Journal of Health and Nutrition Research
Vol. 4, No. 3, 2025, pg. 1036-1047, https://doi.org/10.56303/jhnresearch.v4i3.586
Journal homepage: https://journalmpci.com/index.php/jhnr/index

e-ISSN: **2829-9760**

Effect of Freeze-Drying, Spray-Drying, and Foam-Mat-Drying Encapsulation Techniques on Vitamin C Level in Fruit Powder: A Scoping Review

Durotul Baruroh[1], Yuliana Heri Suselo[1234*], Ratna Kusumawati[34], Dono Indarto[1234]

[1] Master Program of Nutrition Sciences, Universitas Sebelas Maret, Surakarta, Indonesia
[2] Biomedical Laboratory, Universitas Sebelas Maret, Surakarta, Indonesia
[3] Department of Physiology, Universitas Sebelas Maret, Surakarta, Indonesia
[4] Tropical Herbal Medicine, Universitas Sebelas Maret, Surakarta, Indonesia

Corresponding Author Email: yulianaheri@staff.uns.ac.id

SYSTEMATIC REVIEW

Submitted: 15 July 2025

Accepted: 24 September 2025

Keywords:
Encapsulation, Freeze Drying, Spray Drying, Foam-Mat Drying, Vitamin C, Fruit Powder

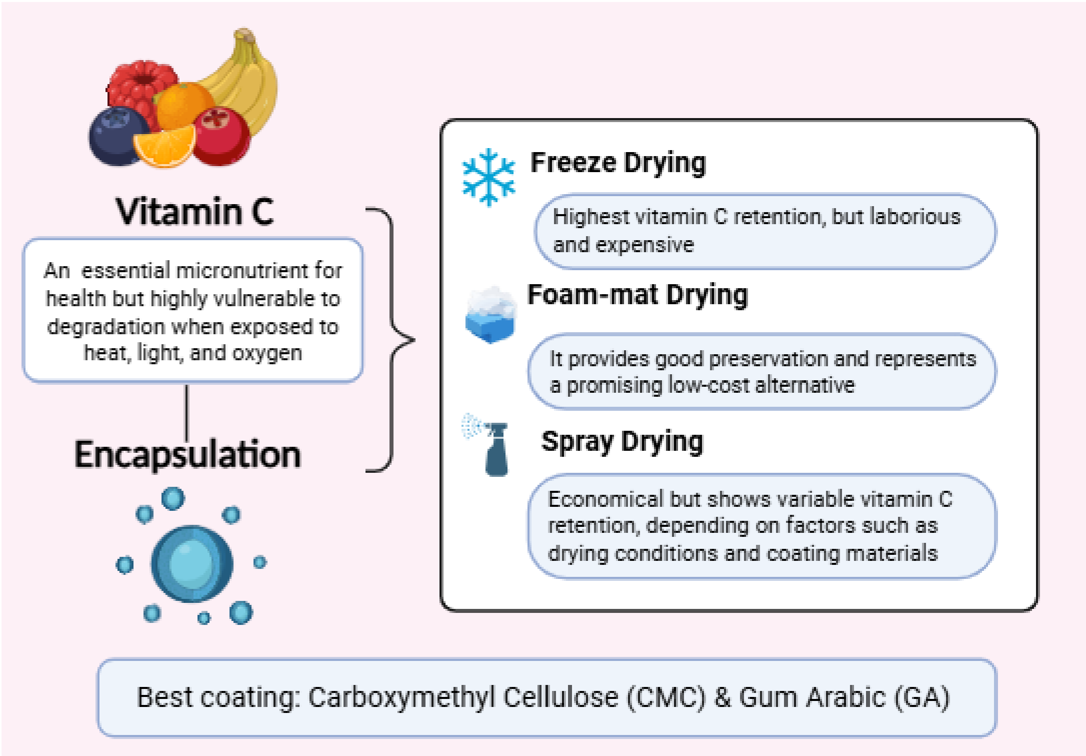
ABSTRACT

Vitamin C is an essential micronutrient with important antioxidant and physiological roles. However, it is highly unstable during processing due to its sensitivity to heat, oxygen, and light. This scoping review mapped evidence on drying-based encapsulation techniques: freeze drying, spray drying, and foam-mat drying. It examines their effect on the vitamin C level in fruit powder. A systematic search was conducted in PubMed, ScienceDirect, Springer, MDPI, and Google Scholar for studies published between 2015 and 2025. The search followed the PRISMA-ScR framework. Seven studies met the criteria and covered acerola, camu-camu, banana, açaí, papaya, satsuma mandarin, orange peel, and mulberry. The findings show that freeze-drying was consistently the most effective technique for retaining vitamin C levels. Some studies even reported an increase in vitamin C levels, possibly due to the breakdown of the fruit matrix, which made the nutrient more available. During Spray drying, low retention values (11%) were obtained in banana paste, and almost total retention (99%) was achieved in camu-camu pulp. The retention of mulberry juice during optimized foam-mat drying amounted to a maximum level of 90%. Coating materials, such as gum Arabic (GA) and carboxymethyl cellulose (CMC), provided better stability in vitamin C levels. However, there are some gaps regarding encapsulation efficiency, degradation kinetics, and particular mechanisms of the matrix that could clarify retention rates beyond 100%. Thus, future studies should focus on these parameters for the refinement of scalable yet low-cost drying strategies of functional fruit powders.

Key Messages:

- Freeze-drying most effectively maintains vitamin C levels, and optimized spray and foam-mat drying can also provide high retention under specific conditions.
- The use of coating materials is also significant in maintaining vitamin C level, where gum Arabic and carboxymethyl cellulose are effective encapsulants.

GRAPHICAL ABSTRACT



INTRODUCTION

Vitamin C, also known as L-ascorbic acid, is one of the most important and beneficial nutrients for health. Vitamin C has numerous benefits, including its high antioxidant levels, which can help protect the body's cells from damage caused by free radicals. Additionally, it serves as an important cofactor in many enzymes involved in tissue formation and hormone synthesis (1). Rich sources of vitamin C include fruits (such as oranges, strawberries, guava, and tomatoes) as well as green and cruciferous vegetables like broccoli, cabbage, and peppers (1). Vitamin C breaks down easily when exposed to heat, light, and oxygen, which also makes it difficult to maintain stability and limits the shelf life of products high in vitamin C (2,3).

Processing fruit into a powder form is one option for extending shelf life and making it easier for consumers to use. The transformation of liquids into powder can be achieved through various drying techniques, such as freeze drying, spray drying, and foam-mat drying (4–7). These drying techniques are considered drying-based encapsulation techniques when coating materials are used. Encapsulation is a process of coating a material with another material to protect a substance that is sensitive to the environment and others (8). By sublimating water in its solid state, freeze-drying effectively halts processes that cause things to break down and microbial activity, as there is no liquid water (9). Each technique has its own unique approach and yields distinct results when it comes to preserving sensitive nutrients during the drying process.

Vitamin C degrades at high temperatures, causing nutrient loss (10). Drying encapsulation processes also result in some degradation, emphasizing the need for better protection (11,12). Previous studies have shown that freeze-drying is more effective in preserving vitamin C than other traditional methods. However, concerns remain regarding its feasibility and cost (13). In spray drying, it was reported that increasing the inlet air temperature improved vitamin retention, whereas reducing the feed rate decreased encapsulation efficiency and affected product quality parameters (14). These differences underscore the need for further research to optimize drying techniques for preserving nutrients.

Despite these findings, comparative data regarding the efficiency of drying-based encapsulation techniques are limited. While freeze-drying can be better in some research, spray-drying could be less

https://doi.org/10.56303/jhnresearch.v4i3.586

expensive (15,16). Foam-mat drying is a new technique that combines drying and encapsulation, potentially leading to enhanced preservation of bioactive compounds (17,18). The process involves whipping liquid with foam agents to form a stable foam, which is then dried in warm air (19). The foam structure improves surface area, increasing moisture removal and potentially reducing drying time, temperature, and cost (20). Results on the effectiveness of every technique for vitamin C preservation are conflicting. The current review specifically evaluates which drying-based encapsulation process best retains vitamin C in powders and fruits.

This review critically examines which drying-based encapsulation technique—freeze-drying, spray-drying, or foam-mat drying—most effectively preserves vitamin C levels in fruit powders. By focusing on comparative performance and stability factors, this analysis aims to provide clear guidance for improving fruit processing techniques and addressing gaps in current research. Maximizing vitamin C retention is crucial for enhancing the nutritional value and shelf life of dried fruits, thereby supporting food quality and public health. This review delivers targeted insights to guide the food industry in selecting optimal preservation strategies.

METHODS

Study Design

This study synthesizes previous research to provide a comprehensive overview of how various techniques influence vitamin C levels, identify key factors affecting nutrient stability, and highlight areas that require further investigation. This study followed a modified scoping review procedure, as outlined in Arksey and O'Malley (Figure 1), and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist (21,22).

The main question this review looks at is: "How do freeze drying, spray drying, and foam-mat drying affect vitamin C levels in fruits? . This question was guided by the PCC framework:

- Population: Fruit-based materials (pulp, peel, juice, and paste)
- Concept: Drying-based encapsulation using freeze, spray, and foam-mat drying
- Context: Application of these techniques for vitamin C preservation in fruits under different processing conditions

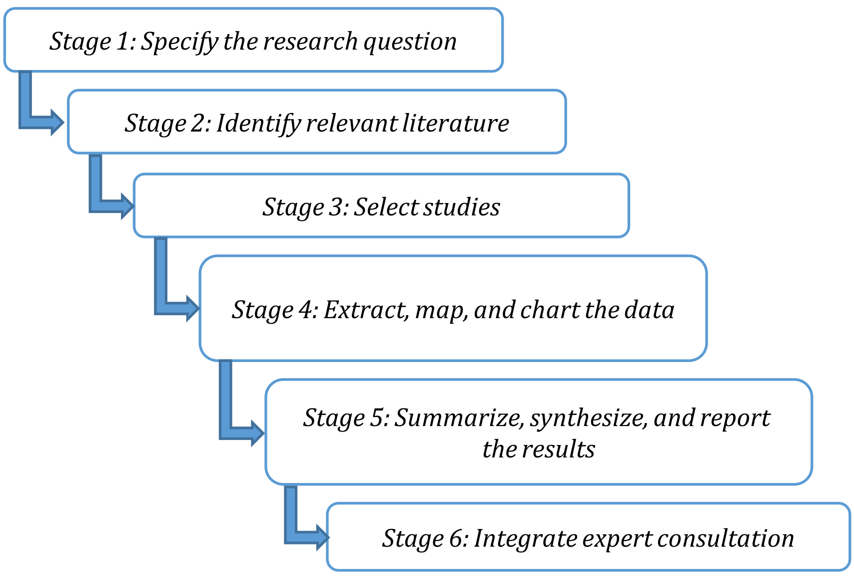


Figure 1. Arksey & O'Malley Framework Stage with Recommended Enhancement (21)

https://doi.org/10.56303/jhnresearch.v4i3.586

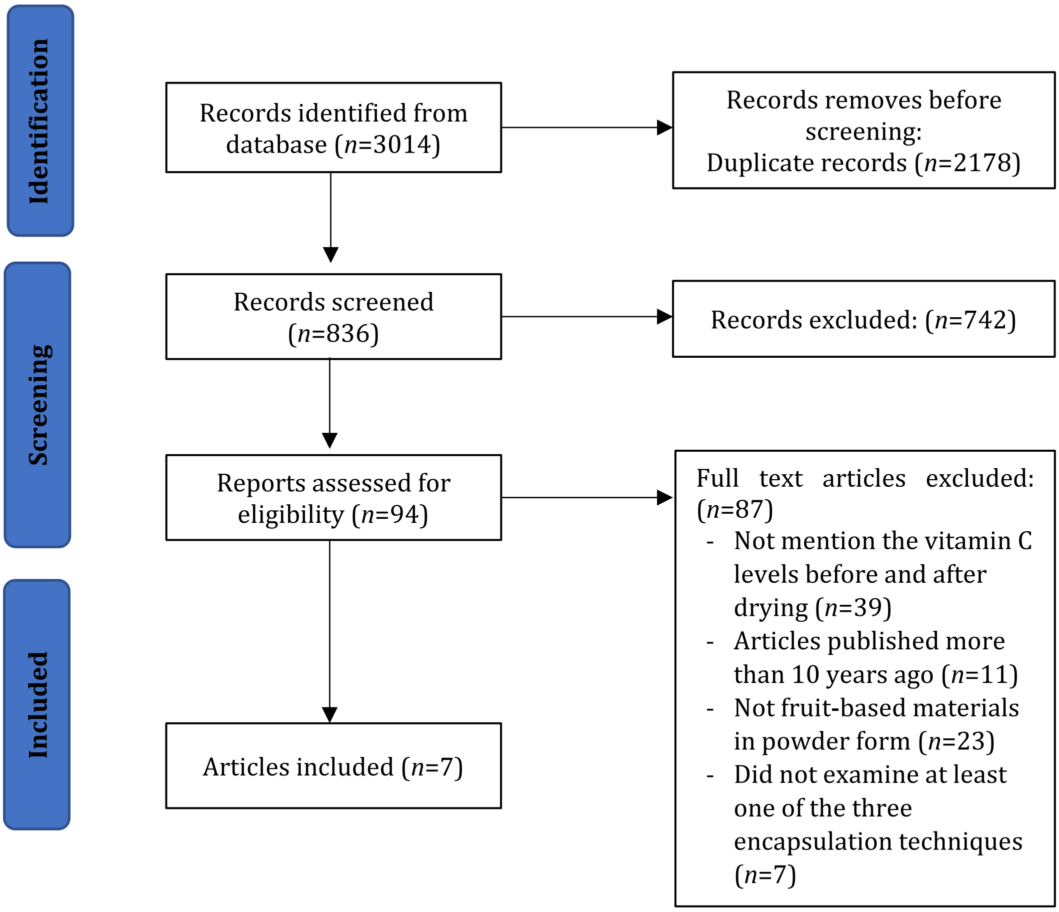


Figure 2. PRISMA flow diagram for study selection

Search Strategy and Eligibility Criteria

A comprehensive literature search was conducted across various databases, including PubMed, ScienceDirect, Springer, MDPI, Frontiers, and Google Scholar, focusing on articles published within the last 10 years (2015-2025). Keywords included are ("vitamin C" OR "ascorbic acid") AND ("encapsulation" OR "drying techniques") AND ("freeze drying" OR "spray drying" OR "foam-mat drying") AND ("fruit" OR "fruit-based materials" OR "fruit powder"). Articles were managed in Mendeley Desktop v.1.19.8, with duplicates removed. Inclusion criteria were: a) articles published in the last 10 years; b) written in English or Indonesian; c) full-text availability; d) examining the effect of drying-based encapsulation techniques (freeze, spray, and foam-mat-drying) on vitamin C level in fruits; and e) investigating at least one of the three techniques of interest (freeze, spray, or foam-mat drying). Exclusion criteria were: a) studies without vitamin C analysis (before and after drying); b) studies unrelated to fruit-based materials in powder form; c) studies that combine two techniques (e.g., foam-mat-drying followed by freeze-drying), which can confound interpretation of isolated technique effects.

Data Extraction and Analysis

Data were extracted using a standardized charting form that included information on drying-based encapsulation techniques, fruit types, drying conditions, coating materials, and vitamin C levels before and after drying, and retention rate. Results were synthesized narratively and in tables to show key findings. A PRISMA-ScR flow diagram (Figure 2) illustrates the study selection process. Full texts of eligible studies will be reviewed for drying techniques, fruit types, vitamin C levels, and factors like drying time and temperature. Data will be summarized and synthesized qualitatively.

https://doi.org/10.56303/jhnresearch.v4i3.586

RESULTS

A total of 3014 articles were initially identified through database searches. After removing duplicates and screening titles and abstracts, 94 articles were selected for full-text review. Following the inclusion and exclusion criteria, 7 articles were included in the final analysis. The selected studies were published between 2015 and 2025 and investigated various fruit matrices.

Table 1. Summary of Studies on Drying-Based Encapsulation Techniques and Vitamin C Levels

Drying-Based Encapsulation Techniques	Drying conditions	Fruits Type	Coating Materials	Vitamin C Levels		Retention	References
				Before drying	After drying		
Spray drying	Pulp and maltodextrin were homogenized for 30 minutes. Following this, drying was carried out using a 2.0 mm diameter injector nozzle, with a peristaltic pump, an inlet temperature of 120 °C, an exit temperature of 80 °C, and a fixed flow rate of 20 mL per minute.	Acerola pulp	Maltodextrin (MD)	2,063.8 mg/100g (dry basis)	1,593.2 mg/100g	77.20%	(23)
		Camu-camu pulp	Maltodextrin	6,754.7 mg/100g (dry basis)	6,690.4 mg/100 g	99%	(23)
Spray drying	Subsequently, a different drying setup used an inlet air temperature of 170 ◦ C, with a constant feed flow rate of 25% (7.5 mL/min). The inlet air flow was 40 m3/h, the compressor air pressure was 0.06 MPa, and the injector nozzle had a 0.7 mm inner diameter. The suction air flow was 100%.	Ripe açai pulp	Maltodextrin	32 mg/100g	244.4 mg/100g	96.35%	(24)
Spray drying	The SJ-MD liquid mixes were spray-dried using a pilot-scale spray drier at input temperatures of 160 °C and 180 °C. Feed flow rates of 1.4-1.8 L/h were adjusted to maintain an exit temperature of 95 ± 3°C.	Satsuma Mandarin (*Citrus unshiu*) Juice	Maltodextrin	5.45 mg/g = 545 mg/100g (wb)	Satsuma juice powder (SJP) after the spray drying process ranges from 2.88 mg/g to 4.01 mg/g (288-401 mg/100g). SJP produced using the CC spray drying configuration exhibited a higher	Vitamin C retention in SJP, with up to ~45% retention achieved at lower inlet temperatures and optimized	(25)

https://doi.org/10.56303/jhnresearch.v4i3.586

Drying-Based Encapsulation Techniques	Drying conditions	Fruits Type	Coating Materials	Vitamin C Levels		Retention	References
				Before drying	After drying		
					vitamin C content (3.56–4.01 mg/g)	configurations such as CC at 160 °C.	
Spray drying	Banana paste (180 ± 10 g) with maltodextrin (22.5 g/100 g) and water (45.2 g/100 g) was spray-dried at 130 °C (outlet 90 °C, feed flow 0.75 L/h) using a pressure nozzle atomizer, yielding 14.37 g of dried powder.	Ripe Nendran banana paste	Maltodextrin	Ripe banana: 9.08 mg/100g (wb)	Banana powder: 1.66 mg/100g (wb)	AR (%): 11% with moisture content ripe banana (56.6 g/100g), (moisture content banana powder (27.7 g/100g)	(26)
Freeze drying	After being frozen at −60°C for 10 hours, the samples were immediately packaged in a freeze dryer and dehydrated at −50°C under vacuum pressure (typically 10 Pa or less) for 36 hours.	Papaya puree	Maltodextrin and corn starch	1.51 mg AAE/g dry matter = 151 mg/100g	3.13 mg/g dry matter = 313 mg/100g	AR (%): 207 %	(27)
Freeze drying	Drying at −45°C ≥48h; drying at 50°C, −50°C condenser, 0.05 mbar for 18h.	Orange juice waste / cop (peel & pulp)	Gum Arabic (GA) and Octenyl succinic acid (OSA)	CoP (not formulated): 86 mg/100g OSA25: 82.1 mg/100g 0SA45: 82.3 mg/100g	CoP (not formulated): 526 mg/100g OSA25: 449 mg/100g 0SA45: 374 mg/100g	All formulations showed VC retention values above 100%, indicating an apparent increase after freeze-drying: CoP (+2%), with OSA (+13%), and	(28)

https://doi.org/10.56303/jhnresearch.v4i3.586

Drying-Based Encapsulation Techniques	Drying conditions	Fruits Type	Coating Materials	Vitamin C Levels		Retention	References
				Before drying	After drying		
				GA45: 80 mg/100g	GA45: 411 mg/100g	with GA (+24%)	
Foam-mat drying	Mulberry fruit juice treated with foaming agents was poured into petri dishes and dried in a hot-air oven at 60 °C until it reached equilibrium moisture content (±4 g/100 ml). It was then scraped, finely ground, and stored in laminated plastic pouches at -4 °C.	Black mulberry juice	Maltodextrin	38.77 mg/100g (mulberry juice)	25.52 (mulberry juice with 10 g/100 ml of md)	The best treatment is mulberry juice CMC (5g/100mL) with 90% retained ascorbic acid	(29)
Foam-mat drying	Mulberry fruit juice treated with foaming agents was poured into petri dishes and dried in a hot-air oven at 60 °C until it reached equilibrium moisture content (±4 g/100 ml). It was then scraped, finely ground, and stored in laminated plastic pouches at -4 °C.	Black mulberry juice	Carboxymethyl cellulose (cmc) Glycerol monostearates (GMS)	38.77 mg/100g (mulberry juice) 38.77 mg/100g (mulberry juice)	26.65 mg/100g (mulberry juice with 5 g/100 ml of cmc) 25.01 (mulberry juice with 4 g/100 mL of GMS)	The best treatment is mulberry juice + cmc (5g/100ml) with 90% retained ascorbic acid	(29)

If the weights of food before and after cooking are unavailable, the retention factor can be calculated on a moisture-free basis, the Apparent Retention Method (%AR):

%AR = [Nc (dry wet basis)] / [Nr (dry wet basis)] * 100

Nc = nutrient content per g of cooked food, Nr = nutrient content per g of raw food (30)

https://doi.org/10.56303/jhnresearch.v4i3.586

Characteristics of Included Articles

The articles reviewed investigated different fruit materials subjected to spray drying, freeze drying, and foam-mat drying. The fruits included acerola, camu-camu, ripe açai, satsuma mandarin, banana, papaya, orange peel and pulp, and black mulberry juice. Each article employed varying drying conditions and formulations to assess the stability of vitamin C. The studies originated from diverse research groups, highlighting global interest in preserving bioactive compounds during the production of fruit powders. Most of the works compared pre-drying and post-drying vitamin C concentrations, allowing for calculation of retention values. Collectively, these articles provide an overview of how fruit type and processing strategy influence vitamin C preservation.

Vitamin C Levels Based on Drying Techniques

Vitamin C levels before and after drying varied considerably depending on the drying techniques applied. Spray drying produced moderate to high retention rates, ranging from 11% in banana paste to 99% in camu-camu pulp (23,26). Surprisingly, freeze drying often led to vitamin C increases of over 100%, for example, in orange peel and pulp products, as well as in papaya puree, perhaps due to matrix changes or improved extractability (27,28). Foam-mat drying provided variable results, with mulberry juice retaining as much as 90% vitamin C under optimal conditions (29). In some cases, vitamin C levels after drying were higher than before, suggesting complex interactions between heat, matrix, and measurement conditions. Freeze drying was the most favorable for maintaining or enhancing vitamin C levels, based on this article, while spray drying produced more variable outcomes.

Coating Materials Used

Different coating materials were incorporated to improve the stability of vitamin C during drying. Maltodextrin was the most frequently used coating material, applied across acerola, camu-camu, banana, açai, satsuma mandarin, and mulberry juice. Other protective coating materials included OSA starch, gum Arabic (GA), carboxymethyl cellulose (CMC), and glycerol monostearates (GMS). Orange peel formulations with OSA and GA showed enhanced stability, with retention levels exceeding 100%. These findings highlight the crucial role of coating materials in reducing nutrient loss during drying processes.

Influence of Drying Conditions on Vitamin C

Reviewed studies indicate that drying temperature and duration have a significant effect on vitamin C retention. Spray drying, which is carried out at high inlet temperatures (120–190 °C) for a short period, often causes significant degradation of vitamin C. However, encapsulation coating materials, such as maltodextrin, can improve the results (23,24,26). Freeze drying, performed at much lower temperatures (−45 to −60 °C) over a longer period (18–48 hours), consistently maintains higher levels of vitamin C, sometimes showing a clear increase due to improved extractability (27,28). Foam mat drying at moderate temperatures (~60 °C) produces intermediate retention (29). The overall trend indicates that lower temperatures, combined with longer drying times, minimize vitamin C degradation, while higher temperatures accelerate losses unless counteracted by stabilizers.

DISCUSSION

The findings of this review confirm that drying techniques have a significant influence on vitamin C retention in fruit powders. Spray drying produced highly variable results, ranging from very low retention in banana paste (11%) to excellent preservation in camu-camu pulp (99%) (21,22). In contrast, freeze drying often resulted in apparent increases in vitamin C level, as observed in orange peel and pulp (from 86 to 526 mg/100 g) (23), which aligns with evidence that low-temperature drying minimizes thermal degradation and enhances extractability of bioactive compounds due to matrix structural changes (24). Likewise, freeze drying was more efficient in retaining vitamin C compared to spray drying or oven drying for grapefruit powder and Kakadu plum powder (31,32). Freeze drying uses water that is transformed into water vapor under low pressure. This helps to insulate against damage from heat and oxidation. Nutrients like vitamin C remain better intact when using this technique (6,28,33).

Nonetheless, spray drying has been shown to be effective under optimized conditions, where acerola and camu-camu powders retained high vitamin C concentrations (1,593.2 and 6,690.4 mg/100 g, respectively) with good stability during storage (23). Foam mat-drying, though less studied, has shown

https://doi.org/10.56303/jhnresearch.v4i3.586

potential, with optimized conditions in black mulberry juice retaining up to 90% of ascorbic acid (29). Similarly, mulberry extract foam-mat drying studies showed that optimal conditions, using egg albumin (7.6%), CMC (0.4%), and digestion-resistant maltodextrin (2%), with a 14.5-minute whipping time, produced stable foams suitable for drying at 65°C (34). The foam structure's larger surface area accelerates moisture removal while maintaining nutritional quality at lower temperatures compared to conventional drying techniques (35). Beyond the drying technique itself, coating materials are another critical factor influencing vitamin C stability.

Maltodextrin, the most widely used coating material, provided moderate protection but was clearly less effective compared to formulations containing additional stabilizers such as carboxymethyl cellulose (CMC) or gum Arabic (GA). Studied reported mulberry juice with CMC retained up to 90% of its ascorbic acid (29), while GA and octenyl succinic acid (OSA)-enhanced freeze drying of orange peel showed retention values above 100% (28). GA was more effective than OSA, as it improved the encapsulation of vitamin C and other bioactive compounds, yielded finer and more homogeneous powders, and enhanced rehydration properties. The emulsifying and foaming capacity was improved by OSA, but it did not significantly impact the retention of bioactive compounds. These findings align with reports showing GA outperforms other coating materials, showing superior microencapsulation efficiency and vitamin C retention compared to maltodextrin (MD) alone or whey protein isolates (36). Moreover, combinations of GA with bamboo fiber or maltodextrin at higher coating material-to-active ratios (e.g., 7:1) were shown to improve stability and antioxidant activity (37,38).

The stability of vitamin C is also influenced by drying conditions, including inlet temperature, time, and coating material. Using lower inlet temperatures, such as 170 °C in spray drying, in combination with 10-15% maltodextrin, maximizes vitamin C retention (over 90%)(24,39). A higher temperature and longer drying time typically result in increased loss of vitamin C from various fruits and vegetables (40). When there is insufficient addition of coating materials, they become poorly encapsulated and lose their nutrients. Similarly, when more coating materials were present, they diluted the fruit matrix, thus hampering the product's quality. Research indicates that the vitamin C content in lemon juice powder can decrease with maltodextrin concentrations of 15-25% (41). Despite these promising findings, several methodological limitations remain that restrict cross-study comparisons and mechanistic understanding.

Due to factors such as the lack of encapsulation efficiency (EE) or inadequate drying kinetics for vitamin C degradation in most studies, comparing results was more challenging. Only one study has quantified EE, which ranged from 17.92% to 98.90%, depending on the type of coating material and inlet temperature used. Higher inlet temperature unexpectedly favoured greater retention in this study (24). Furthermore, methodological differences in vitamin C analysis may bias comparisons across studies. Another gap lies in the limited understanding of matrix-specific behaviors, where unusually high retention (>100%) is observed in fruits such as ripe açaí and orange peel, suggesting phenolic–ascorbic interactions or natural fiber encapsulation (23,24). Foundational drying studies indicate that freeze-drying maintains the nutritional quality of materials because it sublimates water under low-temperature, solid-state conditions that minimize enzymatic and oxidative degradation (9). These findings emphasize the need for mechanistic studies to clarify such anomalies.

From an industrial perspective, these results suggest that selecting the right drying-based encapsulation techniques cannot be generalized for all fruit matrices. Due to the high energy consumption and cost of freeze drying, it is not suitable for large-scale applications (6,42). While spray drying is a more economical and scalable option, optimizing the inlet temperature, drying time, and coating material composition for vitamins is essential to minimize losses (43). Regarding the less studied, foam-mat drying also shows promise as a low-cost alternative, with the potential to retain vitamin C under optimized formulations (32,44). Importantly, the choice of coating material—particularly gum Arabic, maltodextrin blends, or carboxymethyl cellulose—directly influences not only vitamin C retention but also powder quality and shelf stability.

Integrating these insights, future studies should not only refine process parameters but also consider matrix-specific interactions and post-processing stability during storage. This helps keep the benefits achieved on a laboratory scale being translated to the industrial sphere and aids the development

https://doi.org/10.56303/jhnresearch.v4i3.586

of functional fruit products containing stable vitamin C.

CONCLUSION

This review confirms that drying-based encapsulation techniques greatly affect vitamin C levels in fruit powder products. Freeze drying is the best technique for preserving vitamin C. Optimized spray drying and foam drying are also promising alternatives. Coating materials like GA and CMC perform better than maltodextrin. They improve encapsulation efficiency, rehydration, and stability. However, unusual matrix behavior, such as vitamin C retention above 100% shows that mechanistic studies are needed. Although data on encapsulation efficiency and degradation kinetics are still limited, available evidence suggests that careful optimization of drying parameters and coating material formulations minimizes vitamin C losses. Applying these insights enables industry stakeholders to achieve stable, nutrient-rich fruit powders, providing a critical advantage in meeting consumer demands for functional foods and nutraceuticals.

FUNDING

This research was funded by Universitas Sebelas Maret through the Strengthening Research Group Capacity (PKGR-UNS A) Grant scheme (No: 371/UN27.22/PT.01.03/2025).

ACKNOWLEDGMENTS

The authors express their gratitude to all colleagues and to the institutions involved in this study.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Doseděl M, Jirkovský E, Macáková K, Krčmová LK, Javorská L, Pourová J, et al. Vitamin c—sources, physiological role, kinetics, deficiency, use, toxicity, and determination. Nutrients. 2021;13(2):1–36.
2. Lykkesfeldt J. On the effect of vitamin C intake on human health: How to (mis)interprete the clinical evidence. Redox Biol [Internet]. 2020;34(May):101532. Available from: https://doi.org/10.1016/j.redox.2020.101532
3. Ningtiyas OS, Susilawati, Utomo TP. the Effect of Heating Time on Vitamin C Content of Lemon Juice. J Agroindustri Berkelanjutan. 2023;2(1):31–40.
4. Mulyani T, Yulistiani R, Nopriyanti M. PEMBUATAN BUBUK SARI BUAH MARKISA DENGAN METODE "Foam-Mat Drying." J Rekapangan. 2014;19(1):91–7.
5. Ellab. The freeze drying theory and process - Things to consider [Internet]. Ellab White Paper. Denmark: Ellab White Paper; 2018. 1–16 p. Available from: https://www.ellab.com/Files/Files/White-Papers/The-Freeze-Drying-Theory-and-Process_ellab-whitepaper.pdf
6. Camacho M del M, Igual M, Martínez-Lahuerta JJ, Martínez-Navarrete N. Bioavailability of freeze-dried and spray-dried grapefruit juice vitamin C. 2019;(September 2018).
7. Sanjaya R. Penerapan Metode "Foam-Mat Drying" Pada Pembuatan Sari Buah Mengkudu (Morinda citrifolia). J Ilm Mhs Pertan [Internet]. 2022;2(4):187–96. Available from: http://jurnalmahasiswa.umsu.ac.id/index.php/jimtani/article/view/1755
8. Agustin DA, Wibowo AA. Teknologi Enkapsulasi: Teknik Dan Aplikasinya. DISTILAT J Teknol Separasi. 2023;7(2):202–9.
9. Ratti C. Hot air and freeze-drying of high-value foods: a review. J Food Eng [Internet]. 2001;49(4):311–9. Available from: https://www.sciencedirect.com/science/article/pii/S0260877400002284
10. Mieszczakowska-Frąc M, Celejewska K, Płocharski W. Impact of innovative technologies on the content of vitamin C and its bioavailability from processed fruit and vegetable products.

https://doi.org/10.56303/jhnresearch.v4i3.586

Antioxidants. 2021;10(1):1–19.
11. Zhou L, Cao Z, Bi J, Yi J, Chen Q, Wu X, et al. Degradation kinetics of total phenolic compounds, capsaicinoids and antioxidant activity in red pepper during hot air and infrared drying process. Int J Food Sci Technol. 2016;51(4):842–53.
12. Amankwah E, Kyere G, Kyeremateng H, van Boxtel A. Experimental verification of yam (Dioscorea rotundata) drying with solar adsorption drying. Appl Sci. 2019;9(18).
13. Silva-Espinoza MA, Ayed C, Foster T, Del Mar Camacho M, Martínez-Navarrete N. The impact of freeze-drying conditions on the physico-chemical properties and bioactive compounds of a freeze-dried orange puree. Foods. 2020;9(1).
14. Nizori A, Bui LTT, Small DM. Microencapsulation of Ascorbic Acid by Spray Drying: Influence of Process Conditions. World Acad Sci Eng Technol Int J Chem Mol Nucl Mater Metall Eng [Internet]. 2012;6:1123–7. Available from: https://api.semanticscholar.org/CorpusID:53466857
15. Zhou Z, Huang G, Li G. Microwave drying of Siraitia grosvenorii and its effect on the Vitamin C content. Adv Eng Res. 2018;163(Iceesd):1725–9.
16. ElGamal R, Song C, Rayan AM, Liu C, Al-Rejaie S, ElMasry G. Thermal Degradation of Bioactive Compounds during Drying Process of Horticultural and Agronomic Products: A Comprehensive Overview. Agronomy. 2023;13(6).
17. Silva JM, da Silva Crozatti TT, Saqueti BHF, Chiavelli LUR, Matioli G, Santos OO. Optimization of foam mat drying using Central Composite Design to produce mixed juice powder: A process and characterization study. Food Bioprod Process [Internet]. 2024;146:58–68. Available from: https://www.sciencedirect.com/science/article/pii/S0960308524000762
18. Sadowska A, Świderski F, Hallmann E. Bioactive, physicochemical and sensory properties as well as microstructure of organic strawberry powders obtained by various drying methods. Appl Sci. 2020;10(14):9–12.
19. Hardy Z, Jideani VA. Foam-mat drying technology: A review. Crit Rev Food Sci Nutr [Internet]. 2017;57(12):2560–72. Available from: http://dx.doi.org/10.1080/10408398.2015.1020359
20. Koç GÇ, Tekgül Y, Yüksel AN, Khanashyam AC, Kothakota A, Pandiselvam R. Recent development in foam-mat drying process: Influence of foaming agents and foam properties on powder properties. J Surfactants Deterg [Internet]. 2022; Available from: https://api.semanticscholar.org/CorpusID:250037149
21. Westphaln KK, Regoeczi W, Masotya M, Vazquez-Westphaln B, Lounsbury K, McDavid L, et al. From Arksey and O'Malley and Beyond: Customizations to enhance a team-based, mixed approach to scoping review methodology. MethodsX [Internet]. 2021;8:101375. Available from: https://doi.org/10.1016/j.mex.2021.101375
22. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA extension for scoping reviews (PRISMA-ScR): Checklist and explanation. Ann Intern Med. 2018;169(7):467–73.
23. Garcia VA dos S, Borges JG, Vanin FM, Carvalho RA de. Vitamin C stability in acerola and camu-camu powder obtained by spray drying. Brazilian J Food Technol. 2020;23(e2019237):1–13.
24. Vargas V, Saldarriaga S, Sánchez FS, Cuellar LN, Paladines GM. Effects of the spray-drying process using maltodextrin on bioactive compounds and antioxidant activity of the pulp of the tropical fruit açai (Euterpe oleracea Mart.). Heliyon. 2024;10(13).
25. Cruz-Padilla J, Reyes V, Cavender G, Chotiko A, Gratzek J, Mis Solval K. Comparative Analysis of Concurrent (CC), Mixed Flow (MX), and Combined Spray Drying Configurations on the Physicochemical Characteristics of Satsuma Mandarin (Citrus unshiu) Juice Powders. Foods. 2023;12(18):1–16.
26. Kabeer S, Govindarajan N, Preetha R, Ambrose K, Essa MM, Qoronfleh MW. Effect of different drying techniques on the nutrient and physiochemical properties of Musa paradisiaca (ripe Nendran banana) powder. J Food Sci Technol [Internet]. 2023;60(3):1107–16. Available from: https://doi.org/10.1007/s13197-022-05498-x
27. Ali A, Redwan A, Afzal M. Effect of freeze drying on selective bioactive compounds and physicochemical characteristics of papaya puree. Heliyon [Internet]. 2025;11(13):1–15. Available

https://doi.org/10.56303/jhnresearch.v4i3.586

from: https://doi.org/10.1016/j.heliyon.2025.e43626

28. Martínez-Navarrete N, García-Martínez E, Camacho M del M. Characterization of the Orange Juice Powder Co-Product for Its Valorization as a Food Ingredient. Foods. 2023;12(1):1–13.
29. Khatri B, Hamid, Jaiswal AK. Optimizing foaming agents for shelf-stable foam-mat-dried black mulberry juice powder. LWT - Food Sci Technol [Internet]. 2024;205(April):1–13. Available from: https://doi.org/10.1016/j.lwt.2024.116512
30. USDA. USDA Table of Nutrient Retention Factors Release 6 [Internet]. Maryland; 2007. Available from: http://www.ars.usda.gov/nutrientdata
31. Agudelo C, Igual MM, Camacho MM, Martínez-Navarrete N. Effect of process technology on the nutritional, functional, and physical quality of grapefruit powder. Food Sci Technol Int. 2017;23(1):61–74.
32. Phan ADT, Adiamo O, Akter S, Netzel ME, Cozzolino D, Sultanbawa Y. Effects of drying methods and maltodextrin on vitamin C and quality of Terminalia ferdinandiana fruit powder, an emerging Australian functional food ingredient. J Sci Food Agric. 2021;101(12):5132–41.
33. Galindo RG, Chiș MS, Martínez-Navarrete N, Camacho M del M. Dried orange juice waste as a source of bioactive compounds. Br Food J [Internet]. 2017;124(12):4653–65. Available from: https://riunet.upv.es/bitstream/10251/196918/3/GalindoChisMartinez-Navarrete - Dried orange juice waste as a source of bioactive compounds.pdf
34. Thuy NM, Tien VQ, Tuyen NN, Giau TN, Minh VQ, Tai N Van. Optimization of Mulberry Extract Foam-Mat Drying Process Parameters. Molecules. 2022;27(23):1–14.
35. Sangamithra A, Venkatachalam S, John SG, Kuppuswamy K. Foam Mat Drying of Food Materials: A Review. J Food Process Preserv [Internet]. 2015;39:3165–74. Available from: https://api.semanticscholar.org/CorpusID:94232302
36. Al-Ismail K, El-Dijani L, Al-Khatib H, Saleh M. Effect of Microencapsulation of Vitamin C with Gum Arabic, Whey Protein Isolate and some Blends on its Stability. J Sci Ind Res [Internet]. 2016;75:176–80. Available from: https://api.semanticscholar.org/CorpusID:59025903
37. Silva-Espinoza MA, Ayed C, Camacho M del M, Foster T, Martínez-Navarrete N. Impact of Maltodextrin, Gum Arabic, Different Fibres and Starches on the Properties of Freeze-Dried Orange Puree Powder. Food Biophys. 2021;16(2):270–9.
38. Delaporte A, Duchemin B, Grisel M, Gore E. Impact of Wall Material-to-Active Ratio in the Stability of Spray-Dried Ascorbic Acid Using Maltodextrin and Gum Arabic. molecules. 2024;29(3587):1–15.
39. Solval KM, Sundararajan S, Alfaro L, Sathivel S. Development of cantaloupe (Cucumis melo) juice powders using spray drying technology. LWT - Food Sci Technol [Internet]. 2012;46(1):287–93. Available from: http://dx.doi.org/10.1016/j.lwt.2011.09.017
40. Santos PHS, da Silva MAAP. Retention of Vitamin C in Drying Processes of Fruits and Vegetables—A Review. Dry Technol [Internet]. 2008;26:1421–37. Available from: https://api.semanticscholar.org/CorpusID:32163460
41. Rohini C, Kanchana STH, Geetha P S, Mini M L, Arul Arasu P. Optimize the process for encapsulated spray dried Lemon juice powder to enhance the Vitamin C. World J Adv Res Rev. 2024;21(1):2064–72.
42. Nowak D, Jakubczyk E. The Freeze-Drying of Foods — The Characteristic of the Process Course and the Effect of Its Parameters on. Foods. 2020;9(1488):1–27.
43. Suhag Y, Nanda V. Optimisation of process parameters to develop nutritionally rich spray-dried honey powder with vitamin C content and antioxidant properties. Int J Food Sci Technol. 2015;50(8):1771–7.
44. Vimercati WC, Araújo C da S, Macedo LL, Correa JLG, Pimenta CJ. Encapsulation of coffee silverskin extracts by foam mat drying and comparison with powders obtained by spray drying and freeze-drying. J Food Sci. 2022 Apr;87(4):1767–79.

https://doi.org/10.56303/jhnresearch.v4i3.586