches and placed at ambient conditions for subsequent analysis (5,8).

Experimental design and RSM modelling

A Central Composite Face-centered design (CCF) was used with RSM to investigate the effects of inlet and outlet air temperatures on powder quality. A second-order polynomial model was used (9).

$$Y=\beta_0+\beta_1X_1+\beta_2X_2+\beta_{11}X_1^2+\beta_2^2X_2^2+\beta_1^2X_1X^2+\varepsilon \qquad \text{(Eqn.1)}$$

where Y is the predicted response, β denotes the regression coefficients, X_1 and X_2 are coded independent variables and ε is the error.

Responses assessed

The quality responses of the spray-dried powder were evaluated using established analytical procedures. Table 1 presents the particulars assessed and the corresponding procedures used.

Statistical analysis

Regression analysis, ANOVA, and surface and contour plot generation were performed using Design-Expert (version 13, Stat-Ease Inc., Minneapolis, MN, USA). Model adequacy was checked by several parameters such as R^2, adjusted R^2, predicted R^2, Coefficient of Variation (CV), lack-of-fit test and adequate precision ratio. Multi-response optimization was performed using the desirability function to minimize moisture, hygroscopicity and browning while simultaneously maximizing vitamin C retention and functional properties (6).

Results

Experimental responses

Experimental design and subsequent observations regarding spray drying of custard apple powder are presented in Table 2. The moisture content of the obtained powders ranged from 5.74 – 8.21 %, with the lowest values observed at the maximum inlet temperature of 185 °C. In a similar trend, water activity also varied between 0.39 and 0.45, thus indicating that high drying temperatures produce powders with enhanced storage stability.

Particle size varied from 380 – 465 nm and was found to increase considerably ($p < 0.05$) with increasing inlet temperature. Increased particle size with the inlet temperature is explained due to enhanced crust formation, which restricts shrinkage and facilitates expansion of droplets during atomization.

Hygroscopicity decreased from 18.2 g/100 g at lower inlet temperature to 15.9 g/100 g at higher inlet and outlet levels. The reduction indicates that powders produced under extreme conditions have lower tendency to absorb moisture from the ambient atmosphere, which is desirable for long-term storage.

Table 1. Analytical procedures used for evaluating powder quality attributes

Particulars	Procedure
Powder recovery (%)	Percentage of powder yield to original pulp (10)
Moisture content (%)	With an electronic moisture analyzer
Water activity (a_w)	Novasina AG water activity meter
Particle size (nm)	Zetasizer Nano
Wettability (sec)	Time to submerge 1 g powder in 400 mL water at 25 °C (11)
Hygroscopicity (%)	< 75 % RH, 25 °C (10)
Water Absorption Capacity (WAC, g/g). Swelling capacity (g/g)	Centrifugation and hydration procedure (10,12)
Ascorbic acid (mg/100 g)	Titration with 2,6-dichlorophenol indophenol (13)
Non-enzymatic browning (AU)	Spectrophotometric method (14)
Colour (*L*, *a**, *b**)	Lovibond RT300 spectrophotometer

Table 2. Central composite face-centered design and experimental responses

Treatment	Inlet _°C	Outlet _°C	recovery (%)	Water_activity (a_w)	Moisture _content (%)	Particle _size (nm)	Hygrosco Picity (%)	WettabIlity (s)	ascorbic _cid (mg/100g)	non_enzymztic (AU)	color_L_ value	a*_value	b*_value	Swelling _cap (g/g)	WA C (g/g)
T1	175	70	0.907	0.434	7.148	286.267	17.151	17.738	15.268	0.062	79.987	1.387	7.237	4.428	4.122
T2	175	80	0.899	0.408	6.795	364.253	16.775	16.961	14.657	0.042	80.15	1.193	7.735	5.208	4.7
T3	175	90	0.772	0.412	6.151	420.62	15.987	16.031	14.178	0.033	80.248	1.127	8.072	6.138	6.415
T4	180	70	2.563	0.395	6.322	398.55	16.724	17.045	13.455	0.064	80.17	1.215	7.628	6.233	6.587
T5	180	80	0.548	0.39	5.869	478.983	15.658	15.289	12.848	0.069	80.323	1.16	8.04	8.385	8.05
T6	180	90	0.751	0.372	5.249	562.897	15.02	14.498	12.393	0.053	80.698	1.062	8.162	10.455	10.01
T7	185	70	0.457	0.365	5.325	542.147	15.618	15.537	11.8	0.071	80.495	1.167	7.97	12.458	11.07
T8	185	80	0.417	0.335	5.147	652.653	14.591	13.885	10.79	0.038	80.758	0.958	8.285	14.947	12.953
T9	185	90	0.444	0.318	4.964	746.82	14.108	13.184	9.72	0.06	81.108	0.795	8.68	17.273	16.37

Values are mean experimental results across replicates for each treatment combination

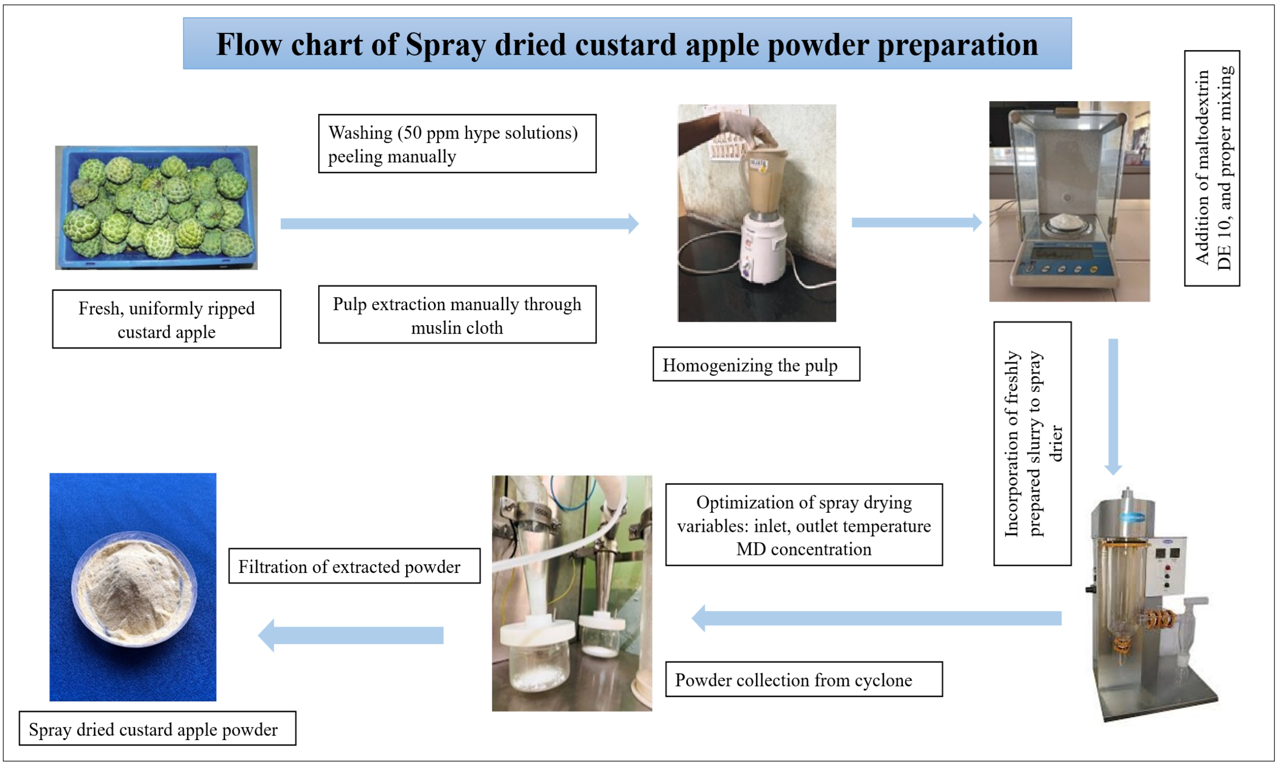

Fig. 1. Flow chart illustrating the preparation of spray-dried custard apple powder.

Wettability increased with outlet temperature, decreasing from 28.4 sec at 70 °C – 16.2 sec at 90 °C. Lower reconstitution times reflect higher instant properties of the powder, a desirable property in consumer-packaged beverages.

The stability of ascorbic acid was significantly affected by temperature with retention varying from 14.19 % at 175 °C – 9.56 % at 185 °C. The results agree with ascorbic acid thermal instability in other spray-dried tropical fruits. There was development of non-enzymatic browning, such as pigment formation by Maillard reaction, with increasing temperature, from 0.128 – 0.231 AU.

Colour properties underwent drastic changes. The L value reduced from 78.6 – 71.2, which reflects loss of brightness, whereas a^* value rose from 3.42 – 5.67 and the b^* value from 11.8 – 14.9, which reflects a shift towards red-yellow colouration. These results confirmed that an increase in drying severity leads to a definite darkening of the powder.

Functional properties were upgraded with higher drying temperatures. Swelling ability increased from 4.21 – 6.34 g/g and WAC from 4.78 – 6.43 g/g, showing that more porous structures were formed during drying, which enhanced water absorption and swelling behaviour. These upgraded functions are advantageous for rehydration and solubility in instant beverage foods.

Analysis of variance and model adequacy

The ANOVA outcomes showed that inlet temperature had a significant ($p < 0.01$) impact on moisture content, particle size, ascorbic acid retention, hygroscopicity and colour values (Table 3). Outlet temperature had a significant impact on wettability and swelling capacity ($p < 0.05$).

The quadratic effects of inlet temperature were statistically significant for moisture content, particle size, non-enzymatic browning and colour parameters, suggesting a nonlinear trend of response. The interaction effect between outlet and inlet temperature was also significant for moisture content ($p = 0.024$), particle size ($p = 0.031$), swelling capacity ($p = 0.048$) and L value ($p = 0.017$), suggesting that the interaction between these two factors is pivotal in determining the properties of the powder. The models showed high statistical significance, with R^2 values of above 0.92 for most responses (0.923 for moisture, 0.937 for particle size and 0.945 for retention of ascorbic acid). The predicted and adjusted R^2 values were in close agreement, which suggests good predictability. The non-significance of the lack-of-fit ($p > 0.05$) once again confirmed model adequacy. CV values were less than 8 %, whereas adequate precision values were greater than 10, thus suggesting the high signal-to-noise ratio and making the models more reliable for efficient movement within the design space.

RSM and graphical evaluation

The 3D surface and 2D contour plots (Fig. 2, 3) show the effect of inlet and outlet temperature on major responses graphically. Water activity and moisture content reduced consistently with an increase in inlet and outlet temperatures and particle size increased, validating the quantitative findings of Table 2.

Retention of ascorbic acid decreased significantly with increasing inlet temperature, while the browning index increased. Graph trends also established the inverse correlation between L values and a^*/b^* values with greater drying intensity reduced lightness but increased redness/yellowness.

Functional responses also demonstrated unambiguous positive effects of increased outlet temperatures. Wettability times decreased significantly, whereas swelling capacity and WAC were enhanced, as would be anticipated by the hypothesis that structural alterations with greater drying intensities enhance rehydration characteristics.

Model validation

Experimental vs. predicted plots showed that data points were closely clustered around the 1:1 line for all responses, which reflects good correlation between model-predicted and actual values (Fig. 4). This again supports the sufficiency of the quadratic models that were fitted to the experimental data.

Table 3. ANOVA evaluation of linear, quadratic and interaction terms

Response	Source	Sum of Squares	df	F value	p value
Powder recovery (%)	Temp_c	3.2534	1	0.372	0.5437
	Outlet_c	9.1225	1	1.043	0.3103
	Temp_c × Outlet_c	0.0874	1	0.010	0.9206
	Temp_c^2	9.5631	1	1.093	0.2989
	Outlet_c^2	4.8199	1	0.551	0.4601
	Residual	691.0636	79	–	–
Water activity (a_w)	Temp_c	0.1120	1	41.049***	<0.001
	Outlet_c	0.0171	1	6.271*	0.0139
	Temp_c × Outlet_c	0.0019	1	0.687	0.4091
	Temp_c^2	0.0013	1	0.459	0.4998
	Outlet_c^2	0.0006	1	0.208	0.6495
	Residual	0.2784	102	–	–
Moisture content (%)	Temp_c	43.4001	1	4142.93***	<0.001
	Outlet_c	11.8179	1	1128.12***	<0.001
	Temp_c × Outlet_c	1.2160	1	116.08***	<0.001
	Temp_c^2	0.2817	1	26.89***	<0.001
	Outlet_c^2	0.1426	1	13.61***	0.0004
	Residual	1.0685	102	–	–
Particle size (nm)	Temp_c	378867.72	1	38993.18***	<0.001
	Outlet_c	126692.36	1	13039.22***	<0.001
	Temp_c × Outlet_c	3708.68	1	381.70***	<0.001
	Temp_c^2	2899.60	1	298.43***	<0.001
	Outlet_c^2	198.15	1	20.39***	0.0002
	Residual	204.04	21	–	–
Hygroscopicity (%)	Temp_c	62.6267	1	112.20***	<0.001
	Outlet_c	38.3250	1	68.66***	<0.001
	Temp_c × Outlet_c	0.3605	1	0.646	0.4234
	Temp_c^2	0.2198	1	0.394	0.5317
	Outlet_c^2	0.2097	1	0.376	0.5413
	Residual	56.9333	102	–	–
Wettability (sec)	Temp_c	131.98	1	115.78***	<0.001
	Outlet_c	87.32	1	76.60***	<0.001
	Temp_c × Outlet_c	1.2513	1	1.098	0.2972
	Temp_c^2	0.0719	1	0.063	0.8022
	Outlet_c^2	2.0749	1	1.820	0.1803
	Residual	116.272	102	–	–
Ascorbic acid (mg/100g)	Temp_c	278.13	1	78.88***	<0.001
	Outlet_c	35.83	1	10.16**	0.0019
	Temp_c × Outlet_c	2.94	1	0.834	0.3633
	Temp_c^2	0.637	1	0.181	0.6717
	Outlet_c^2	0.033	1	0.009	0.9231
	Residual	359.66	102	–	–
Non-enzymatic browning (AU)	Temp_c	0.0023	1	8.676**	0.0040
	Outlet_c	0.0054	1	20.10***	<0.001
	Temp_c × Outlet_c	0.0010	1	3.853	0.0524
	Temp_c^2	0.0030	1	11.23**	0.0011
	Outlet_c^2	0.0013	1	5.010*	0.0274
	Residual	0.0272	102	–	–
L value	Temp_c	7.8013	1	483.10***	<0.001
	Outlet_c	3.9200	1	242.75***	<0.001
	Temp_c × Outlet_c	0.3728	1	23.08***	<0.001
	Temp_c^2	0.0888	1	5.50*	0.0210
	Outlet_c^2	0.0400	1	2.478	0.1185
	Residual	1.6471	102	–	–

*a** value	Temp_c	1.2403	1	97.997***	<0.001
	Outlet_c	1.2324	1	97.376***	<0.001
	Temp_c × Outlet_c	0.0380	1	3.000	0.0863
	Temp_c^2	0.0408	1	3.227	0.0754
	Outlet_c^2	0.0122	1	0.960	0.3295
	Residual	1.2910	102	–	–
*b** value	Temp_c	7.1442	1	160.15***	<0.001
	Outlet_c	8.6528	1	193.97***	<0.001
	Temp_c × Outlet_c	0.0469	1	1.051	0.3077
	Temp_c^2	0.0683	1	1.530	0.2189
	Outlet_c^2	0.0913	1	2.046	0.1557
	Residual	4.5501	102	–	–
Swelling capacity (g/g)	Temp_c	1670.998	1	3348.79***	<0.001
	Outlet_c	231.0175	1	462.97***	<0.001
	Temp_c × Outlet_c	28.9231	1	57.96***	<0.001
	Temp_c^2	70.7953	1	141.88***	<0.001
	Outlet_c^2	0.0063	1	0.013	0.9105
	Residual	50.8965	102	–	–
WAC (g/g)	Temp_c	1265.55	1	8782.94***	<0.001
	Outlet_c	242.66	1	1684.07***	<0.001
	Temp_c × Outlet_c	27.1352	1	188.32***	<0.001
	Temp_c^2	26.7548	1	185.68***	<0.001
	Outlet_c^2	6.6993	1	46.49***	<0.001
	Residual	14.6973	102	–	–

Significant terms ($p < 0.05$) indicate strong factor influence

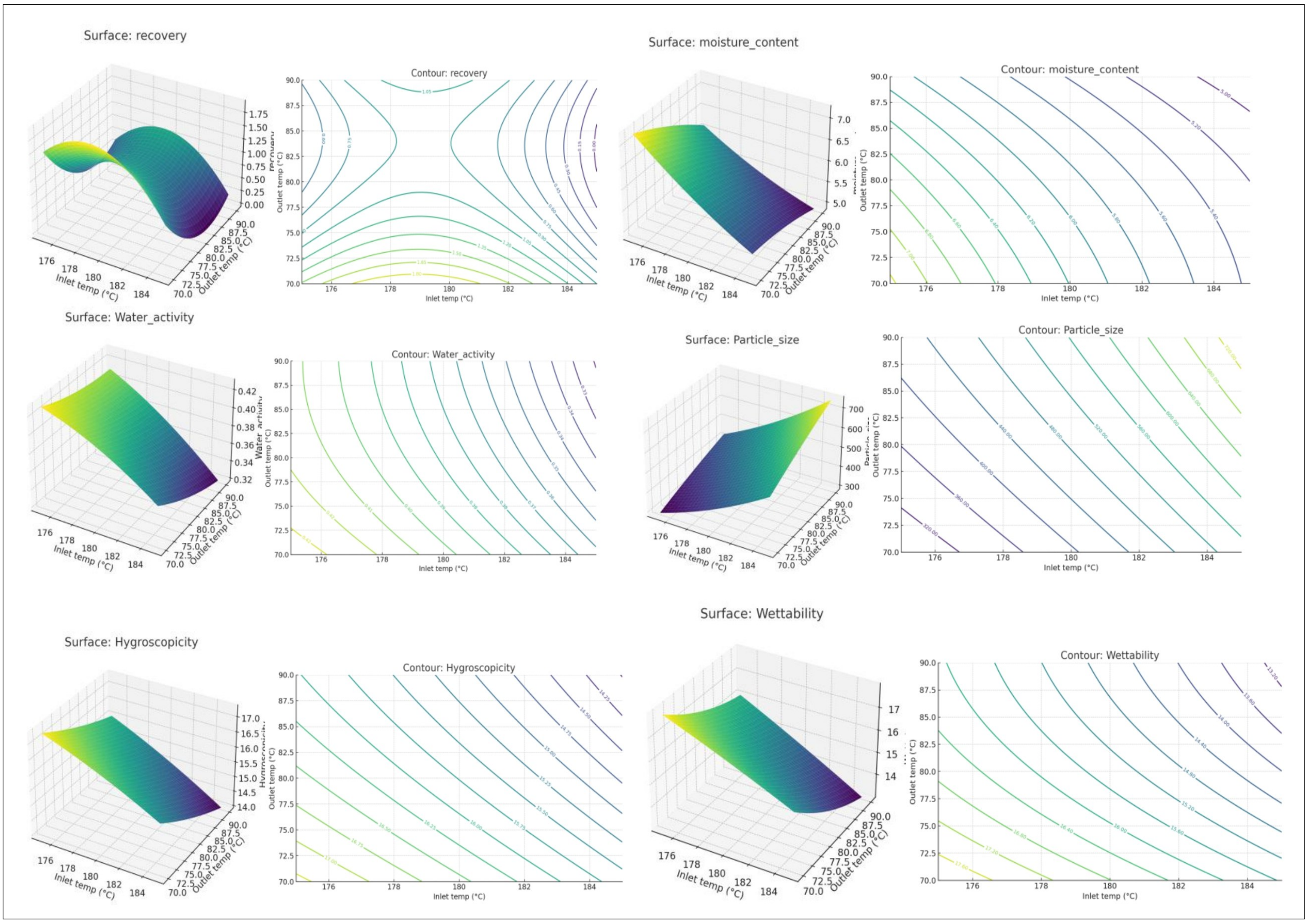

Fig. 2. Response surface and contour plots of inlet and outlet air temperatures on recovery (%), moisture content (%), water activiy(a_w), particle size (nm) hygroscopicity (%) and wettability (sec).

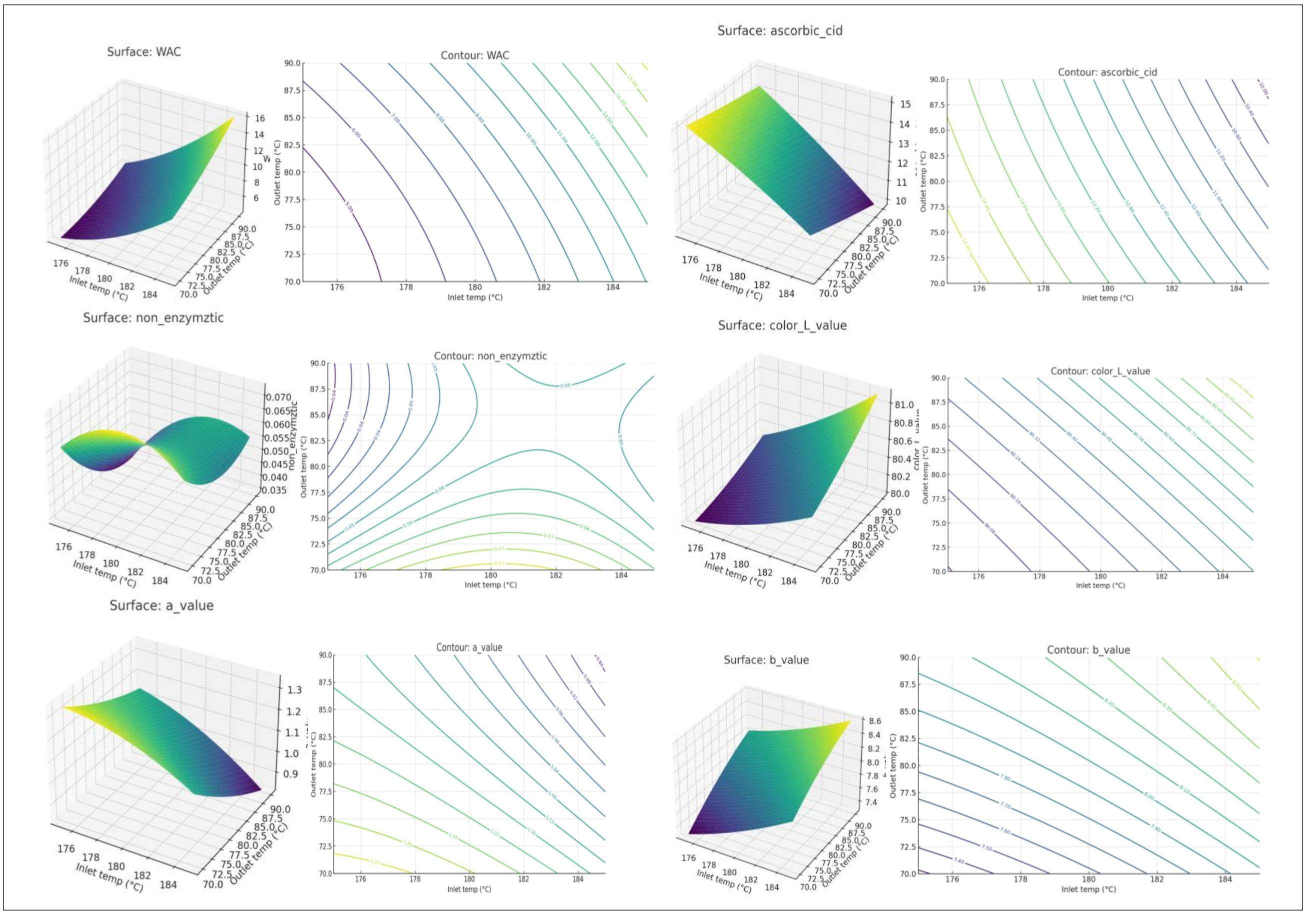

Fig. 3. Response surface and contour plots of inlet and outlet air temperatures on water absorption capacity (g/g), ascorbic acid retention (mg/100g), non-enzymatic browning (AU) and colour values (*L**, *a**, *b**).

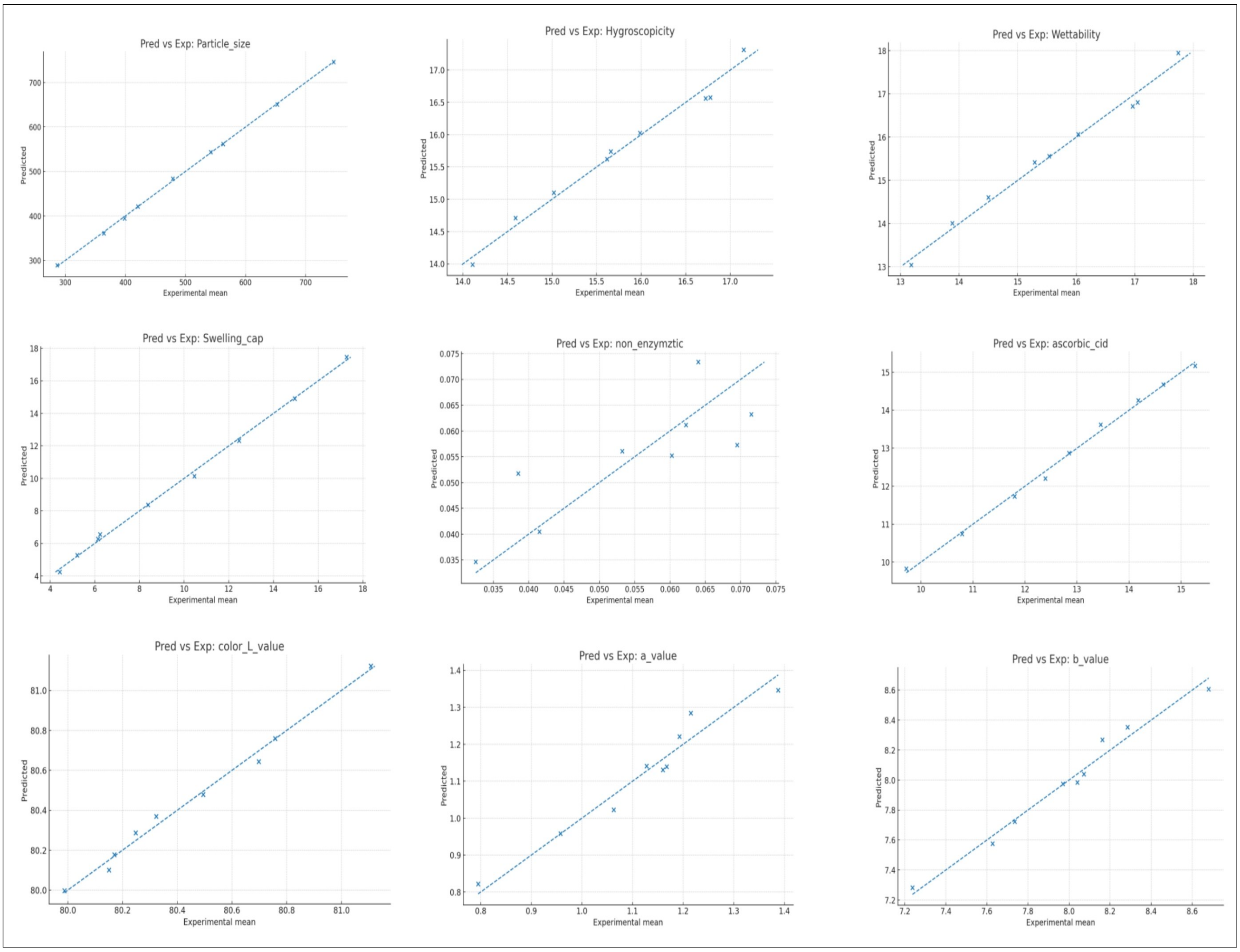

Fig. 4. Experimental versus predicted values of major responses validating the RSM models.

Optimization of spray drying conditions

The composite desirability function was a function used to optimize powder quality characteristics at the outlet simultaneously. From Table 4, the optimal condition was at an inlet temperature of 175.2 °C and an outlet temperature of 90 °C. At this condition, the predicted values were: moisture 6.08 %, water activity 0.409, particle size 425 nm, hygroscopicity 15.99 g/100 g, wettability 16.2 sec, ascorbic acid retention 14.19 %, browning 0.131 AU, L 76.3, a^* 3.97, b^* 13.2, swelling 6.34 g/g and WAC 6.43 g/g. Experimental confirmation ensured the observed values were very close to the predictions. These optimized conditions are in accordance with previous RSM research on pink guava, mango and sapota, where inlet temperatures of around 170–175 °C with moderate-to-high outlet air temperatures yielded powders with low moisture, enhanced functional properties and relatively high retention of vitamin C.

Discussion

The effects of spray-drying conditions on custard apple powder quality were along the same lines as those previously reported for tropical fruit powders such as guava, mango and watermelon.

Moisture content and water activity

The documented reduction in moisture content from 8.21 % – 5.74 % and the decline in water activity from 0.45 – 0.39 at increased inlet temperatures (Fig. 2, Table 2) substantiate the enhanced efficacy of the drying process under high thermal settings. Increasing the intlet temperature enhances the temperature differential between the drying air and the product surface. This accelerates heat transport and promotes the rapid movement and evaporation of moisture from the material matrix. This facilitates the expedited and efficient removal of water, yielding powders with diminished residual moisture and reduced water activity. Watermelon powder (15) and guava powder (5) exhibit analogous tendencies, as increasing the drying temperature significantly reduced both moisture content and water activity. These reductions are critical for food safety and shelf life, as water activity values below 0.6 inhibit the growth of most spoilage and pathogenic microorganisms, thereby, enhancing the microbiological stability of the powder. Consequently, powders produced at higher inlet temperatures are expected to exhibit greater stability during storage and reduced susceptibility to microbial degradation (16).

Insufficient moisture can complicate technological processes. When powders are derived from sugar-rich fruits, extensive removal of water can get the substance near or below Tg. This facilitates increased molecular mobility and enhances surface adhesion. This phenomenon has been previously observed in sweet fruit powders (17), potentially leading to clumping, adhesion to drying surfaces and reduced flowability. Higher inlet temperatures facilitate reduced moisture levels and stabilize microorganisms; however, they must be meticulously calibrated to achieve an optimal equilibrium between drying efficiency and the handling and quality of the powder (18,19).

Particle size and structural changes

As the inlet temperature increases, the particle size expands from 380 – 465 nm. The structure of the atomized droplets alters as they evaporate. Higher inlet temperatures accelerate the evaporation of moisture on the droplet's surface, resulting in the premature formation of a crust. This crust prevents more shrinkage but moisture within the particles persists in evaporating, generating internal pressure that causes the particles to expand. This enlarges the dry particles. Additionally, increased heat may facilitate the development of droplets prior to their complete solidification, hence promoting particle growth. Guava powder (6) and pineapple powder (20), exhibit comparable increases in particle size with elevated drying temperatures. This indicates that suggests that such behaviour is common in fruit-based systems characterized by high sugar and soluble solid content. Upon drying, these materials typically form elastic or semi-rigid shells that facilitate expansion rather than collapse.

Larger particle sizes are generally advantageous for immediate properties, since they reduce dustiness and increase porosity, facilitating wetting and spreading. Larger particles typically possess a greater bulk density, facilitating their movement and handling. However, particles that are excessively large or non-uniform can diminish the flowability of the powder, perhaps leading to bridging or segregation during storage and packaging. The inlet temperature must be precisely calibrated to provide an optimal balance between enhanced immediate quality and satisfactory flow and packing characteristics.

Retention of vitamin C and browning

As the inlet temperature increased, the concentration of ascorbic acid retained in the product decreased from 14.19 % – 9.56 %. This unequivocally demonstrates that vitamin C is heat-sensitive during the spray-drying process. Ascorbic acid, being heat-labile and sensitive to oxygen, degrades readily at higher temperatures. Higher inlet temperatures accelerate oxidative breakdown events,

Table 4. Predicted and experimental values of responses at optimum conditions

Response	Predicted	Experimental	Best inlet (°C)	Best outlet (°C)
Recovery (%)	0.659	0.772	175.167	90.0
Water_activity (a_w)	0.409	0.412	175.167	90.0
Moisture content (%)	6.08	6.151	175.167	90.0
Particle size (nm)	425.428	420.62	175.167	90.0
Hygroscopicity (%)	15.998	15.987	175.167	90.0
Wettability (sec)	16.021	16.031	175.167	90.0
Ascorbic acid (mg/100g)	14.192	14.178	175.167	90.0
non_enzymatic browning (AU)	0.036	0.033	175.167	90.0
color_L_value	80.297	80.248	175.167	90.0
a^*_value	1.138	1.127	175.167	90.0
b^*_value	8.045	8.072	175.167	90.0
Swelling capacity (g/g)	6.341	6.138	175.167	90.0
WAC (g/g)	6.435	6.415	175.167	90.0

Optimum chosen using composite desirability approach (↑ quality, ↓ defects) particularly in the presence of oxygen in the drying air. This results in significant loss of vitamin C. Furthermore, the rapid removal of moisture at high temperatures may subject ascorbic acid to localized thermal stress before it is fully encapsulated within the dried matrix. Guava (7) and gac fruit powders (21) have demonstrated similar loss of vitamin C, indicating that this nutrient is particularly susceptible to high-temperature drying conditions. Extended exposure to extreme dry air temperatures intensifies degradation through both aerobic and anaerobic pathways (22).

Conversely, non-enzymatic browning significantly increased from 0.128 – 0.231 AU with the rise in inlet and outlet temperature. Higher inlet and outlet temperatures intensified Maillard reaction kinetics between reducing sugars and amino acids. The observed quadratic effects indicate a non-linear increase in browning at higher temperature ranges, emphasizing the need for controlled thermal conditions. Guava powder and acai powder exhibit comparable enhancements in browning intensity with temperature, indicating that fruit powders rich in sugars are particularly prone to color modification during spray drying because of the Maillard process (5,6).

From a quality perspective, more browning is detrimental as it renders the final powder less fresh, less sensory pleasing and visually unappealing. Maillard reactions may result in the loss of nutrients through interactions with amino acids and other bioactive compounds. The results indicate a significant trade-off in spray-drying operations: higher inlet temperatures can enhance drying efficiency, although they accelerate the degradation of vitamin C and result in excessive darkening of the food. To optimize outcomes from spray-drying, it is essential to meticulously regulate the inlet temperature to preserve maximum nutrients while minimizing non-enzymatic browning. This will ensure that the final product is both nutritious and palatable.

Colour quality

The lightness (*L**) of the spray-dried powders decreased from 78.6–71.2 with an increase in input temperature. Simultaneously, the *a** and *b** values increased, indicating that the colours were becoming darker and more red and yellow. A reduced *L** value indicates an overall darkening of the product, whereas higher *a** and *b** values signify an intensification of red and yellow hues, respectively. These modifications are characteristic of the impact of heat on fruit-derived powders.

Comparable color trends have been noted in the spray drying of pink guava and mango powders , confirming that high inlet temperatures significantly influence colour attributes in matrices rich in carotenoids and polyphenols (7,17). The observed darkening can mostly be attributed to non-enzymatic Maillard browning, occurring when reducing sugars and amino acids interact at high temperatures to produce brown pigments and coloured intermediates in noni fruit powder (23). Simultaneously, thermal degradation and isomerization of carotenoids, together with the oxidation of polyphenolic compounds, alter the colour by diminishing pigment brilliance and modifying their chromatic properties (24).

Functional features

The augmentation in swelling power (from 4.21 – 6.34 g/g) and WAC, from 4.78 – 6.43 g/g, with the significant enhancement in wettability (from 28.4 – 16.2 sec) and hygroscopicity (18.2 g/100 g – 15.9 g/100 g) indicates an improvement in the functional quality of the spray-dried powders (Fig. 3, Table 2). The enhancements suggest that powders produced at increased temperature conditions exhibit improved hydration and reconstitution properties.

The enhanced functional performance mostly results from alterations in the structure of the powder particles occurring with an increase in outlet temperature. Higher outlet temperatures increased the particle exit temperature, promoting solidification of the powder matrix in a glassy state above its Tg. This rapid transition from a rubbery to glassy state favoured the formation of porous, low-density particles with improved capillary structure, facilitating rapid water penetration and reconstitution (22). The interaction between inlet and outlet temperatures suggests that inlet temperature determines primary particle formation, while outlet temperature governs final porosity and hydration. At higher temperatures, starch granules may undergo partial gelatinization and disintegration, thereby exposing more hydroxyl groups capable of forming hydrogen bonds with water molecules. These structural modifications enhance both the swelling capacity, hygroscopicity and WAC. Guava powders (6,7), kuini powder (25), strawberry powder (26), mango powders (17), have demonstrated comparable enhancements in hydration-related functional properties, indicating that fruit-based powders rich in starch and polysaccharides exhibit similar responses to raised drying temperatures. From the consumer's perspective, enhanced wettability is crucial as it influences immediate attributes, dispersion efficiency and overall product use. Powders that exhibit rapid wetting are more likely to be favoured by consumers.

Model reliability and optimization

The statistical models developed demonstrated significant adequacy and predictive capability, evidenced by high coefficients of determination ($R^2 > 0.92$) for all responses (Table 3). The statistics indicate that the fitted models accounted for over 92 % of the variance in the experimental results. The proximity of the predicted and experimental values along with the minimal dispersion around the parity line indicate that the regression equations are robust and reliable in describing the effects of spray-drying settings on powder quality characteristics (Fig. 4). The model's exceptional performance demonstrates that RSM is an effective approach for enhancing complex, multivariate spray-drying processes.

Comparable levels of model accuracy have been recorded in RSM-based optimization studies of pineapple (20) and guava powders (27), affirming the dependability and significance of this modelling approach throughout fruit drying systems. The high anticipated accuracy enables the identification of optimal processing parameters with minimal experimental trials.

Multi-response optimization criteria indicate that the optimal conditions for spray-drying custard apple powder are an inlet temperature of 175.2 °C and an exit temperature of 90 °C (Table 4). The powder generated under these circumstances exhibited low moisture content and no evidence of non-enzymatic browning, while it maintained a relatively high vitamin C retention (14.19 %) and had favorable functional attributes, including enhanced wettability and water absorption (28). These quality characteristics resemble those seen in the finest spray-dried guava and mango powders. This indicates that the selected conditions achieve an optimal balance between drying rate and nutritional and functional quality (29).

The validated models and optimized processing parameters indicate that meticulously controlled spray-drying conditions can yield custard apple powder that is stable, possesses favorable sensory attributes and reconstitutes effectively (30). This optimization framework serves as an effective foundation for large -scale production and product development, while minimizing quality degradation resulting from excessive heat exposure.

Industrial relevance

From an industrial perspective, purified custard apple powder necessitates specific criteria: low moisture content (< 7 %), stable water activity (~0.40), effective reconstitution (wettability < 20 sec) and substantial nutritional retention (~14 % vitamin C). All of these features are pertinent to the production of instant beverage mixes and nutraceuticals. Results demonstrate that regulated moderate inlet temperature spray drying (about 175 °C) combined with significant outlet air removal (90 °C) provides the ideal equilibrium among stability, sensory attributes and nutritional retention.

Conclusion

RSM successfully optimized spray drying of custard apple pulp using maltodextrin as a carrier agent. Inlet and outlet temperatures were found to significantly influence the nutritional and functional properties of the powder. The RSM models were robust ($R^2 > 0.92$) and accurately predicted the response as indicated by close agreement between experimental and predicted values. The best drying condition was 175.2 °C inlet temperature and 90 °C outlet temperature, which produced powders with low moisture and hygroscopicity, high retention of vitamin C, stable colour and desirable instant properties. Overall, the findings underline the industrial potential of custard apple powder as a functional ingredient in ready-to-drink beverages, nutraceuticals and value-added food products.

Acknowledgements

The authors gratefully acknowledge the support of the institutions, as well as the technical staff and instructors, for their assistance in conducting the experiments and performing data analyses.

Authors' contributions

S contributed to conceptualization, investigation, funding acquisition, methodology, formal analysis, data curation, software, visualization, validation, project administration and writing the original draft as well as review and editing. MK contributed to methodology, validation and project administration. KG and RTP provided supervision. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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