ACTA SCIENTIARUM POLONORUM
Acta Sci. Pol. Technol. Aliment. 24(3) 2025, 427–440
www.food.actapol.net pISSN 1644-0730 eISSN 1898-9594 http://doi.org/10.17306/J.AFS.001417

ORIGINAL PAPER

Received: 26.06.2025
Accepted: 21.07.2025

COMBINING CARRIER MATERIALS FOR SPRAY-DRYING ANTIOXIDANT EXTRACTS FROM PALMYRA PALM PEEL (*BORASSUS FLABELLIFER*): OPTIMIZATION USING RSM AND ANN-GA

Dao Van Thanh[1,3]✉, Ho Thi Ngan Ha[1,3], Nguyen Duy Tan[1,3], Nguyen Thi Ngoc Giang[2,3]

[1]Food Technology Department, Agriculture and Natural Resource Faculty, An Giang University
Ung Van Khiem, 18, Dong Xuyen Ward, Long Xuyen city, An Giang province, **Vietnam**
[2]Experimental-Practical Area, An Giang University
Ung Van Khiem, 18, Dong Xuyen Ward, Long Xuyen city, An Giang province, **Vietnam**
[3]Vietnam National University
Thu Duc, Ho Chi Minh City, 720325, **Vietnam**

ABSTRACT

Background. The spray-drying method is employed to produce value-added powder products from the extract of palmyra palm peel (*Borassus flabellifer*), an agricultural byproduct rich in antioxidants such as polyphenols, flavonoids, vitamin C, and carotenoids.

Material and methods. This study investigated the influence of two natural carriers – gum arabic (0.25–1%) and maltodextrin(5–12.5%) – on the retention of bioactive components in palm fruit husk extract. Two optimization strategies employed in parallel: response surface methodology (RSM) and artificial neural networks integrated with genetic algorithms (ANN-GA).

Results and discussion. Both carriers significantly enhanced the concentration of bioactive compounds in the spray-dried powder. The combination of maltodextrin and gum arabic synergistically improved the microencapsulation efficacy of antioxidants. The ANN-GA model demonstrated superior prediction accuracy over RSM, reducing the experimental error to approximately 1–2% compared to 5% with RSM. The optimal formulation – 6.53% maltodextrin and 0.44% gum arabic – yielded 14.09 mg TAE/100 g polyphenol, 0.0039 mg QE/100g flavonoid, 1.29 mg/100 g carotenoid, and 7.36 mg/100 g vitamin C.

Conclusion. This study highlights the importance of artificial intelligence models in optimizing food processing techniques and offers a promising approach for the valorization of nipa palm husks in functional food development.

Keywords: ANN-GA model, antioxidant, palmyra palm peel, RSM, spray-drying

INTRODUCTION

The palmyra palm (*Borassus flabellifer*) is a native tree commonly found in An Giang and other southern provinces of Vietnam. It is well known for its water, palm sugar and edible flesh (Thi Le et al., 2021). The ripe fruit features a vibrant orange-yellow pulp that is rich in micronutrients, particularly provitamin A (carotenoid) and vitamin C (ascorbic acid). In addition to sugar and minerals, studies have revealed that palm

✉dvthanh@agu.edu.vn, https://orcid.org/0000-0002-5877-8603

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fruit contains natural bioactive compounds such as flavonoids, polyphenols, tannins, and saponins, which are known for their antioxidant, anti-inflammatory, and antibacterial properties, contributing to overall health benefits (Huynh Thi Le et al., 2020). Despite this, the fruit shell, also known as the seed coat or the fibrous layer surrounding the seed, is often discarded as agricultural waste and remains underutilized. Recent studies have shown that ethanol extracts from palm peels contain high levels of phenolic compounds, particularly flavonoids and tannins, which exhibit strong antioxidant activity. Although palmyra palms are abundant in Vietnam, there has been limited research on the valorization of their peels (Truong, 2022). Proper extraction and processing of these antioxidant-rich peels could unlock their potential as functional food ingredients.

Spray drying is a widely adopted method for transforming liquid extracts into stable powdered products. It involves the use of carrier agents to microencapsulate bioactive compounds, protecting them from environmental stressors such as pH, temperature and light (Jiménez-González and Guerrero-Beltrán, 2021). This technique reduces moisture content, extends shelf life, and preserves the biological activity of sensitive ingredients. The choice of carrier (also known as a wall material) is critical to the success of microencapsulation, as it shields the active components during thermal processing. Current trends favor the use of food-safe, natural carriers, such as maltodextrin (a starch-derived polysaccharide) and gum arabic (acacia resin) (Kandasamy and Naveen, 2022). Numerous studies have demonstrated that maltodextrin and gum arabic, used either individually or in combination, can significantly improve the retention of antioxidants during spray drying (Ribeiro et al., 2020; Sukri et al., 2021). For example, when applied to chokeberry juice, these carriers enabled retention rates of bioactive compounds ranging from approximately 63% to over 97% (Bednarska and Janiszewska-Turak, 2020). These findings suggest that natural carrier combinations can effectively preserve polyphenols, flavonoids and other antioxidants in plant-derived materials.

In the field of food science, Response Surface Methodology (RSM) has long been a standard approach for experimental design and process optimization. RSM systematically evaluates how multiple input factors (e.g., carrier ratio, drying temperature, feed rate) affect output parameters (e.g., encapsulation efficiency, antioxidant content), using polynomial modeling to identify optimal conditions (Jalalizand and Goli, 2021). While effective for moderately complex problems, RSM has limitations when handling nonlinear relationships or when optimal conditions fall outside the predefined parameter space (Jalalizand and Goli, 2021). Recently, advances in artificial intelligence have introduced a promising alternative: artificial neural networks integrated with genetic algorithms (ANN-GA). This hybrid technique enables the modeling of complex, nonlinear systems by learning variable relationships and leveraging genetic algorithms to search for global optima (Loan et al., 2024; 2025; Luangsakul et al., 2025; Thuy et al., 2024a; 2024b; 2025; Ibrahim et al., 2022). Comparative studies have shown that ANN-GA outperforms RSM in accuracy and optimization outcomes, particularly in applications such as extracting bioactive compounds or maximizing antioxidant retention (Luangsakul et al., 2025; Thuy et al., 2024; 2025).

Given this context, the present study was conducted to valorize the underutilized palmyra palm peel from An Giang province by converting it into an antioxidant-rich powder via spray drying. For the first time, this research simultaneously applies both RSM and ANN-GA optimization strategies to identify the optimal mixing ratio of maltodextrin and gum arabic as carriers. This dual-method comparison not only evaluates the effectiveness of traditional AI-based approaches under identical conditions but also explores the novel use of combined natural carriers for encapsulating palm peel extract. To the best of our knowledge, no prior studies have investigated the microencapsulation of palm peel extract or the combined use of these two carriers for this purpose. The findings are expected to contribute valuable insights into the application of natural carrier combinations in microencapsulation, while offering a data-driven comparison between RSM and ANN-GA methodologies for optimizing food spray drying processes.

MATERIALS AND METHODS

Sample preparation

Ripe palm fruits were sourced from Tri Ton district, An Giang, Vietnam. Fruits of uniform size and moderate ripeness were selected to ensure consistency. The fruits were thoroughly washed with clean water

Fig. 1. Extraction procedure

to remove any surface dirt and impurities. Following cleaning, the outer shell of the ripe palm fruit was carefully removed. The processed fruit was then manually rubbed to collect the palm peel extract, as illustrated in Figure 1. The extract was prepared using water as a solvent, with the addition of 2% pectinase enzyme. The enzyme extraction was carried out for 45 min to facilitate the breakdown of the fibrous matrix, thereby enhancing the efficiency of ripe palm fruit flesh recovery. The resulting liquid was filtered through a sieve to remove solid residues. The filtration step aimed to eliminate pulp, simplify subsequent processing, and improve the sensory quality of the final product.

Experimental setup

The extract obtained from ripe palm peel, after selecting optimal extraction parameters using pectinase enzyme, was mixed with maltodextrin (5–12.5%) and gum arabic (1.25–5%). Each formulation used 500 mL of extract and was spray-dried at an inlet air temperature of 150°C with an input flow rate of 3 mL/min using a Yamato AD311 (Japan). The resulting powder was collected, stored in a sealed glass jar, and analyzed for the required parameters.

Determination of antioxidant properties

Vitamin C concentration (%) was determined following the method described by Sharaa and Mussa (2019). Total phenolic content (mg TAE/100 g DM) was measured using the protocol developed by Martial-Didier et al. (2017). Flavonoid content (mg QE/100 g DM) was quantified according to the method of Andrade et al. (2021). Carotenoid concentration (mg/100 g dry matter) was assessed using a spectrophotometric technique based on the work of Alamu et al. (2021).

Data analysis

The RSM model, employing multi-level regression analysis, was used to analyze and graph the data. The ANN model was trained by dividing the dataset into training (70%), testing (15%), and validation (15%) subsets. The ANN-GA optimization followed the parameters established by Luangsakul et al. (2025) to determine the optimal processing conditions.

RESULTS AND DISCUSSION

RSM model for antioxidant properties of spray-dried palmyra palm peel powder

The regression models developed for the four antioxidant indicators – polyphenols, flavonoids, vitamin C, and carotenoids – demonstrated a relatively high overall fit to the experimental data, as shown by their statistical indices. Specifically, the polyphenol model achieved an R^2 = 86.99% and adjusted R^2 = 86.28%, indicating that approximately 87% of the variance in

the data was explained by the model (Table 1). This represents a strong model fit. Similarly, the total flavonoid content (TFC) model had an R^2 = 80.95%, slightly lower than the polyphenol model but still high. The vitamin C model showed a comparable R^2 to the TFC model, explaining around 80% of the variation – still acceptable for empirical studies. Among these models, the carotenoid model showed the best fit, with an R^2 = 90.38%, indicating that over 90% of the variance in carotenoid content was accounted for. All models passed the lack-of-fit test, with *p*-values > 0.05, meaning that there was no statistically significant evidence at the 5% level to suggest that the chosen quadratic regression models did not adequately fit the experimental data. In summary, all four regression models showed a good overall fit (R^2 reached ~80% or more). However, their predictive reliability varied. The carotenoid model had the highest R^2 (almost 90%), indicating the strongest predictive performance. The polyphenol model also showed strong predictive power with an R^2 of approximately 87%. In contrast, the flavonoid and vitamin C models had slightly lower R^2 values (around 80–81%), suggesting somewhat weaker explanatory power. While values ~80% are generally acceptable in empirical modeling (Kothakota et al., 2021), these two models were clearly less reliable than the polyphenols and carotenoids models.

The regression coefficients provided insight into the magnitude and direction of the effects of each independent variable – maltodextrin (A) and gum arabic (B) – as well as their interaction on the antioxidant indicators (Equations 1–4). The linear coefficients for both maltodextrin (A) and gum arabic (B) were positive in all models, indicating that increasing the concentration of either carrier (within the tested range) led to increased levels of polyphenols, flavonoids, vitamin C and carotenoids in the spray-dried powder. In other words, the addition of carriers improved the retention of antioxidant compounds, likely by protecting them during the drying process. This finding aligns with the results reported by Akbarbaglu et al. (2021). When comparing the two carriers, gum arabic generally had a stronger effect than maltodextrin. For example, in the polyphenol model, the coefficient for maltodextrin was +0.43, while that for gum arabic was +0.71. Similar trends were observed in the flavonoid, vitamin C,

Table 1. ANOVA analysis and regression model fit for TPC, TFC, vitamin C, and carotenoid content

Source	TPC			TFC			Vitamin C			Carotenoid		
	MS	F-Ratio	*p*-value	MS ($\times 10^{-6}$)	F-Ratio	*p*-value	MS	F-Ratio	*p*-value	MS	F-Ratio	*p*-value
A	434.46	398.35	0.000	9.23	685.97	0.0000	64.82	1130.15	0.0000	6.73	4756.94	0.0000
B	29.13	26.71	0.0000	2.30	171.06	0.0000	14.15	246.71	0.0000	0.31	224.55	0.0000
A^2	117.26	107.52	0.0000	9.08	675.22	0.0000	15.47	269.70	0.0000	0.84	594.47	0.0000
AB	4.56	4.18	0.0441	1.01	75.64	0.0000	1.978	34.49	0.0000	0.06	44.32	0.0000
B^2	14.20	13.02	0.0005	1.35	100.54	0.0000	11.38	198.42	0.0000	0.31	217.58	0.0000
Lack-of-fit			0.0546			0.0567			0.0910			0.1200
R^2		86.99%			80.95%			80.01%			90.37%	
R^2 adjusted		86.28%			80.01%			78.89%			89.84%	

MS – Mean square; TPC – total polyphenol content; TFC – total flavonoid content; A – maltodextrin content (%); B – gum arabic content (%).

$$\text{Polyphenol content} = 5.58 + 0.43A + 0.71B - 0.007A^2 + 0.01AB - 0.25B^2 \quad (1)$$

$$\text{Flavonoid content} = 0.0013 + 0.000134A + 0.000149B - 0.000002A^2 + 0.0000053AB - 0.000078B^2 \quad (2)$$

$$\text{Vitamin C content} = 3.98 + 0.143A + 0.82B - 0.00257A^2 + 0.007AB - 0.226B^2 \quad (3)$$

$$\text{Carotenoid content} = 0.74 + 0.03A + 0.135B - 0.0006A^2 + 0.0013AB - 0.037B^2 \quad (4)$$

and carotenoid models, where the coefficient value for B consistently exceeded that for A. This suggests that gum arabic offers better protective capabilities per unit mass. A possible explanation is that gum arabic forms a stable and compatible film with the extract, reducing evaporation and oxidation of active compounds, while maltodextrin primarily acts as a non-sticky filler to increase dry matter content (Iesa et al., 2023; Mahdi et al., 2020). Furthermore, the quadratic coefficients (A^2 and B^2) were negative and statistically significant in all models ($p < 0.01$). These negative coefficients indicate a non-linear effect: increasing carrier concentrations initially improves antioxidant retention, but beyond a certain point, further increases lead to a decline in active compound content. This reflects the existence of an optimal carrier concentration, after which adverse effects such as dilution or processing inefficiencies may occur. Notably, the absolute value of the B^2 coefficient (gum arabic) was significantly larger than that of A^2 (maltodextrin) in all models. For example, in the vitamin C model: $A^2 = –0.00257$, while $B^2 = –0.22647$ (nearly 100 times larger). A similar trend was observed in the flavonoid model, where B^2 was dozens of times larger than A^2, indicating that excessive gum arabic had a far more detrimental effect than excessive maltodextrin. This finding is supported by Iesa et al. (2023), who reported that a MD:GA ratio of 3:7 (i.e., high gum arabic content) resulted in the lowest antioxidant activity, while a balanced ratio of 1:1 (MD:GA = 5:5) provided the highest polyphenol retention (about 68% activity). These results support the conclusion that using excessive gum arabic reduces the protective effect, likely due to the dilution of active compounds and interference with microcapsule formation mechanisms (Wang et al., 2023). Thus, the negative quadratic coefficients confirm a peak-maximized response, indicating that both carriers have optimal usage levels, and that overdosing, particularly of gum arabic, should be avoided. A positive *AB* coefficient means that the combined effect of the two carriers is greater than the sum of their individual effects. Specifically, when maltodextrin and gum arabic were increased simultaneously, the resulting antioxidant content was higher than when each carrier was increased independently. For example, the polyphenol model had an *AB* coefficient of +0.0111, and the carotenoid model had an *AB* of +0.0013058 – both positive and significant. This confirms that the two carriers complement each other in preserving polyphenols and carotenoids during spray drying. Mechanistically, this synergy may be due to their differing but complementary functions: maltodextrin helps increase total solids and reduce viscosity, while gum arabic forms a strong coating around the droplets, improving microencapsulation efficiency (Di Battista et al., 2015; Rahman Mazumder and Ranganathan, 2020). By combining maltodextrin with an appropriate amount of gum arabic, a more stable powder structure is formed, enhancing active compound retention compared to using either carrier alone. This synergistic effect also explains why the models predicted relatively high optimal levels for each carrier when the other was present. Experimental results confirmed that the combinations of both carriers yielded significantly higher levels of polyphenols, flavonoids, vitamin C, and carotenoids than when using either carrier alone, demonstrating the benefits of positive *AB* interactions. In conclusion, the regression coefficients accurately reflect the nature and extent of the factors' influence.

Effect of carrier agents on the antioxidant compounds of spray-dried palmyra palm peel powder

Total polyphenol content

The positive first-order regression coefficients of both maltodextrin (0.432) and gum arabic (0.705), as previously discussed, indicate that increasing the concentration of these carriers from low levels significantly enhanced the polyphenol content in the spray-dried powder (Fig. 2). This suggests that the addition of carriers helps reduce the loss of polyphenols during drying, possibly due to their encapsulating effect, which protects polyphenols from high temperatures and oxidative degradation. In contrast, the negative second-order coefficients (especially gum arabic: –0.253) imply that at higher concentrations, the polyphenol content began to decrease, as also seen in Figure 2. This trend highlights the existence of an optimum carrier concentration: excessive carrier levels may cause dilution effects, lowering the proportion of polyphenols per unit of dry powder. Additionally, increased viscosity at higher carrier concentrations may prolong drying time, leading to greater degradation of

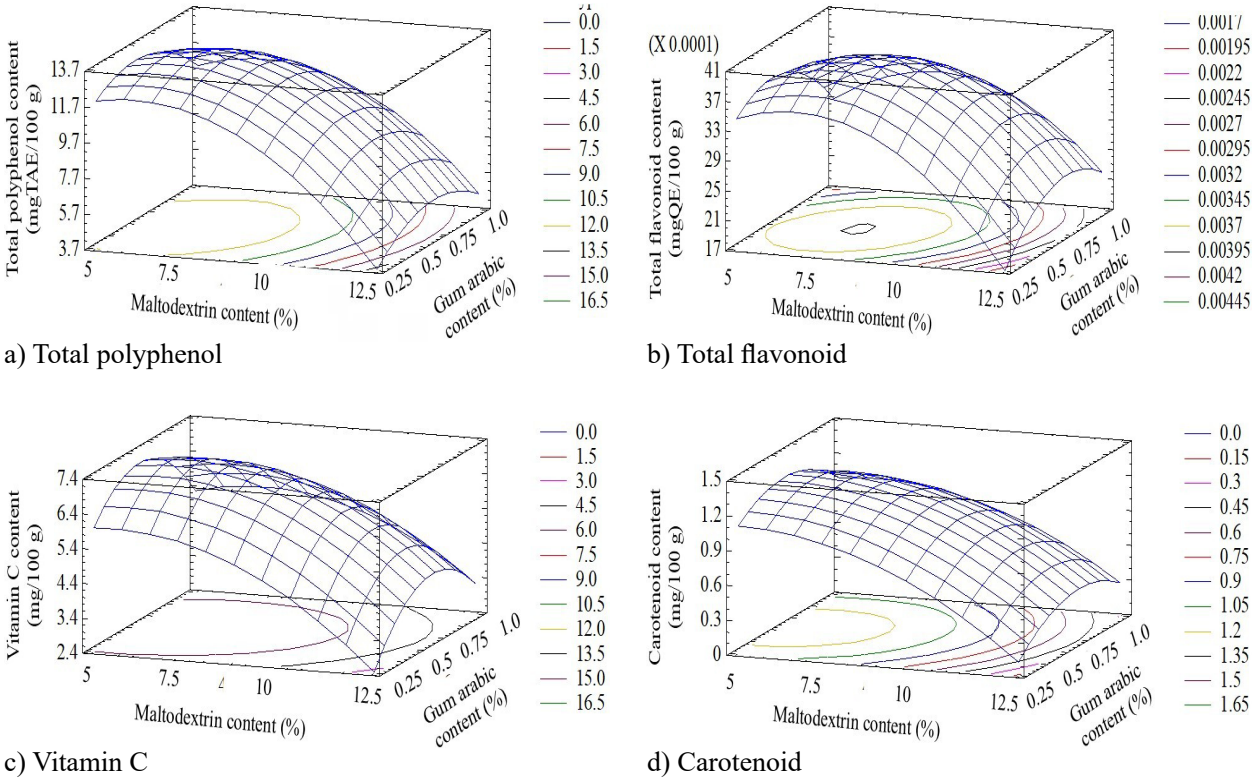

Fig. 2. Effects of maltodextrin and gum arabic content on total polyphenol content (a), total flavonoid content (b), vitamin C (c) and carotenoids of spray-dried palmyra palm peel powder

polyphenols (Nordin et al., 2024; Thuy et al., 2025). Indeed, the optimal model predicted a maximum polyphenol content of 13.29 (mg GAE/g) at ~6.5% maltodextrin and ~0.4% gum arabic – relatively low concentrations within the tested range. At higher concentrations of maltodextrin (~12.5%) or gum arabic (~1%), the model predicted a decline in polyphenol content, consistent with the negative regression coefficients mentioned above. When added to the extract, maltodextrin and gum arabic form a matrix that encapsulates polyphenol molecules, thereby reducing their exposure to heat and oxygen during spray drying (Laureanti et al., 2023; Parhizkary et al., 2025). Maltodextrin is widely used as a carrier due to its low cost, high solubility at high solid concentrations, and ability to increase the glass transition temperature of the dried product. It also reduces stickiness and helps retain volatile compounds (Xu et al., 2024). Therefore, an adequate level of maltodextrin can quickly form a solid shell around drying droplets, effectively trapping polyphenols and preventing oxidation. Although gum arabic is used at lower concentrations than maltodextrin, it acts as an excellent emulsifying and film-forming agent, helping to uniformly coat polyphenols within the microcapsules (Rahman Mazumder and Ranganathan, 2020). However, at excessively high levels, gum arabic significantly increases solution viscosity (Keivanfard et al., 2022), which can prolong drying time or cause clogging, resulting in greater thermal degradation of polyphenols. Moreover, an excess of carrier can reduce the concentration of polyphenols per unit mass due to dilution effects. Similar experimental observations have been reported: with increasing maltodextrin content, fewer polyphenols were found on the surface of microcapsules, suggesting more were retained in the core, thus better protected from oxidation. Ćujić-Nikolić et al. (2018) achieved approximately 84% anthocyanin

retention after spray drying Aronia juice using gum arabic as a carrier. In another study comparing carriers for polyphenols encapsulation from coffee juice, maltodextrin proved to be more effective than gum arabic, yielding higher polyphenol and flavonoid content when spray dried (Buljeta et al., 2022). Overall, the results align with microencapsulation theory: polysaccharide-based carriers provide a protective matrix that shields polyphenols from degradation (e.g., heat and oxygen). However, it is essential to optimize carrier concentrations to balance protection efficiency and avoid diluting the active compound in the final product (Buljeta et al., 2022).

Total flavonoid content

The effect of maltodextrin and gum arabic on flavonoid content followed a similar trend to that observed for polyphenols. The regression equation for flavonoids included positive first-order coefficients (approximately 1.34×10^{-4} for maltodextrin and ~1.49×10^{-4} for gum arabic), while the second-order coefficients were negative, particularly -7.81×10^{-5} for gum arabic. This indicates that increasing carrier concentrations from low to moderate levels enhanced flavonoid recovery, reaching a maximum at an optimal point, after which further increases led to a decline in flavonoid content. Specifically, the model predicted a maximum flavonoid content of approximately 0.00397 mg QE/100 g at ~7.4% maltodextrin and ~0.44% gum arabic. This optimum point was slightly skewed towards a higher maltodextrin content compared to the polyphenol model, suggesting that flavonoids may require a slightly higher maltodextrin content for optimal protection. ANOVA results confirmed that the effects of both carriers on flavonoid content were statistically significant ($p < 0.05$). This implies that flavonoid content was more sensitive to variations in maltodextrin ratio, though gum arabic also played a crucial supporting role. Mechanistically, the action of the carriers on flavonoids mirrors their effects on polyphenols, as flavonoids are a subclass of polyphenols and share similar chemical properties. Maltodextrin forms a rigid structural matrix that rapidly encapsulates flavonoid molecules, shielding them from evaporation and oxidation. Meanwhile, gum arabic contributes to the formation of a stable, uniform coating and aids in the even dispersion of flavonoids within the microcapsules (Iesa et al., 2023). Therefore, an optimized maltodextrin–gum arabic combination produced the highest flavonoid retention after spray drying. Similar protective effects have been reported in other studies using polysaccharide carriers. For example, Gomes et al. (2018) observed that the polyphenol and flavonoid content in spray-dried papaya powder was even higher than that of freeze-dried papaya, due to the rapid encapsulation provided by the spray-drying process. However, if the carrier concentrations were suboptimal – especially too high – flavonoid content decreased, likely due to dilution effects. Our results showed that using more than 8% maltodextrin or 0.6–1% gum arabic significantly reduced flavonoid content. This finding supports the principle that the carrier amount must be sufficient to offer protection but not so excessive that it dilutes the active compounds. Buljeta et al. (2022) also observed that flavonoid and polyphenol losses during spray drying could reach up to 73% in the absence of proper encapsulation, while the use of maltodextrin as a carrier markedly reduced these losses. Therefore, optimizing the carrier ratio is critical to maintaining high flavonoid content after spray drying.

Vitamin C content

The vitamin C (ascorbic acid) content obtained after spray drying was strongly influenced by both maltodextrin and gum arabic. According to the regression model, the first-order coefficient of gum arabic (0.8235) was significantly larger than that for maltodextrin (0.1433). This indicates that in the lower concentration range, increasing gum arabic led to a more substantial increase in vitamin C content than increasing maltodextrin. This may be because vitamin C is highly sensitive to heat and oxygen, and even a small amount of gum arabic – known for its excellent oxygen barrier properties – can immediately offer strong protection (Al-Maqtari et al., 2021). In contrast, while maltodextrin also provided protection, its effect per unit concentration was less pronounced in the low–ratio range. However, similar to other antioxidant compounds, the negative quadratic coefficient of gum arabic (–0.2265) suggests that excessive amounts of gum arabic reduce vitamin C retention. ANOVA results confirmed that both carriers had highly significant effects on vitamin C content ($p < 0.0001$). Interestingly, despite

gum arabic having a higher linear coefficient, maltodextrin contributed more overall to the variability to vitamin C retention across the tested range. This is because maltodextrin had a much broader concentration range (5–12.5%) compared to gum arabic (0.25–1%), making its influence more dominant in explaining the variation. The model predicted a maximum vitamin C content of 7.17 mg/100 g at 31.2% maltodextrin and 2.32% gum arabic. Beyond this point, particularly as gum arabic approached 1%, the vitamin C content decreased markedly. This supports the observation that the optimal gum arabic concentration for preserving vitamin C lies within the low–to–medium range. Vitamin C is particularly susceptible to thermal and oxidative degradation, making microencapsulation with suitable carriers essential to preserve its content during spray drying (Hu et al., 2022). Maltodextrin has proven to be an effective stabilizer for vitamin C, as it creates a chemically inert sugar-based environment around the ascorbic molecule, limiting its interactions with oxidizing agents (Phan et al., 2021). In addition, maltodextrin lowers water activity and promotes rapid shell formation, effectively isolating vitamin C from exposure to hot air (Ozcelik and Kulozik, 2023). Gum arabic contributes by forming a thicker, more spatially structured polymer film, which slows oxygen diffusion into the microcapsules containing vitamin C (Atgié et al., 2019). The combination of maltodextrin and gum arabic in the right proportions, therefore, offers enhanced protective efficiency. Research by Delaporte et al. (2024) showed that increasing the carrier-to-active ingredient ratio significantly improved the stability of microencapsulated vitamin C. Conversely, insufficient carrier levels led to considerable vitamin C loss. In fact, spray drying of fruit juice without any carrier resulted in almost complete degradation of vitamin C. When maltodextrin was added at moderate levels, the vitamin C content in the resulting powder increased significantly, confirming the carrier's protective role. However, similar to polyphenols, excessive use can dilute the vitamin C concentration in the final product or result in a matrix that is too thick, which can hinder the dissolution or release of vitamin C during use. Therefore, optimizing the ratio of maltodextrin to gum arabic is essential to achieve a balance between protection and maintaining the highest possible vitamin C content.

Carotenoid content

Unlike polyphenols and vitamin C, carotenoids are hydrophobic compounds, so their degradation mechanisms and carrier requirements differ (Rezagholizade-shirvan et al., 2024). The regression model showed that both maltodextrin and gum arabic positively influenced the carotenoid content, and the positive interaction coefficient suggested that their combination enhanced carotenoid retention more effectively than when used individually. Notably, the relatively high gum arabic coefficient indicated that, at low concentrations, even a small addition significantly increased carotenoid content. This is consistent with gum arabic's emulsifying role, which helps disperse oil-soluble carotenoids into the aqueous phase before drying. However, as with other bioactive compounds, the negative quadratic coefficients – particularly for gum arabic (–0.0373) – demonstrated that excessive carrier use led to a decline in carotenoid content. According to ANOVA results, maltodextrin had the strongest influence on carotenoid retention, with an extremely high F-ratio (4756.94), approximately 21 times greater than that of gum arabic (224.55). This suggests that maltodextrin plays a dominant role in forming a stable powder structure. When maltodextrin levels are too low, most of the carotenoids either stick to the equipment or are oxidized during drying, resulting in very low recovery (Ozcelik and Kulozik, 2023). In contrast, increasing maltodextrin within the optimal range significantly improves carotenoid recovery. The model predicted a maximum carotenoid content of 1.27 mg/100 g at approximately 6.4–6.6% maltodextrin and 0.44% gum arabic. Beyond these concentrations – particularly above 12–12.5% maltodextrin or near 1% gum arabic – carotenoid content declined, mainly due to dilution effects, previously discussed. These findings align with established principles of carotenoid microencapsulation. Because carotenoids are water-insoluble, an effective emulsifying agent is required to create a stable emulsion prior to drying. Gum arabic, a well-known natural emulsifier, is frequently used in combination with maltodextrin to microencapsulate hydrophobic compounds such as essential oils, vitamin A, and carotenoids (Henao-Ardila et al., 2024). In this study, even small amounts of gum arabic facilitated the uniform dispersion of carotenoids

in the aqueous phase, preventing oil droplet coalescence and reducing carotenoid losses due to adhesion. Meanwhile, maltodextrin played a critical role in forming solid particle structures and accelerating the drying process, effectively "locking" fat droplets containing carotenoids inside the capsule. The poor emulsification capacity of maltodextrin is offset by gum arabic, while maltodextrin compensates for gum arabic's low glass transition temperature and sticky nature by promoting faster solid shell formation (Iesa et al., 2023). Thus, the combined use of maltodextrin and gum arabic at an appropriate ratio offers optimal protection for carotenoids during spray drying. González-Peña et al. (2021) reported that using a total carrier concentration of 10% (w/v) of maltodextrin and gum arabic significantly reduced carotenoid losses compared to a 5% concentration in microencapsulation of carotenoids from mamey fruit and carrots. Furthermore, the microencapsulated carotenoids demonstrated improved stability during storage. Carotenoid powders coated with MD–GA showed almost no loss of antioxidant activity after 3 months of dark storage at 25°C. In contrast, carotenoids without protective carriers rapidly degraded under heat and oxygen, resulting in discoloration and loss of activity. In summary, polysaccharide-based carriers such as maltodextrin and gum arabic play complementary roles in carotenoid microencapsulation. Maltodextrin provides structural integrity and accelerates drying, while gum arabic contributes emulsification and oxygen barrier functions. Together, they optimize the carotenoid retention in spray-dried products.

Comparison between multi-objective optimization by RSM and ANN-GA

The multi-objective optimization results obtained utilizing the RSM method indicated that the optimal spray drying conditions for the palm bark extract were 6.55% maltodextrin and 0.45% gum arabic (Fig. 3). Under these conditions, the resulting product exhibited a total phenolic content (TPC), total flavonoid content (TFC), carotenoid content, and vitamin C content of 13.28 mg TAE/100 g, 0.0039 mg QE/100 g, 1.27 mg/100 g, and 7.16 mg/100 g, respectively. The ANN model, trained under the parameters described in the Methods section, demonstrated high predictive accuracy, with an R value consistently exceeding 0.99 (Fig. 4). The application of the ANN model in combination with GA optimization indicated optimal spray drying conditions of 6.53% maltodextrin and 0.44% gum arabic. These results closely aligned with those predicted by the RSM model. Under the optimized conditions predicted by the ANN-GA model, the estimated contents of TPC, TFC, carotenoids, and vitamin C were 14.12 mg TAE/100 g, 0.0041 mg QE/100 g, 1.29 mg/100 g, and 7.34 mg/100 g, respectively. The observed values exceeded those anticipated by the RSM method. In practical application, the ANN-GA model produced results that closely aligned with predicted values, whereas the RSM model exhibited a deviation of approximately 5% in predicting the quality of the spray-dried powder (Table 2). These findings are consistent with previous studies, which also reported that ANN-GA offer higher predictive accuracy compared to the RSM model (Luangsakul et al., 2025; Thuy et al., 2024a; b).

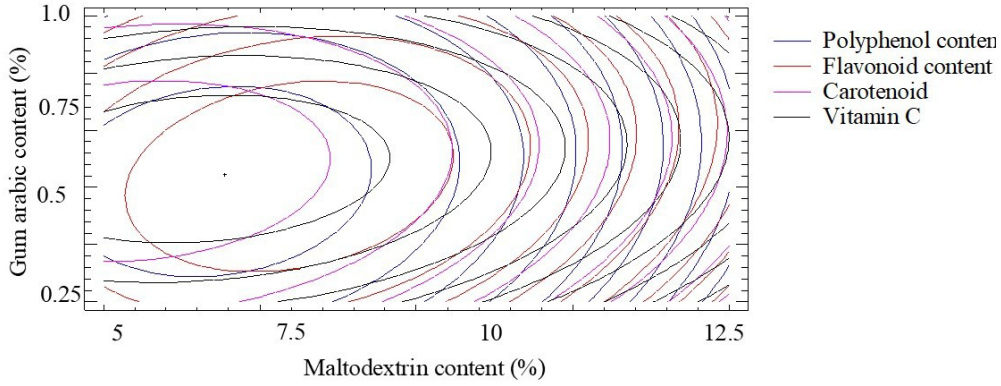

Fig. 3. Overlay contour plot of multi-objective optimization by RSM

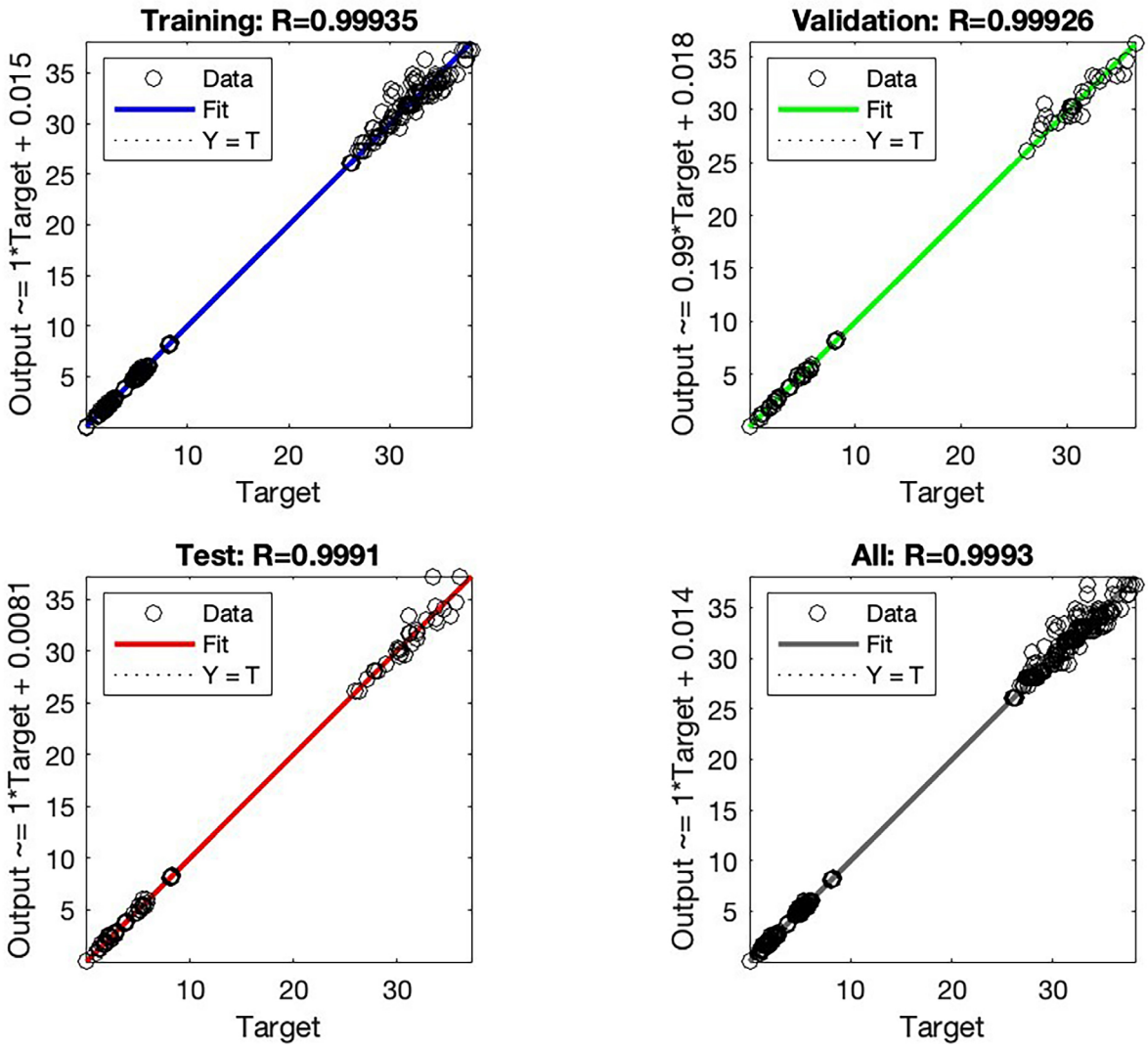

Fig. 4. Regression plot of the ANN model

Table 2. Comparison of prediction capacity between RSM and ANN-GA model

Model	Conditions	Predicted values (per 100 g)				Actual values			
		TPC mg TAE	TFC mg QE	Caroteinoid mg	Vitamin C mg	TPC mg TAE	TFC mg QE	Caroteinoid mg	Vitamin C mg
RSM	6.55% maltodextrin and 0.45% gum arabic	13.28	0.0039	1.27	7.16	12.54 ±0.07	0.0037 ±0.0000	1.27 ±0.02	7.03 ±0.12
ANN-GA	6.53% maltodextrin and 0.44% gum arabic	14.12	0.0041	1.29	7.34	14.09 ±0.02	0.0039 ±0.0004	1.29 ±0.01	7.36 ±0.04

CONCLUSIONS

The formulation of the carrier components – maltodextrin and gum arabic – significantly influences the nutritional profile of the spray-dried powder, particularly with respect to bioactive compound retention. The results clearly demonstrate that the concentration of these compounds is markedly affected by the amount of carrier used, as illustrated in the graphs generated by the RSM model. Both the RSM and ANN-GA models successfully identified optimal carrier formulations based on predictive modeling. However, the findings indicate that the ANN-GA model outperforms RSM in predicting optimal blending conditions and antioxidant content. These results offer a strong foundation for the application of palm fruit peel extract in value-added food processing, contributing to increased economic value and promoting sustainable agriculture practices. Future research should focus on scaling up for industrial production and exploring commercialization pathways for products with the highest nutritional and sensory value.

ACKNOWLEDGEMENTS

This research was funded by Vietnam National University Ho Chi Minh City (VNU-HCM) under Grant No. C2024-16-08.

DECLARATIONS

Data statement

All data supporting this study has been included in this manuscript.

Ethical Approval

Not applicable.

Competing Interests

The authors declare that they have no conflicts of interest.

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