Food Research International 187 (2024) 114420

Contents lists available at ScienceDirect

Food Research International

journal homepage: www.elsevier.com/locate/foodres

Review

Microencapsulation of vitamins: A review and meta-analysis of coating materials, release and food fortification

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ARTICLE INFO

Keywords:
Coefficient-determination
Deprotonation
Encapsulating agent
Fortification
Microcapsules
Protonation
Vitamins

ABSTRACT

Vitamins are responsible for providing biological properties to the human body; however, their instability under certain environmental conditions limits their utilization in the food industry. The objective was to conduct a systematic review on the use of biopolymers and lipid bases in microencapsulation processes, assessing their impact on the stability, controlled release, and viability of fortified foods with microencapsulated vitamins. The literature search was conducted between the years 2013–2023, gathering information from databases such as Scopus, PubMed, Web of Science and publishers including Taylor & Francis, Elsevier, Springer and MDPI; a total of 49 articles were compiled The results were classified according to the microencapsulation method, considering the following information: core, coating material, solvent, formulation, process conditions, particle size, efficiency, yield, bioavailability, bioaccessibility, in vitro release, correlation coefficient and references. It has been evidenced that gums are the most frequently employed coatings in the protection of vitamins (14.04%), followed by alginate (10.53%), modified chitosan (9.65%), whey protein (8.77%), lipid bases (8.77%), chitosan (7.89%), modified starch (7.89%), starch (7.02%), gelatin (6.14%), maltodextrin (5.26%), zein (3.51%), pectin (2.63%) and other materials (7.89%). The factors influencing the release of vitamins include pH, modification of the coating material and crosslinking agents; additionally, it was determined that the most fitting mathematical model for release values is Weibull, followed by Zero Order, Higuchi and Korsmeyer-Peppas; finally, foods commonly fortified with microencapsulated vitamins were described, with yogurt, bakery products and gummy candies being notable examples.

1. Introduction

The vitamins are organic molecules that trigger biological and biochemical functions in the human body (Couto et al., 2023). Despite the body's ability to synthesize and produce some vitamins, it is necessary to supplement micronutrient intake through nutritional supplements, balanced diets and a variety of animal and plant-based foods to ensure an adequate amount for the body's needs (Carlan et al., 2017; Gonçalves et al., 2017; Whitfield et al., 2021). The human body requires both types of vitamins (fat-soluble and water-soluble) for optimal functioning.

The fat-soluble vitamins are composed of A, D, E and K; they are soluble in lipids and are stored in the adipose tissue of the human body (Richard et al., 2020). This property allows the vitamins to be released gradually at times when the body needs them; they play a role in processes such as blood clotting, calcium absorption, neurological diseases and protection of cell membranes (Santos et al., 2021; Gonçalves et al., 2017; Parthasarathi and Anandharamakrishnan, 2016 ; Sharipova et al., 2016). Water-soluble vitamins such as vitamin C and the B-complex vitamins; play a role in the production of adenosine triphosphate (ATP), promote human development and growth, strengthen the immune system and quickly synthesize deoxyribonucleic acid (DNA) (Chalella Mazzocato et al., 2019; Marcela et al., 2016; Szczuko et al., 2018; Whitfield et al., 2021).

The incorporation of vitamins into food systems represents a significant strategy in the formulation of functional foods (Barrios-Renteria

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https://doi.org/10.1016/j.foodres.2024.114420
Received 16 December 2023; Received in revised form 20 April 2024; Accepted 22 April 2024
Available online 26 April 2024

et al., 2022; Mauricio-Sandoval et al., 2023), given that it improves the health and well-being of consumers (Gonçalves et al., 2016). It is important to recognize that vitamins are highly sensitive compounds susceptible to degradation during food handling, manufacturing and storage processes (Estevinho et al., 2019). Below, Table 1 shows structure and major instability causes of vitamins A, B, C, D and E; it is important to mention that these five vitamins have participated concurrently in the microencapsulation processes.

For this reason, the implementation of protection systems is required to preserve the integrity of vitamins and prevent undesirable alterations. To counteract these threats, various microencapsulation methods involving polymeric matrices have been developed for the coating of vitamins (Al-Ismail et al., 2016; Alborzi et al., 2013; Comunian et al., 2014; Dang et al., 2017; Palma-Rodríguez et al., 2018; Silva et al., 2013).

Microencapsulation is a promising technology in the field of preservation and extension of the shelf life of compounds in solid, liquid and gaseous states (Borrmann et al., 2013), this process forms capsules with various morphologies ranging from nanometers to micrometers (Couto et al., 2023). The coating isolates the active compound from environmental influences such as temperature, humidity, oxygen and interactions with other compounds, preventing destabilization, oxidation and deterioration of the encapsulated material (Muñoz-More et al., 2023; Parthasarathi and Anandharamakrishnan, 2016)). The methods for microcapsule production are divided into chemical and physical categories; chemical processes include complex coacervation (Constantino and Garcia-Rojas, 2023) simple and double emulsion (Fraj et al., 2021; Sharipova et al., 2016), solvent evaporation (Mohammed et al., 2021) and ionic gelation (Teng et al., 2013); while, physical methods encompass electrohydrodynamic processes (Couto et al., 2023), ultrasonics (Zhu et al., 2021), lyophilization (Parthasarathi and Anandharamakrishnan, 2016) cooling and spray drying (dos Carvalho et al., 2019; Gonçalves et al., 2022). Microencapsulation offers numerous advantages, including the ability to achieve controlled release in the intestinal tract, improve absorption, enhance bioavailability and facilitate transport (Mendes and Chronakis, 2021).

In food systems, microencapsulation is employed to protect microorganisms, polyphenols, micronutrients, lipids and enzymes; using biopolymers as coating structures (Böger et al., 2021; Selamat et al., 2018). The most suitable biopolymers in microencapsulation processes are polysaccharides and proteins (Al-Ismail et al., 2016; Ribeiro et al., 2021; Samborska et al., 2021), highlighted for their emulsifying capacity and film-forming properties (Labuschagne, 2018). The advantages of natural biopolymers in the food industry lie in their non-toxic nature, stability in aqueous media and biodegradability (Carlan et al., 2021), these attributes make biopolymers suitable for the microencapsulation of bioactive components, aligning with the growing industry demands to adopt sustainable practices. The participation of lipid bases as coating materials has also been adapted to microencapsulation methods such as spray cooling, in order to maintain the stability of vitamins in foods with high fat content (Chalella Mazzocato et al., 2019; de Matos-Jr et al., 2017). Currently, there have been no studies on biopolymers and lipid bases as materials that protect vitamins; in this regard, there is an opportunity to strengthen the application of biopolymers and lipid bases as coating agents, studying their properties, advantages and challenges. Therefore, the objective of this study is to systematically review the use of biopolymers and lipid bases in microencapsulation processes, assess their impact on the stability, controlled release and viability of foods fortified with microencapsulated vitamins.

2. Methods

The methodological structure adopted in this study is based on the recommendations proposed by Ponce-Corona et al. (2020) and Sharif et al. (2020), which provide guidelines for various phases of the research process, covering planning the study, conducting the review and analyzing the results.

2.1. Review planning

Planning is the initial phase of the systematic review, involving the creation of the review protocol. This process includes a series of stages ranging from formulating research questions to considering the following activities: identifying the need for the review, establishing research questions, creating the search strategy, and selecting data sources.

2.1.1. Identification of the need for systematic review

Technological advancements have revealed that microencapsulation has become an essential necessity for the food, nutritional and pharmaceutical industry. This process involves the formation of microscopic particles, usually composed of biopolymeric materials; its purpose lies in the protection and preservation of the encapsulated substance against exposure to environmental factors while allowing controlled release in the organism. It is important to highlight those vitamins represent essential micronutrients for the vital functioning of the human body. However, they exhibit notable sensitivity to environmental factors such as moisture, heat, and light; therefore, the relevance of vitamin microencapsulation lies in its ability to enhance stability, absorption and bioavailability, allowing the formulation of products without altering organoleptic attributes. Unlike the scope of previous studies on the microencapsulation of vitamins, where the focus has been on microencapsulation techniques, this research stands out by emphasizing the study of biopolymers and lipid bases as coating materials. The choice of good coating materials plays a fundamental role in achieving controlled release, preserving the stability of vitamins, improving the quality of microcapsules, and extending the shelf life of products.

2.1.2. Formulation of research questions

The following research questions were established.

- PI01: Which effects are exhibited by coating materials in the microencapsulation of vitamins?
- PI02**:** What effect does pH and cross-linking have on the release of microencapsulated vitamins?
- PI03: Which foods are fortified with microencapsulated vitamins?

2.1.3. Creation of the search string

The concept of microencapsulation was divided into microencapsulation, microcapsules, natural biopolymers, encapsulating agents, and coating material. The main problems identified were: vitamins, controlled release and release profile. The selected keywords were as follows: *Microencapsulation, microcapsules, natural biopolymers, encapsulating agent, coating material, vitamin, release controlled, release profile and foods applications.*

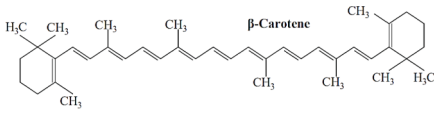
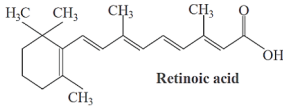
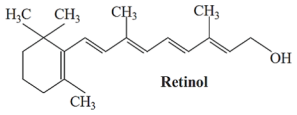
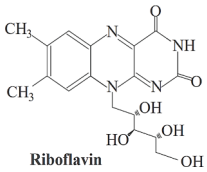
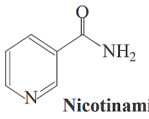
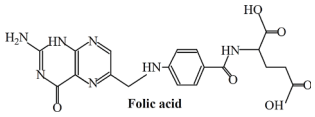
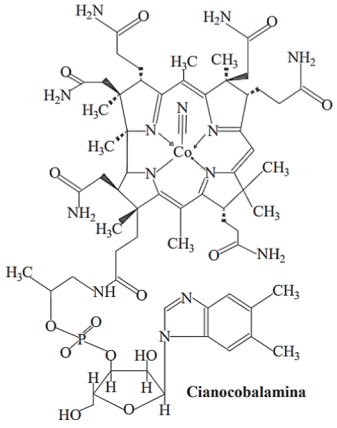
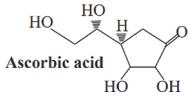
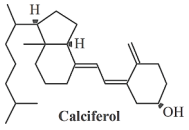
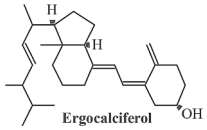
(““Microencapsulation”” OR ““microcapsules””) AND (““natural biopolymers”” OR ““encapsulating agent”” OR ““coating material””) AND (“vitamins” OR “vitamin”) AND (““release controlled”” OR ““release profile””) AND (““foods applications””).

In this study, microencapsulation is understood as the technique of protecting and preserving encapsulated substances; vitamins are micronutrients essential for the organism; biopolymers are macromolecules used as coating material, and release profile describes the release time of the encapsulated matrix.

2.1.4. Selection of data sources

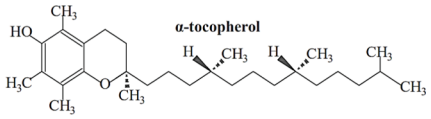
The databases selected for this review included Scopus, PubMed, and Web of Science, along with publishers such as Taylor & Francis, Elsevier, Springer and MDPI. A temporal restriction was applied, limiting the inclusion of studies published between 2013 and 2023. Specific selection criteria were established, covering aspects such as particle size, efficiency, yield, coating material, core, and release profile, to ensure the

Table 1
Structure and instability of vitamins mentioned in this study.

Vitamins	Basic structure	Instability	References
A	 β-Carotene	Presence of light, temperature, oxygen and high pH.	Dadon and Reifen, 2017 and El Ghazzaqui Barbosa et al., (2022)
	 Retinoic acid		
	 Retinol		
B	 Riboflavin	Sensitive to light and alkaline solutions	Zaborniak and Chmielarz, 2021and Hrubša et al. (2022)
	 Nicotinamide	Resistant to atmospheric oxygen, acids, heat and light in aqueous systems	
	 Folic acid	Low pH, temperatures above 180 °C and UV radiation	Liu et al. (2015) and Gazzali et al. (2016)
	 Cianocobalamina	Acidic and alkaline solutions, temperatures above 120 °C	Bajaj and Singhal, 2020 and Osman et al. (2021)
C	 Ascorbic acid	Exposure to light, heat, alkaline solutions and presence of metals	Ravetti et al. (2019) and Yin et al. (2022)
D	 Calciferol	Acid solutions, high temperatures and oxidation	Verkaik-kloosterman et al. (2017) and Maestro et al. (2019)
	 Ergocalciferol		

(*continued on next page*)

Table 1 (*continued*)

Vitamins	Basic structure	Instability	References
E	 α-tocopherol	High temperature, oxygen and light exposure	Hategekimana et al. (2015) and Miyazawa et al. (2019)

rigor and relevance of the studies included in the review.

2.2. Research development

The purpose of the second phase consists of the identification and selection of primary studies, by means of the search strategy. In order to answer the research questions for the elaboration of the systematic review, the following activities were carried out:1) Selection of primary studies and 2) Comprehension and synthesis of the information.

2.2.1. Selection of primary studies

For a more rigorous selection, inclusion (IC) and exclusion (EC) criteria were applied (Table 2.).

Procedure for the selection of primary studies:

1. Adjust the search strategy to the data source.
2. Apply inclusion criteria.
3. Thoroughly read the abstract, introduction, methodology, results, and conclusions.

Table 3 shows the data sources used for information retrieval, the results obtained from the search string and the primary studies selected for the development of the review.

2.2.2. Extraction and synthesis of information

Primary studies were organized in PDF files and in the Mendeley reference manager. The selection of essential data was conducted through the classification, compilation, and organization of the articles. The information was divided by microencapsulation method and subdivided into: core (type of vitamin), coating material, solvent, formulation (core and coating material), process conditions, particle size, efficiency (EE), yield (Y), bioavailability (BV), bioaccessibility (BA), in vitro release, determination coefficients R^2 (zero and first order, Higuchi, Korsmeyer-Peppas and Weibull) and references.

2.3. Statistical analysis

Comparative analysis was conducted among the results of the primary studies and subjected to analysis of variance (ANOVA) to identify statistical differences. The Tukey multiple comparison test with a confidence level of 95 % was applied. Statistical data and graphical designs were generated using Minitab 18 and Origin 2018 software.

3. Results

The results are structured and organized according to subsection 2.2.2. (Extraction and synthesis of information); the breadth of the tables indicates a profound interest in developing an accessible, favorable, controllable, sensorially friendly and applicable alternative in food systems (Tables 4-8). As observed in Fig. 1, the microencapsulation methods most frequently used for the protection of vitamins are spray drying, complex coacervation, spray cooling, electrohydrodynamic process, simple and double emulsion.

Table 2
Inclusion and exclusion criteria.

Code	Inclusion criteria	Code	Exclusion criteria
IC01	English language studies	EC01	Studies that do not exercise study parameters on microcapsules.
IC02	Publication period 2013–2023	EC02	Undergraduate thesis
IC03	Titles of research with at least one keyword	EC03	Studies published in languages other than English or Spanish

Table 3
Number of published research studies and selected primary studies.

	Source of data	Search string results	Primary studies
Database	Scopus	20	8
	PubMed	28	5
	Web Of Science	10	1
Publishers	Taylor & Francis	54	5
	ElSevier	123	23
	Springer	104	4
	MDPI	10	3
Total manuscripts reviewed		**349**	**49**

With respect to efficiency in the microencapsulation of vitamins, the methods described in Fig. 1, present no significant difference ($p > 0.5$); however, spray drying is the most used method due to its easy handling and good yield. In the case of spray cooling, it is a specific method for using lipid bases, taking advantage of their ability to handle substances with a low melting point. Multiple materials often play a role in the food and pharmaceutical industries due to their emulsifying, stabilizing and film-forming capabilities. These materials can be synthetically modified, losing their natural origin structure, as in the case of hydroxypropyl methylcellulose, which is beyond the scope of this review. Despite this, the use of natural biopolymers has increased over time due to their ability to provide stability, protection, release, and bioavailability to the active compound. Biopolymers used in the formation of microcapsules are of sustainable origin (animal and vegetable) and are often classified as polysaccharides and proteins. However, due to the nature and internal structure of lipophilic vitamins, the intervention of lipid sources is necessary for the formation of microcapsules. Fig. 2 shows the most common coating materials for the microencapsulation of vitamins.

The need to use two or more coating materials in microencapsulation offers many advantages, ranging from obtaining specific properties that enhance the functionality and effectiveness of the microcapsules to leveraging the individual strengths of each material, such as improved stability, resistance to external factors and controlled release. Likewise, in situations where the encapsulated core contains components that may interact adversely with a single coating material, the combination of materials provides the opportunity to create an effective barrier, preserving the stability and shelf life of the core. Fig. 3 shows that combinations of different coating materials are favorable, such as polysaccharides – proteins, polysaccharides – polysaccharides and proteins – proteins.

4. Discussions

4.1. PI01: Which effects are exhibited by coating materials in the microencapsulation of vitamins?

4.1.1. Gums

Fig. 2 shows that gums are the polysaccharides most frequently used in the microencapsulation of vitamins. The use of Arabic gum produces

Table 4
Microencapsulation of vitamins by the complex coacervation method.

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
β-carotene	−Lactoferrin −Amaranth carboxymethyl starch	−H_2O and agitation for 1hr −B-C (5 % p/p) in SO	LF:CMS 1:2 g:g Core:Coating 1:4 g:g	−0.02 % NaN_3 and 10 % (v/v) CH^3COOH in each biopolymer (pH 4) −pH 5 adjusted with NaOH 0.5 mol/L −Agitation at 10.000 rpm, 3 min	4.247 μm	98.47/ NR/ 27.39/ NR	70 % was released in the gastric phase. 86 % released in soybean oil 19 % was released in 50 % methanol	NR —/ 0.979 —/0.969	. NR 0.558 0.388	NR	NR	(Constantino and Garcia-Rojas, 2023)
β-carotene	−Casein −Guar gum	−1g CA + 10 mL NaOH (0.5 N) + 100 mL distilled H_2O. −GG:100 mL H_2O distilled 40 °C. −25 mg de B-C: + 4 mL SO	W/O B-C 1.0 % (w/v) + Solution CA W/O:GG 1:0.5 pH 5 adjusted with 10 % (v/v) of NaOH	−W/O agitation at 9000 rpm, 30 min and 40 °C −500ul of 0.5 % (w/v) genipin and agitation 45 min. −Storage at −80 °C and lyophilized at 0.0098 mbar pressure.	176.47 μm	65.95/ 71.34/ NR/NR	The release was slow, sustained and controlled under hydrogen chloride (0.1 N) at pH 1.2 and 8 h.	0.679/ 0.606	0.839	0.889	NR	Thakur et al. (2017)
β-carotene	−Whey protein isolate −Arabic gum	−WPI: 2 g + 100 mL distilled H_2O −Ag: 1 % +100 mL H_2O distilled 40 °C −B-C: 0.5 %+ 5mL SO.	AG:WPI = Coating 1:2 Coating + Solution B-C pH 4.2 adjusted with HCl 1 N	−Agitation at 4000 rpm, 30 min and 40 °C −Glutaraldehyde as crosslinker and agitation for 60 min. −Storage at 7 °C overnight and freeze-drying −Release under 0.1 N HCl + 2.0 % T80	140 μm	77.30/ 80/NR/ NR	The release evidenced a biphasic pattern, an initial burst, followed by a sustainable, slow and steady release. Up to 8 h > 60 % was released.	NR	NR	NR	NR	Jain et al. (2015)
Ascorbic Acid	−Gelatin −Arabic gum	− Solution of G and AG at 7.5 g % (w/v) − AA solution at 30 % (w/w) + corn oil in 1:1 ratio	Core:Coating 0.5:1 (w/w) pH 4.4 adjusted with HCl (1 mol/L)	−Incorporation of PGPR 90 at 0.8 % (w/w) −Low, constant homogenization for 30 min and 45 °C. −Freeze-dried (−52 °C) for 48 h prior to freezing (−18)	10.3 μm	93.8/ NR/NR/ NR	pH 5.4 in 240 min 97.08 % was released. pH 7.4 in 300 min 96.13 % was released. pH 9.6 in 270 min 96.13 % was released.	0.7387/ 0.8821 0.8961/ 0.9177 0.7221/ 0.8157	NR	NR	NR	Rodrigues da Cruz et al. (2019)
Core	**Coating material**	**Solvent**	**Formulation Core:Coating material**	**Process conditions**	**Particle size**	**EE/Y/ BV/BA (%)**	***In vitro* release**	**Kinetic release models — Coefficient of determination (R^2)**				**References**
								Zero/ First order	**Higuchi**	**Korsmeyer-Peppas**	**Weibull**	
Ascorbic Acid	− Gelatin − Arabic gum	−G and AG solution at 7.5g% (w/v) −AA solution at 30% (w/w) + corn oil in a 1:2 ratio	G:AG:AA 1:1:0.75 pH 4.4 adjusted with HCl (1mol/L)	−Incorporation PGPR 90 at 0.5% (w/w) −Constant agitation for 30 min and 45°C. −Storage at −18, freeze-drying for 12h, 1–0.1 kPa pressure, −20°C	38.82 μm	97.41/ NR/NR/ NR	5% NaCl and 1% SDS. −30 days, 20°C microcapsules contained 57 and 80% of AA −37°C contained 32% and 44%	NR	NR	NR	NR	Comunian et al. (2013)

(*continued on next page*)

Table 4 (*continued*)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models – Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Calciferol (VD_3)	−Maltodextrin −Gelatin	Ratio **1:10** −G+H_2O at 40°C −M+H_2O at 40°C	G:M:VD_3 40:60:500(w/w): (w/w): (IU/100 mL)	−Agitation at 16.128 g for 5 min. −Freeze-drying at −65°C and storage at 4°C	2.2 μm	97.28/ NR/NR/ NR	At 360 min in gastric and intestinal media, 96.4% was released.	NR	NR	NR	NR	Nami et al. (2023)
Calciferol (VD_3)	−Type A Gelatin −Carboxy-methyl tara gum	−H_2O ultrapure −G-A: solubilized 20 min,50°C and 300 rpm. −CMTG solubilized in 1h –CO + VD_3 1%	G-A: CMTG 6:11% (w/v) Core:Coating1:2 (w/w) pH 4.0 adjusted CH_3COOH (10%)	−Agitation 10,000 rpm, 30 min. −Ice bath <5°C was applied for 30 min −5mL of TGasa (30U/g. ptn) at 25°C for 4h at 50rpm.	256 nm	79.76/ NR /NR/53	−SSF: 2 min released 60%. −SGF: 2h released 50% −SIF: 2h released 80%	NR	NR	NR	NR	Santos et al., 2021
Vitamin D	− Gelatin −Berrio seed mucilage	−G solution at 3%. −CSM solution at 1% −Dispersion 10% of VD in SFO.	Ratio G/CSM 0.35 Core/Coating 0.25pH 8 adjusted NaOH (0.1M)	−Agitation G: 18 rpm,4 min 40°C −Emulsion agitation at 40°C, 10 min. −pH 4 adjusted with HCl (0.1M). −Centrifuge 15min, 25°C, 10,000 rpm, freeze −80 and freeze-drying.	137.22 μm	81.7/ 91.5/ NR/NR	−In 2h, 28% was released in the VD and after 6h, 70% in the gastrointestinal tract.	NR	NR	NR	NR	Jannasari et al. (2019)
Calciferol (VD_3)	−Sodium alginate −Chitosan	−SA 0.23% (w/v) +H_2O distilled. –Ch + CH_3COOH (1% pH=4)	VD_3:SA 1:5 VD_3:SA:Ch 1:1:5pH 7.0 adjusted with NaOH (0.1M) .	SA Microcapsules −T80 (1% w/w) + $CaCl_2$ −Ultrasound time and power: 13.7 min and 200 W	11.32 μm	92.86 /NR/ NR/NR	93% of VD_3 was released into intestinal fluids (pH 7.4) during 4 h of incubation.	0.145 /0.692	0.730	0.731	0.824	Eslami et al. (2018)
				SA-Ch Microcapsules −Dry the emulsion at 7000g of strength				0.296 /0.898	0.925	0.928	0.987	

β-C: β-carotene; AA: Ascorbic Acid; VD_3: Vitamin D3; SO: Soybean oil; CO: Canola oil; SFO: Sunflower oil; CH_3COOH: Acetic acid; HCl: Hydrochloric acid; NaN_3: sodium azide; NaOH; Sodium hydroxide; SSF: Simulated salivary fluid; SGF: Simulated gastric fluid; SIF: Simulated intestinal fluid; PGPR 90: Polyglycerol polyricinoleate; T80: Polysorbate; SDS: Sodium dodecyl sulfate; WPI: Whey protein isolate; GG: Guar Gum; AG: Arabic gum; CMTG: Carboxy-methyl tara gum; M: Maltodextrin; SA: Sodium alginate; Ch: Chitosan. G-A: Type A gelatin; LF: Lactoferrin; CSM: Berrio seed mucilage; EE: Efficiency; Y: Yield; BV: bioavailability; BA: Bioaccessibility and NR: Not reported.

Table 5
Microencapsulation of vitamins by electrohydrodynamic processes: electrospinning/electrospraying.

Core	Coating material	Solvent	Formulation Core: Coating material	Process conditions	Particle size	EE (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Vitamin B12	−Zein	70 % C_2H_6O	VB12:Z 1:15 (%p/p):(%p/p)	−Flow rate: 0.6 mL/h −Stainless steel needle: 22G −Distance between needle and collecting plate: 5 cm. −Voltage: 20 kV −Process at 23 °C	0.2–0.8 μm	81.1	Release in deionized H_2O, in a time > 30 min 100 % released.	0.780/ 0.664	NR	0.877	0.765	Couto et al. (2023)
			VB12:Z 1:30 (%p/p):(%p/p)		0.4–1 μm	93.9		0.970/ 0.462		0.919	0.994	
Vitamin B12	−Zein	60 % C_2H_6O	Z:VB12: C_2H_6O 3:10:60 (% w/w):(% w/w):(%w/w)	−Flow rate: 0.7 mL/h −Stainless steel needle: 18 G −Distance between needle and collecting plate: 7 cm. −Voltage: 20 kV −Process at 22 °C	1.25–4.38 μm	91.0	In C2H6O, 100 % was released in a time > 20 h.	NR	NR	0.98	0.97	Coelho et al. (2021)
Folic acid (VB9)	−Zein −Modified starch	C_2H_6O al 70 %	MS:VB9 12:1(%w/w): (% w/w)	−Flow rate: 0.4 mL/h −Stainless steel needle: 20 G −Distance between needle and collecting plate: 5 cm −Voltage: 15.97 kV −Process at 22 °C	20 μm	90.4	Release in Ethanol solution (22 °C): 100 % − 6.5 h SGF (37 °C) was: 90 % − 14 min.	NR	NR	NR	NR	Coelho et al. (2022)
			MS:T80:G: VB9 15:4:4:5	−Flow rate: 0.1 mL/h −Stainless steel needle: 20 G −Distance between needle and collecting plate: 11.5 cm −Voltage:20 kV −Process at 22 °C		86.7	Release in Ethanol solution (22 °C): 100 % − 6.7 h SGF (37 °C) fue: 100 % − 10 s					

VB12: Vitamin B12; C_2H_6O: Ethanol; Z: Zein; MS: Modified starch; G: Glycerol; T80: Polysorbate; SGF: Simulated gastric fluid; EE: Efficiency and NR: Not reported.

irregular formation, significant depths and rough surfaces in the microcapsule, leading to its rupture and rapid release (Carlan et al., 2021), its utility stems from its high molecular weight, branched structure and polarity, which are associated with lower solubility. While covalent bonding of proteins and branched polymers grants low viscosity, aggregates macromolecules and is biodegradable (Al-Hamayda et al., 2023; Burin et al., 2011; Jain et al., 2015). However, Gonçalves et al. (2017) demonstrated that the microencapsulation of retinol in Arabic gum provides spherical microcapsules with a rough surface and a yield between 10 and 30 %; concentrations of 15 % and 20 % of gum offer stability and good protection of retinol for 1 month. To enhance stability, the combination of coating materials has proven to be a useful practice. The utilization of Arabic gum and gelatin in the microencapsulation of ascorbic acid results in a smooth, multinucleated sphere with low solubility and prolonged stability (60 days at 20 °C); the efficiency exceeds 97 % and high hygroscopicity is observed when the polar groups are exposed to the solution (Comunian et al., 2013). However, it should be noted that the negatively charged carboxyl groups in the gum hinder the formation of complexes with gelatin, leading to a low yield and ionic imbalance; meanwhile, the hydro-solubility of ascorbic acid, viscosity

Table 6
Microencapsulation of vitamins by single and double emulsion, solvent evaporation, and ionic gelation techniques.

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Riboflavin (VB2)	−Sodium alginate −Chitosan	−3.5 % of SA + H_2O −3% Ch + 1 % CH_3COOH	W/O W: 80 mg VB2 + 30 mL SA O: W + 70 mL PO W/O + 125 mL of $CaCl_2$ at 1 % W/O/W W/O/W: W/O + Ch + GH at 2 %	−PO contained 0.3 mL of span 80 −O agitation 20 min −W/O agitation 60 min. −W/O/W agitation 15 min and upon addition of GH 60 min	500 μm 400 μm	NR/ NR	NR	NR	NR	NR	NR	Danarto et al. (2020)
Riboflavin (VB2)	− Poly (L-L-Lactic Acid)	−Methylene chloride −PVA −Destilled H_2O	W/O W: 250 PLLA + 15 mL MeCl + 20 mg PVA + 30 mL H_2O O: W + 250 mg VB2	−First agitation: 700 rpm, 25 °C −Second agitation: 700 rpm + 40 mL H_2O at 70 °C	NR	85/ 93	Optimal release by glycolic acid copolymerization and crystallization reduction	0.9663/-	NR	NR	NR	El-Hay et al. (2016)
Folic acid (VB9)	−Whey protein concentrate. −Pectin	−Deionized H_2O (100 °C)	W/O W: SFT + VB9 O: CO:SFT:VB9 76:12:12 % W/O/W W/O (10 %) + WPC + P + M + Span 80 W/O W: SFT + VB9 O: CO:SFT:VB9 W/O/W W/O (10 %) + WPC + P + M + PGPR	−3mg/mL TF at pH 9 −W and O: 1000 rpm −P solution (100 g) −WPC solution (100 g) + NaN_3 0.02 % agitation 30 min −The difference of 1 and 2 is the type of surfactant and 3 only contains WPC. −Spray drying as the last process, 30 g of M −pH was adjusted to 4–7-11 with HCl and 0.1 M NaOH.	NR	NR/ NR	The microcapsules manufactured with Span 80 obtained low release in acidic solutions (pH 4) and high release in alkaline conditions (pH 11).	pH 4 0.882/ 0.881 pH 11 0.903/ 0.931 pH 4 0.591/ 0.604 pH 11 0.895/ 0.912	pH 4 0.882 pH 11 0.903 pH 4 0.591 pH 11 0.895	NR	NR	Assadpour et al. (2017)
Ascorbic Acid	−Gelatin −Sodium caseinate	−H_2O desionizada	W/O: Ratio 20/80. W:25 % (w/v)AA + H_2O O:1.6 % (w/v) VE + 3 % (w/v) of PGPR:Caprol 10G100 (1:1) W/O/W 30 g of W/O + 70 g of G at 1.71 % (w/w)	−Dispersion W in O 40 °C, 20.000 rpm,10 min. −Addition of 2 mmol/g G-P + 2 % A. − Spray drying. −Dispersion W in O 40 °C, 20.000 rpm, 10 min. −Addition NaCAS in ratio to G (0.5 %:1%) w/w. − Spray drying.	12.34 μm	98/ NR 99/ NR	Application of 0.1 M HCl (pH 1.8) For both variables G-P and G/ NaCAS AA was completely released after 60 min.	0.9253/ 0.9316 0.9565/ 0.9581	0.9616 0.9824	0.9648 0.9842	NR	Fraj et al. (2021)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	

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Table 6 (*continued*)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y (%)	*In vitro* release	Kinetic release models – Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
α-Tocopherol (VE)	–Polystyrene sodium sulfonate –Dodecyl trimethyl ammonium bromide	–H_2O Mili-Q	W/O W:15 mL of DoTAB: PSS (1:3) O: 0.75 mL of VE + 0.75 mL NOM W/O + 100 mL of Ch 1% w/v + 100 mL of PSS 1% w/v	–O/W emulsions at 10% v/v with 50% VE and 50% NOM. –Ultrasound-assisted; Amplitude 27% for 3 min. –pH 4 adjusted 0.1M HCl –Emulsions were washed 3 times and centrifuged at 2500rpm and 10 min..	350 nm	47/NR	Ethanol at 50%; 30% was released in 1h. Ethanol at 50%; 70% was released in 12h. Ethanol at 50%; 100% was released in 80h	NR	NR	NR	NR	Sharipova et al. (2016)
Vitamin E	–Poly (L-L-Lactic Acid)	–Polyvinyl alcohol	W/O W: 50 mL PVA (1% weight) O: 5 g PLLA + 10 mL of ChO + 0.2 g of VE	–Homogenization of W+O was at 5000 rpm, 5 min. –The emulsion was agitated for 3 days to evaporate the solvent. –Centrifugation at 5000 rpm, 10 min.	> 10 μm	NR/ NR	NR	NR	NR	NR	NR	Chaiyasat et al. (2013)
Folic acid (VB9)	–Sporopollenin of Lycopodium clavatum	Dimethyl sulfoxide	Step 1: 200 mg VB9 + 10 mL DMS Step 2: Step 1 + 300 mg LCS	Evaporation of dissolvents 1. Agitation 1.5h 2.Agitation 500 rpm, 1h –Desiccator 2h –Filtration and drying at 78-80°C until constant weight.	28 μm	21.6/ NR	–SGF pH 1.2: 40% in 10*h* –SIF pH 7.4: 75% in 10*h* –0.1N NaOH: 95% in 10*h*	0.7478/ 0.7863 0.7620/ 0.8636 0.9297/ 0.9937	0.8948 0.9053 0.9913	0.9601 0.9986 0.9948	NR	Mohammed et al. (2021)
Vitamin D3 (VD3)	–Soy protein isolate –Carboxymethyl chitosan	–DeionizedH₂O	SPI:CMCS 1:1 pH 8.0 Coating: Core 10:1 (w/w)	Ionic gelation –Total coating concentration of 0.9 mg/mL –0.30 mg/mL of $CaCl_2$ –Centrifugation 30.000 g, 15 min dispersion in water and freeze-drying.	243.1 nm	96.75/ NR	–SGF pH 1.2: 40% en 30 min –SIF pH 7.4: 80% en 4h -0.1N NaOH: 95% en 10*h*	NR	NR	NR	NR	Teng et al. (2013)

AA: Ascorbic Acid; VE: Vitamin E; PGPR: Polyglycerol polyricinoleate; Caprol 10G100: Decaglycerol decaoleate; NaCAS: Sodium caseinate; A: Aerosil; CH_3COOH: Acetic acid; $CaCl_2$: Calcium chloride; GH: Glutaraldehyde; Span 80: Sorbitan monooleate; TF: Phosphate buffer; NaN_3: Sodium azide; SFT: Surfactant; DMS: Dimethylsulfoxide; PO: Paraffin oil; CO: Canola oil; NOM: Neutral miglyol oil; ChO: Chloroform; MeCl: Methylene chloride; PVA: Polyvinyl alcohol; SA: Sodium alginate; Ch: Chitosan; G: Gelatin; G-P: Genipin; WPC: Whey protein concentrate; P: Pectin; M: Maltodextrin; PLLA: Poly (L-L-Lactic Acid); PSS: Polystyrene sodium sulfonate; DoTAB: Dodecyl trimethyl ammonium bromide; LCS: Sporopollenin of Lycopodium clavatum; SPI: Soy protein isolate; CMCS: Carboxymethyl chitosan; SGF: simulated gastric fluid; SIF: simulated intestinal fluid; EE: Efficiency; Y: Yield and NR: Not reported.

Table 7
Microencapsulation of vitamins by ultrasonic, cooling and spray freeze-drying processes.

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Vitamin A	−Egg whites −Green tea/ iron complex	−H_2O Mili-Q −50 μL of VE + 1 mL of EW = Solution 1 Ratio of Tea infusion (2 sachets) and Iron solution (4:1) = Solution 2	−10 mg FS + 10 mL Solvent −GT infusión in 200 mL of H_2O at 80 °C and 5 min. Ratio of Solutions 1 and 2 1 mL and 200 μL	−Ultrasound 20 kHz. −Titanium tip: 3 mm. −Sonication at 160 W and 1 min. −Vortex mixer: 10 s for complexing and orbital agitation of solutions 1 and 2 at 40 rpm for 2 min. −Centrifugation of solutions at 95g for 1 min and resuspension in 500 μL of H_2O Mili-Q	5.3 ± 1.3 μm 5.2 ± 1.6 μm 5.3 ± 1.2 μm	NR/ NR/ NR/NR NR/ NR/ NR/NR NR/ NR/ NR/NR	67 % of the VD was released in the intestine and 32 % of the ingested vitamin is absorbed in the intestine due to degradation in the stomach.	NR NR NR	NR NR NR	NR NR NR	NR NR NR	Zhu et al. (2021)
Cyanocobalamin (VB12)	−Vegetable fat −Soy lecithin	NR	VB12:VF:SL 1:5:94 %:%:% VF melted 65 °C	−Spray-Chiller with air compressor at 8.2 bar and cooling bath at 5 °C. −Air velocity at 1,60 ms^{-1} and feed flow rate of 60 mL/min.	16.87 μm	101.1/ 102.6 /NR/ NR	−SGF at 90 min 90 % of the product was released. −SIF at 180 min 100 % released	NR	NR	NR	NR	Chalella Mazzocato et al. (2019)
Vitamin E	−Whey protein isolate	−WPC: H_2O Mili-Q −VE: Sunflower oil	Emulsion W/O = Core W: 90 % Saponin 0.1 % (w/w) O: 10 % (2 % of VE (w/w) and 8 % of SFO) Core:WPI 1:3	**Spray freeze-drying** −Double fluid nozzle at 10 cm of liquid nitrogen. −Primary drying temperature −25 °C and vacuum of 0.8 Torr. −Secondary drying temperature 10 °C and vacuum of 0.3 Torr.	145.3 μm	89.3/ NR /NR/ NR	NR	NR	NR	NR	NR	Parthasarathi and Anandharamakrishnan, (2016)
Ascorbic Acid	−Refined palm oil −Fully hydrogenated palm oil	NR	PO: FHPO = Coating30:70 (w:w) AA:Coating 20:80 −AA ground and sieved (0.125 mm) −PO and FHPO 80 °C.	−Spray nozzle of 2.0 mm and 80 °C −Flow rate of 0.60 kg/ h −Spray and cooling air flow rate of 831 L/h and 35,000 L/h −Inlet and outlet temperatures of 4 °C and 7.5 °C	140.14 μm	96.05/ NR /NR/ NR	Release was performed in H_2O at 25 °C At 180 min, 16 % of AA was released	0.9882/ 0.9563	0.9690	0.9564	NR	(dos Carvalho et al., 2019)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	

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Table 7 (*continued*)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models – Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Ascorbic Acid	–Interesterified fat –Soy lecithin	–H_2O	AA:H_2O 3.5:20 g:g SL:IF 0.3:35 g:g	–IG at 58°C –Chamber spray at 13°C with 1.2mm spray nozzle. –Air pressure 216 kPa. –Flow rate 50 mL/min. –Storage 7°C	72.87 μm	72.5/ NR /NR/ NR	After 2 months of storage at 7 and 24°C the microcapsules are stable; 80% AA.	NR	NR	NR	NR	(de Matos-Jr et al., 2017)
Ascorbic Acid	–Lauric acid –Oleic acid	NR	LA:OA=Coating 80:20 w:w AA: Coating 25:75 w:w LA and OA at 45.7°C	–PGPR-90 (5g/100g fatty acids) –Solution homogenization at 30.000 rpm, 5 min. –Double fluid spraying with 0.7mm nozzle. –Flow rate: feed, spray air and cooling: 5,28.104 m^3/h, 0.66m^3/h and 35m^3/h. –Inlet and outlet temperatures of 6°C and 9.5°C. –Storage: 10°C.	33 μm	80/ 73/ NR/ NR	H_2O at 25°C and in 120 min released 37mg/100mg of AA. The lipid solid microcapsules have a slow, controlled release.	NR	0.9651	NR	NR	Sartori et al. (2015)
Ascorbic Acid	–Stearic acid –Hydrogenated vegetable fat	NR	HVF:SA 1:1 Core:Coating 1:4 Total solids content was 25g/ 100g HVS and SA at 70°C for 30s	–AA ground and sieved (0.150mm) –Ultrasonic bath of the final solution at 70°C for 1 min –Spraying speed and flow rate: 12 mL/min and 24.5 m^3/h –Inlet and outlet temperature of 5°C and 15°C	31.2 μm	97.8/ NR /NR/ NR	Coating material protects up to 85% of AA when subjected to 170°C	NR	NR	NR	NR	Alvim et al. (2016)

AA: Ascorbic Acid; VE: Vitamin E; VD: Vitamin D; EW: Egg white; GT: Green tea; FS: Ferrous sulfate; VF: vegetable fat; HVF: Hydrogenated vegetable fat; SL: Soy lecithin; PO: refined palm oil; FHPO: fully hydrogenated palm oil; SGF: simulated gastric fluid; SIF: simulated intestinal fluid; IF: Interesterified fat; LA: Lauric acid; OA: Oleic acid; SA: Stearic acid; PGPR-90: Polyglycerol polyricinoleate; EE: Efficiency; Y: Yield; BV: bioavailability; BA: bioaccessibility and NR: Not reported.

Table 8
Microencapsulation of Vitamins by spray drying.

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/ BA (%)	*In vitro* release	Kinetic release models – Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Retinoic acid	Modified chitosan	–H_2O Mili-Q for biopolymers 1 % (w/v)	The ratio was 2.77 g/g	–Agitation:1200 rpm for 5 min –Standard nozzle: 0.5 mm	12.9 μm	65/18/NR/ NR	The release was in Octanol at 37 °C.At 138 min more than 80 % was released	0.911/-	0.992	0.937	0.937	Gonçalves et al. (2022)
	Sodium alginic acid	– AR used CO at 0.1 % (w/v)	For Ch, the pH was 7.41 and for AAS the pH was 7.42.	–Solution flow rate: 2 and 6 mL/min –Air flow rate: 35 m^3/h –Air pressure: 5–6 bar –Inlet and outlet temperature: 130 °C and 60–70 °C	5.9 μm	62/30/NR/ NR	The release was in Octanol at 37 °C.At 480 min more than 80 % was released	0.990/-	0.989	0.920	0.916	
Retinol	–Arabic gum –Maltodextrin –Starch	– Deionized H_2O –2mL CO + 0.04 g VA	AG:M:S = Coating 33.3:33.3:33.3 %:%:% Coating:VA 15 %:2% VA solution (w/v): (w/v)	–Agitation: 10.200 rpm for 5 min –Standard nozzle: 0.5 mm –Solution flow rate: 4 mL/min –Spray speed: 36 m^3/h –Air pressure: 5–6 bar –Inlet and outlet temperature: 150 °C and 80 °C	7.76 μm	97.5/20.1 /NR/NR	In coconut oil solution, 80 % of VA was released in 74 min and 100 % at 117 min.	0.949/ 0.771	0.951	0.951	0.964	Ribeiro et al. (2020)
Retinol	–Arabic gum	–100 mL H_2O Mili-Q at 15 and 20 % (w/v) AG. –2 mL of VA in CO at 2 % (w/v) and 37 °C	15 % AG solution + 2 mL of VA in 2 % CO (w/v)	–Agitation: 10.200 rpm for 5 min –Standard nozzle: 0.5 mm –Solution flow rate: 3–6 mL/min –Air flow rate: 35 m^3/h –Air pressure: 5–6 bar –Inlet and outlet temperature: 150 °C and 88 °C	4—–6 μm	NR/NR /NR/NR Yields ranged from 15 to 20 %	At 120 min and in both ratios of AG, all the initial amount of VA was released.	NR	NR	NR	NR	Gonçalves et al. (2017)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models – Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Vitamin B2	Modified chitosan	–Deionized H_2O	Coating: – 1% (w/v) + 200mL H_2O	–Solvent agitation: 1200 rpm for 2h –Homogenization of solutions: 500 rpm for 30 min	6.70 μm	99.8/ 45–54 /NR/ NR	100% release in SGF pH 1,2: 48 min 100% release in H_2O 11 min	0.998/- 0.996/-	0.986 0.960	0.981 0.998	0.982 0.995	Carlan et al. (2021)
	Arabic gum		Core: – 0,25% (w/v) of Vitamin B2 + 4 mL H_2O	–Standard nozzle: 0.5mm –Solution flow rate: 4 mL/ min –Air flow rate: 32 m^3//h –Air pressure: 6 bar	4.12 μm	99.3/ 45–54 /NR/ NR	100% release in SGF pH 1,2:10 min 100% release in H_2O 16 min	0.996/- 0.995/-	0.977 0.984	0.989 0.995	0.997 0.970	

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Table 8 (*continued*)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Vitamin B3	Modified chitosan		− 0,5% (w/v) of VB3 + 4 mL H_2O	−Inlet temperature: 120°C −Outlet temperature of Vit B2: 63-72°C	9.78 μm	98.9/ 58/ NR/NR	100% release in SGF pH 1,2:23 min 100% release in H_2O 11 min	0.983/- 0.995/-	0.996 0.982	0.942 0.982	0.994 0.994	
	Sodium alginate			−Outlet temperature of Vit B3: 55-63°C	4.77 μm	100/ 58/ NR/NR	100% release in SGF pH 1,2:26 min 100% release in H_2O 19 min	0.977/- 0.997/-	0.994 0.977	0.881 0.994	0.978 0.999	
Folic acid (VB9)	−Arabic gum	−Deionized H_2O	Coating: − 1% (w/v)	− Coating agitation: 1200 rpm for 2h −Homogenization of solutions: 500 rpm and 30 min −Standard nozzle: 0.5mm	0.2 ± 0.3 μm	NR/ 13.1/ NR/NR	The fastest release was in Arabic gum, starch and Modified chitosan; while the release was slow in alginate.	NR	NR	0.85	0.98	Estevinho et al. (2020)
	−Modified chitosan		Core: − 1% (w/w)		0.2 ± 0.3 μm	NR/ 13.1/ NR/NR		NR	NR	0.85	0.98	
	−Pectin			−Solution and air flow rate: 4 mL/min and 32 m^3/h	1.9 ± 1.0 μm	NR/ 30.6/ NR/NR		NR	NR	0.91	0.99	
	−Sodium alginate			−Air pressure: 6 bar −Inlet and outlet temperature: 120°C and 58°C	2.6 ± 1.2 μm	NR/ 44.4/ NR/NR		NR	NR	0.39	0.95	
	−Modified starch				1.0 ± 0.8 μm	NR/28/ NR/NR		NR	NR	0.49	0.99	

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Vitamins B12 and D3	−Arabic gum −Modified starch −Maltodextrin	−VD3: RBO was used − Para VB12, AG, SM and M, H_2O was used	Coating: AG:SM:M 38:60:2 Core: −VD3 (250μg/g of RBO) + 125 μg/g of coating	−Agitation: 3000 rpm for 2 min −Homogenization of solutions: 3000 rpm for 10 min −Standard nozzle: 0.5mm −Aspirator and feed rate: 1400 rpm and 20 rpm. −Air pressure: 2 bar −Inlet and outlet temperature: 140°C and 60°C	3 and 7 μm	VB12 NR/NR/ NR/151 VD3 NR/NR/ NR/109	SGF in 90 min 70% of VB12 was released and in 120 min 70% of VD3. SIF in 30 min 95% of VB12 was released and in 240 min 90% of VD3.	NR	NR	NR	NR	Bajaj et al. (2021)
Vitamin B12	−Arabic gum −Cyanobacteria *Cyanothece* sp. CCY 0110	−AG and CBC: Deionized H_2O at 1% (w/v) −VB12: 2% (w/v) desionized H_2O	100% of CBC solution at 1% (w/v) + 100% of VB12 solution at 2% (w/v). 50% of 1% (w/v) CBC solution + 50% of 1% (w/v) AG solution + 100% of 2% (w/v) VB12 solution.	−Agitation: 1200 rpm for 10 min −Standard nozzle: 0.5mm −Solution flow rate: 4 mL/min −Air flow rate: 32 m^3/h −Air pressure: 6 bar −Inlet and outlet	6–9 μm 5.12–5.91μm	NR/4/NR/ NR NR/18.8/ NR/NR	63.2% of released in 170 min. 63.2% released in 10 min.	0.976/ 0.968 0.990/ 0.858	0.898 0.847	0.551 0.585	0.744 0.990	Estevinho et al. (2019)

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Table 8 (*continued*)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
				temperature: 120°C and 65°C.								
Vitamin B12	Sodium alginate	−1% (w/v) of coating + deionized H_2O	100 mL of coating solution + 10 mL of VB12 solution	−Solvent agitation: 500 rpm for 30min	3.35 μm		H_2O and SGF was released in 15 min.	NR	NR	NR	NR	Carlan et al. (2018)
	Carrageenan			−Standard nozzle: 0.5mm		NR/NR/ NR/NR	H_2O and SGF was released in 5 min.					
		−2% (w/v) of VB12 + deionized H_2O		−Solution flow rate: 4 mL/min	5.16 μm							
	Maltodextrin			−Air flow rate: 32 m^3/h	4.83 μm	Yields ranged						
	Pectin			−Air pressure: 6 bar		from 27%	H_2O was released					
				−Inlet and outlet temperature: 120°C and 60-68°C	6.67 μm	to 50%.	in 70 min and SGF 40 min.					

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/ Y/ BV/ BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Vitamin B12	−Modified chitosan	−Deionized H_2O	Coating1% (w/v) Core:3,4 and 5% (w/w)	−Solvent agitation: 1200 rpm for 2h − Agitation of solutions: 500 rpm for 30 min −Standard nozzle: 0.5mm −Solution flow rate: 4 mL/min −Air flow rate: 32 m^3/h −Air pressure: 6 bar −Inlet and outlet temperature: 120°C and 53-58°	3 and 8 μm	NR/ 57/ NR/ NR	SGF pH 1.2 − Release times up to 63.2%: 3%: 8 min 4%: 6 min 5%: 6.5 min	NR	NR	NR	3%: 0.96 4%: 0.96 5%: 0.98	Carlan et al. (2017)
Vitamin B12	−Modified chitosan −Chitosan −Sodium alginate	−VB12 and VC: Deionized H_2O (10g/L). −M−Ch: 1% (w/v) of Ch and CH_3COOH at 1% (v/v) –Ch and SA at 1% (w/v) in Deionized H_2O	Vitamin concentration in the solution was 2.0% (w/w) for all treatments.	−Agitation:1200 rpm for 10 min −Standard nozzle: 0.5mm −Solution flow rate: 4mL/min −Air flow rate: 32m^3/h −Air pressure: 6.0 bar −Inlet and outlet temperature: 120°C and 65°C	3 μm	NR/ 47/ NR/ NR	63.2% was released in 3.5 min 63.2% was released in 39.5 min 63.2% was released in 7 min	0.921/ 0.986/- 0.938/-	0.884 0.761 0.696	0.925 0.951 0.878	0.958 0.961 0.953	(Estevinho and Rocha, 2017)
Vitamin C	−Modified chitosan −Chitosan −Sodium alginate					NR/ 45/ NR/ NR	63.2% was released in 4.5 min 63.2% was released in 30 min 63.2% was released in 4.5 min	0.914/- 0.889/- 0.947/-	0.843 0.551 0.837	0.842 0.870 0.874	0.967 0.927 0.964	
Vitamin B12	−Modified chitosan −Chitosan	−VB12 and VC: Desionized H_2O (10g/L). −M−Ch: 1% (w/v)	Vitamin concentration was 2.0% (w/w) for all treatments.	−Agitation1200 rpm por 10 min −Standard nozzle: 0.5mm	3 μm	NR/ NR/ NR/ NR	Release at H_2O. All samples were released before 20 min.	NR	NR	NR	NR	Estevinho et al. (2016)

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Table 8 (*continued*)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/First order	Higuchi	Korsmeyer-Peppas	Weibull	
Vitamin C	−Sodium alginate −Modified chitosan −Chitosan −Sodium alginate	of Ch and CH_3COOH at 1% (v/v) –Ch and SA at 1% (w/v) of desionized H_2O		−Solution flow rate: 4mL/min −Air flow rate: 32m^3/h −Air pressure: 6.0 bar −Inlet and outlet temperature: 120° and 65°C			M−Ch and SA microcapsules were released in 10 min and Ch microcapsules in 80 min.					

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/First order	Higuchi	Korsmeyer-Peppas	Weibull	
Ascorbic Acid	−Sodium alginate −Arabic gum	Distilled H_2O	Dispersed total solids 12.5 (g/L) AA:SA 1:1 Dispersed total solids 12.5 (g/L) VC:AG 1:2	−Homogenization of solutions: 1000 rpm, 3h and 25°C − Nozzle 0.7 mm −Solution flow rate: 2-7mL/min −Inlet and outlet temperature: 140°C and 86°C	10.9 μm 4.0 μm	98.9/63.1/NR/NR 98.4/83.2/NR/NR	SA and AG microcapsules keep the AA stable up to 188°C.	NR	NR	NR	NR	Barra et al. (2019)
Ascorbic Acid	−Enzyme-treated corn starch at 16 and 20h −Arabic gum	Distilled H_2O	17.6% (w/w to starch) AG + 15% (w/w) ETCS-16h + 10.6% AA (w/w to starch) 17.6% (w/w to starch) AG + 15% (w/w) ETCS-20h + 10.6% AA (w/w to starch) 10% (w/w) VC + AG	Homogenization of solutions:1000 rpm, 3h and 25°C −Solution flow rate: 7mL/min −Inlet and outlet temperature: 160°C and 130°C	1087.44 μm 1245.43 μm 12.72 μm	NR/NR/NR/NR	ETCS microcapsules with AG allow slow release of AA in SFG	NR	NR	NR	NR	Leyva-López et al. (2019)
Ascorbic Acid	− Taro starch	Distilled H_2O	AA:TS 10:100 g:g	−TS dispersion at 45°C and 30g/100g of H_2O. −Spraying and rotation speed: 19.5 g/min and 35,000 rpm −Inlet and outlet temperature: 145°C and 80°C	14.5 μm	20.9/NR/NR/NR	The TS is able to preserve AA under humidity and temperature conditions.	NR	NR	NR	NR	Hoyos-Leyva et al. (2018)
Ascorbic Acid	−Type A gelatin −Oxidized corn starch	Distilled H_2O	G:OCS 50:50 Core:Coating 20%: 80%	− Homogenization of solutions: 500 rpm, 30 min and 80°C. −Standard nozzle: 1.5 mm −Solution flow rate and Air pressure: 10 mL/min and 0.06 MPa −Inlet temperature: 150°C	NR	NR/NR/NR/NR	In solutions of pH 7.4 and 10 the release was similar; at 50h less than 80% of AA was released.	NR	NR	NR	NR	Dang et al. (2017)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)	References

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Table 8 (*continued*)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Ascorbic Acid	−Arabic gum	Distilled H_2O	AA:AG 1:4 Total solids content was 25g/100g	−Homogenization of solutions: 40°C. −Nozzle: 0.7 mm −Spray speed: 8 mL/min −Spray flow rate: 35 m^3/h −Spray gas flow: 10 L/min. −Inlet and outlet temperature: 150°C and 75°C	9.3 μm	100.8/NR/ NR/NR	Coating material protects up to 89% AA when subjected to 170°C	NR	NR	NR	NR	Alvim et al. (2016)
Vitamin D3 and rutin	−Chitosan −Zeina	−Distilled H_2O and ethanol (H_2O-E) (70%:30%) −Acetic acid	First step 45 mg of VD3 + 30 mg of R + 15 mL of absolute ethanol + 0.5g of Z + 40 mL of H_2O-E Second step 0.5 g of Ch + 150 mL of Distilled H_2O + CH3COOH (1% v/v)	−The first step solution was agitated for 1h and pumped (1.7 mL/min) to the second step solution. −pH 4 was adjusted with 1M NaOH. −Homogenization of solution 200 rpm and 1h. −Pumping at 15%. −Aspiration at 95%. −Inlet and outlet temperature: 180°C and 85-90°C.	< 10μm	74.97/77.7 /NR/NR	Optimal particle size for fortification in foods	NR	NR	NR	NR	Tchuenbou-Magaia et al. (2022)
Vitamin D3	− Whey protein isolate −Modified starch −Maltodextrin	Distilled H_2O	VD3-loaded nanoliposomes. 5 g EYL + 30 mL SO + 5 g GY + 500 UI of VD3 + 60 mL of Distilled H_2O Spray-drying solutions Coating WPC:SM:M 2%:3%:25% Core:Coating 1:4 Solids concentration was set at 30%.	−VD3 nanoliposomes were agitated at 60°C and subjected to ultrasound cycling for 5 min. −Solutions were homogenized at 10,000 rpm for 5 min. −Standard nozzle: 0.5 mm −Air flow rate: 73 m^3/h −Air pressure: 0.06 MPa −Inlet and outlet temperature: 170°C and 80°C	140 nm	NR/96.4/ NR/NR High percentages of M form spherical powders with a smooth surface.	NR	NR	NR	NR	NR	Jafari et al. (2019)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Vitamin D2	−Casein micelles	H_2O Agitation of CM at 2°C overnight	Coating 3.5% CM + H_2O To the coating was added 0.04 mmol/	−Agitation of CM + VD2 at 10°C for 1h −The process passes through ultrafiltration before spray drying.	105 nm	NR/ 76/ NR/ NR	90% of VD2 remained active in pepsin at pH 2.0 and pH 7.8. In addition, there was no loss in VD2 at 85°C and pH 4.0–4.3.	NR	NR	NR	NR	Moeller et al. (2018)

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Table 8 (*continued*)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
			L VD2. −pH 5.5 adjusted with 10% HCl	−Air flow rate: 6.7 kg −Feed flow rate: 191 and 203 g/min −Inlet temperature and outlet: 180°C and 80°C Pilot plant scale data								
Vitamin E	−Chitosan −Sodium dodecyl sulfate	Coating: H_2O buffered pH 4.0 VE: Medium chain triglycerides	Emulsion W/O W: Ch:SDS:AG (1:2:2) AG: Crosslinker O: 10% of VE in MCT	−The aqueous phase was homogenized: 5000 rpm, 30°C and 2h. − 2% silica emulsions −Nozzle: 0.7 mm −Aspiration: 0.6 m^3/min −Feed flow rate: 2.2 mL/min. −Inlet and outlet temperature: 160°C and 100°C.	6.23 μm	94/ 34/ NR/ NR	In 80% ethanol the total release was in 10 min.	0.8685/ 0.9902	0.8205	0.9938	NR	(Budinčić et al., 2022)
Vitamin E	−Chitosan − Sodium lauryl ether sulfate	Coating: H_2O buffered pH 4.0 Core: Medium chain triglycerides	Emulsion W/O (80:20) W: Ch:SLES:AG (1:2:2) AG: Crosslinker O: 10% of VE in MCT	−Homogenization of the aqueous phase for 24h. −Homogenization of the W/O solution, 5000 rpm, 30°C and 10 min. −2% aerosil as crosslinker for 2h. −Nozzle: 0.7 mm −Aspiration: 0.6 m^3/min −Feed flow rate: 2.2 mL/min. −Inlet and outlet temperature: 160°C and 100°C	5.04 μm	99.5/ NR/ NR/ NR	In 80% ethanol the total release was in 20 min.	0.9244/ 0.9195	0.9627	0.9999	NR	(Budinčić et al., 2021)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models — Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
Vitamin E	Starch	Coating: Desionized H_2O	1% VE (w/w) + 1% Coating concentration (w/w)	−Air pressure: 5-6bar −Aspiration rate: 36 m^3/h. −Inlet and outlet temperature: 150°C and 80°C	18.71 μm	99.25/ 15.10 /NR/ NR	Coating materials exceed 800 min of 100% release with octanol.	NR	NR	0.904	0.976	Ribeiro et al. (2021)
	Modified starch	Core: Ethanol		− Throughout the process the emulsion was continuously agitated.	25.10 μm	99.34/ 50.95 /NR/ NR				0.986	0.997	
	Modified chitosan				5.47 μm	97.45/ 55.39 /NR/ NR				0.994	0.997	

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Table 8 (*continued*)

Core	Coating material	Solvent	Formulation Core:Coating material	Process conditions	Particle size	EE/Y/ BV/BA (%)	*In vitro* release	Kinetic release models − Coefficient of determination (R^2)				References
								Zero/ First order	Higuchi	Korsmeyer-Peppas	Weibull	
	Arabic gum				4.37 μm	70.14/ 38.18 /NR/ NR				0.998	0.982	
Vitamin E	−Maltodextrin −Sodium caseinate	NR	M:SC:VE 18.5:7:24.5(w/w): (w/w): (w/w)	−Homogenization of the solution at 3000 rpm and 30 min. −Nozzle de 1.5 mm −Air pressure: 55 kgf/cm^2. −Spray speed: 20.000–25.000 rpm. −Inlet and outlet temperature: 110°C and 90°C.	23 μm	71.5/ NR/ NR/NR	Water-soluble microcapsules because the solubility time is no longer than 5 min.	NR	NR	NR	NR	Selamat et al. (2018)
Vitamin E	−Corn Starch	−MS: H_2O Mili-Q −VE: Absolute ethanol	MS:VE 9.5:0.5(w/w): (w/w)	−Dilution of MS for 2h, heated at 70°C for 15 min and stored at 4°C overnight. −Nozzle de 0.5 mm −Air pressure: 250 kPa −Spray rate: 7.5 mL/min. −Inlet and outlet temperature: 120°C and 75°C.	15 μm	90/58/ NR/NR	NR	NR	NR	NR	NR	Panyoyai et al. (2017)

AR: Retinoic acid; VA: Retinol; VC: Ascorbic Acid; VD3: Vitamin D3; VE: Vitamin E; R: Rutin; CH_3COOH: Acetic acid; HCl: Hydrochloric acid; NaOH: Sodium hydroxide; M−Ch: Modified chitosan; RBO: Rice bran oil; SO: Sesame oil; CO: Coconut oil; SFO: Sunflower oil; AAS: Sodium alginic acid; AG: Arabic gum; SA: Sodium alginate; M: Maltodextrin; S: Starch; SM: Modified starch; MS: Corn Starch; Ch: Chitosan; CBC: Cyanobacteria Cyanothece; G: Type A gelatin; OCS: Oxidized corn starch; ETCS: Enzymatically treated Corn Starch; TS: Taro Starch; Z: Zein; WPI: Whey protein isolate; CM: Casein micelles; EYL: Egg yolk lecithin; GY: Glycerol; SC: Sodium caseinate; SDS: Sodium dodecyl sulfate; SLES: Sodium lauryl ether sulfate; MCT: Medium chain triglycerides; SFG: Simulated gastric fluid; EE: Efficiency; Y: Yield; BV: bioavailability; BA: bioaccessibility and NR: Not Reported.

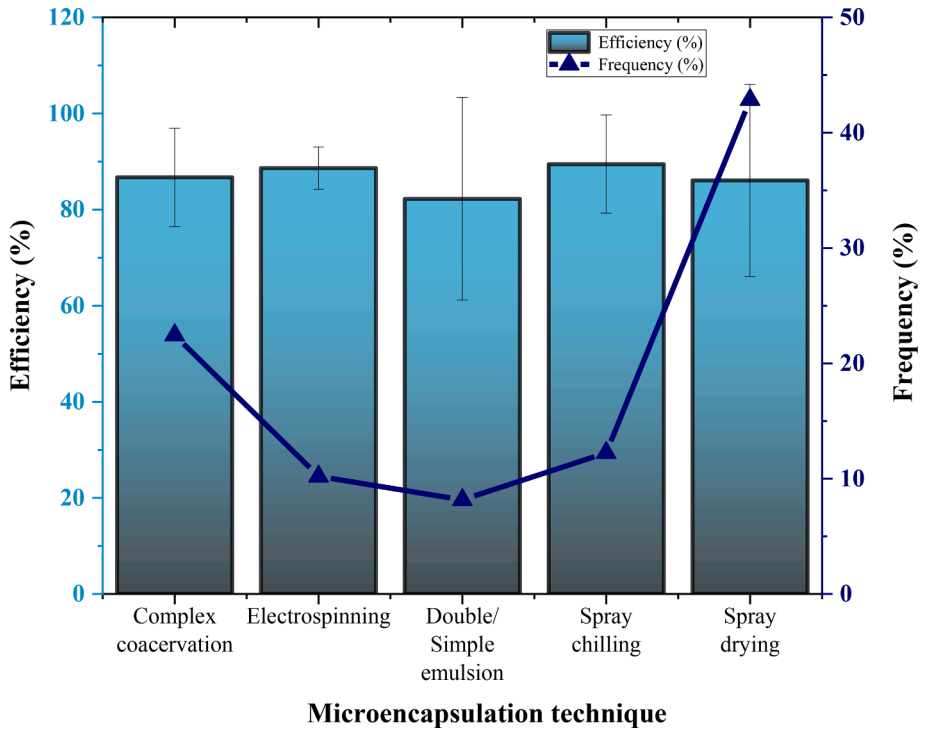

Fig. 1. Percentage efficiency and frequency of microencapsulation techniques in the microencapsulation of vitamins. Values are expressed as mean ± standard deviation.

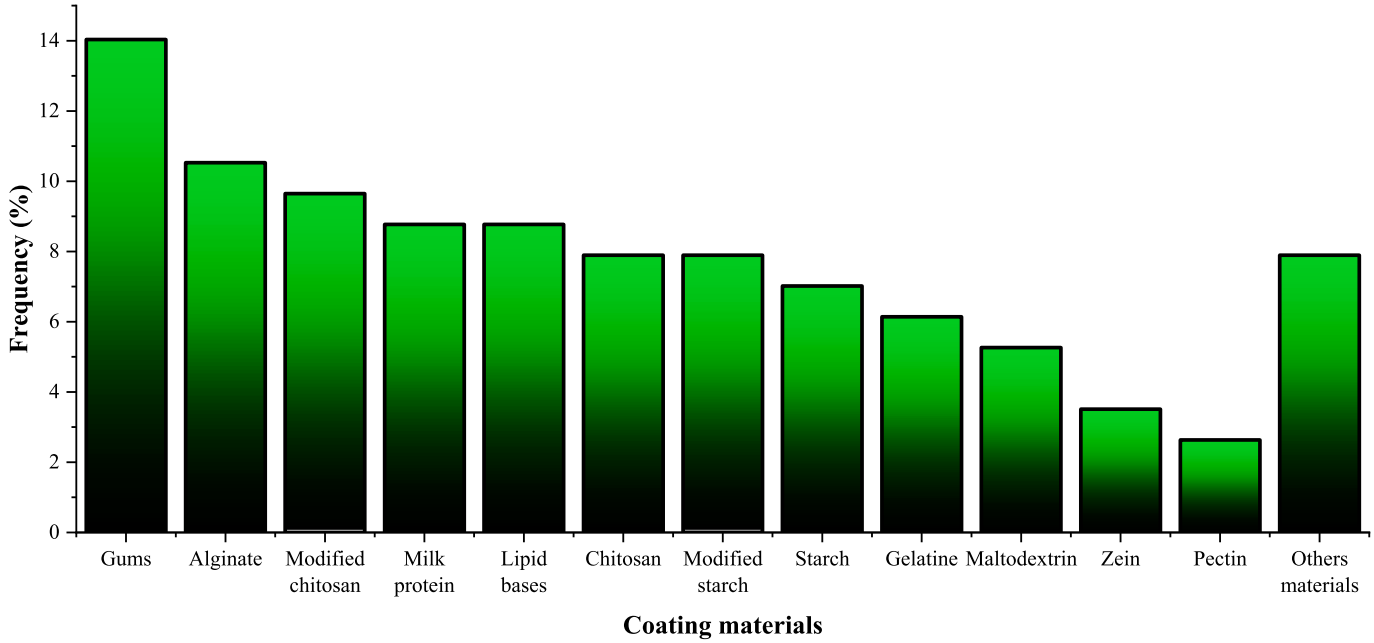

Fig. 2. Coating materials used in the microencapsulation of vitamins.

and electrostatic interactions between the coating material and the core contribute to efficiency values exceeding 90 % (Rodrigues da Cruz et al., 2019). Arabic gum and maltodextrin produce microcapsules with irregular surfaces and large pores. When starch is used, they exhibit an oval and regular shape, attributed to the elasticity of starch in the drying processes. Meanwhile, the combination of all three coating materials results in higher efficiency (97.5 %) and a release time of 117 min in coconut oil (Ribeiro et al., 2020). The interaction between Arabic gum and galactomannan has led to the formation of solid, oval-shaped microcapsules with a smooth surface, good efficiency, yield and a high load of vitamin E; these characteristics are attributed to the high viscosity values of galactomannan, which, upon interaction with Arabic gum, balance their properties and achieve stable microcapsules (Tarigan et al., 2018).

4.1.2. Alginate

The gelling capacity of sodium alginate is provided by the interaction of free carboxylic groups (COOH) with basic units in the presence of

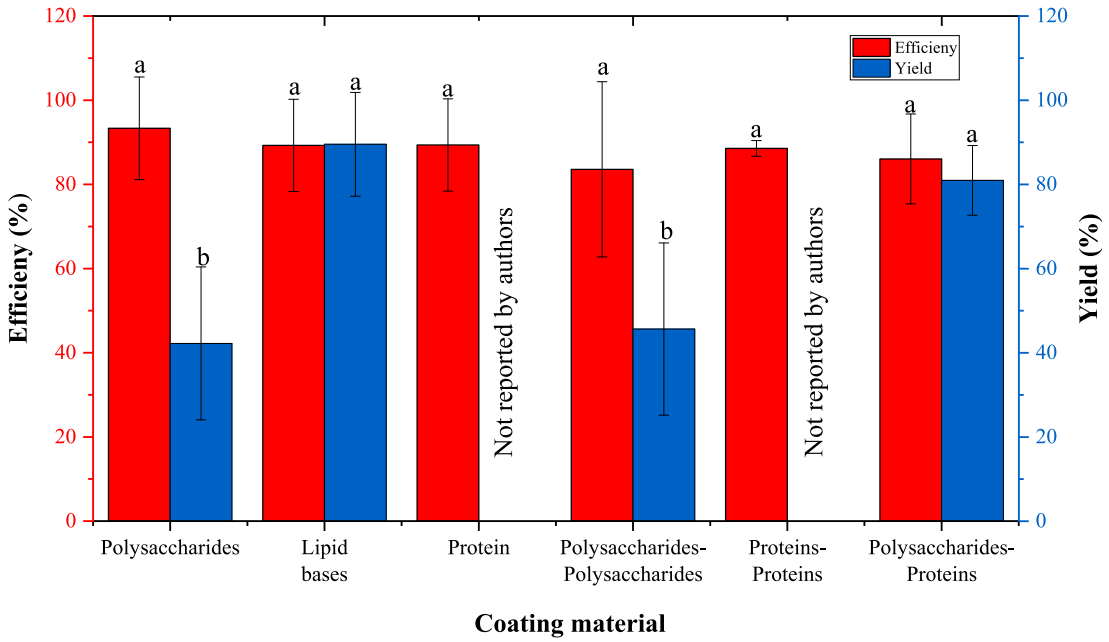

Fig. 3. Efficiency and yield of coating materials. The values are expressed as mean ± standard deviation and means not sharing a letter are significantly different.

basic divalent cations under moderate environmental conditions (Eslami et al., 2018). In comparison with the rough structure and depths of Arabic gum, sodium alginate provides a spherical shape, smooth surface area and a cavity on its surface (Estevinho et al., 2020; Estevinho and Rocha, 2017)). It has the ability to coat vitamins such as riboflavin (Danarto et al., 2020) and achieve their release within 1.5 h in simulated gastric fluid (SGF), while in water, it is released in less than 30 min (Carlan et al., 2021). The formation of vitamin D3 microcapsules in calcium alginate and chitosan is beneficial for the stability, efficiency, and release of the compound. The ionized free carboxylic acids of alginate form ionic bonds with the amino group of chitosan; this not only reduces pores across the entire surface of the microcapsule but also minimizes vitamin loss; however, when using only alginate, calcium ions and the carboxyl group of alginate create a rough and amorphous surface (Eslami et al., 2018). The use of sodium alginate is one of the parameters that must be optimized; the stability of the vitamin often depends on the relationship between the core and the coating. A higher proportion of vitamin results in a yield of less than 50 % (Carlan et al., 2018), while balancing, increasing and properly diluting the coating material increases viscosity, provides good ability to mask the vitamin and achieves efficiency values greater than 90 % (Carlan et al., 2021; Eslami et al., 2018).

4.1.3. Chitosan

Chitosan is a polymer derived from the deacetylation of chitin; its main monomer is 2-amino-2-deoxy-β-D-glucopyranose, which is linked through β-(1–4) bonds with 2-acetamino-2-deoxy-β-D-glucopyranose residues (Mohite et al., 2023). Chitosan achieves the formation of microcapsules with smooth, hole-free surfaces, spherical shape, 77.7 % yield and 74.97 % efficiency, proving to be of great interest in the food industry for the preservation of unstable compounds (Tchuenbou-Magaia et al., 2022). Due to its cationic nature, chitosan carries a positive charge, giving it the ability to form complexes with negatively charged biopolymers such as Arabic gum; the complex formation is directly related to the pH and the weight of the biopolymers (Butstraen and Salaün, 2014). However, due to the presence of the amine group, chitosan is soluble under acidic conditions, undergoing protonation. However, when exposed to solutions with a pH higher than 6, it loses its charge, deprotonates and transforms into an insoluble polymer (Jiménez-Gómez and Cecilia, 2020), this motivates the need to modify its chemical structure to make it adaptable in controlled delivery systems.

The structural modification of chitosan is an effective way to expand its applications and enhance its physicochemical, rheological and antibacterial properties such as solubility, thermal stability and resistance to oxidation (Azmy et al., 2019). To obtain chitosan derivatives, structural modification occurs in the hydroxyl, amino or both groups (da Silva Alves et al., 2021). The modification process can be carried out through chemical processes such as carboxylation, alkylation, acylation, quaternization and crosslinking, while physical processes involve the use of radiation, ultrasonic and thermal treatments (Baran, 2017; Estevinho et al., 2013; Fonseca-Santos & Chorilli, 2017; Klaypradit & Huang, 2008; Trimukhe & Varma, 2008; Wang et al., 2019; Wang et al., 2020). The modified chitosan is used to protect fat-soluble and water-soluble vitamins such as retinoic acid with 65 % efficiency and a zeta potential of 38 mV; generally, microcapsules with a zeta potential greater than 30 mV indicate good stability (Gonçalves et al., 2022). The solubility acquired by chitosan after modification allows for a uniform, homogeneous and non-coagulating dispersion; this characteristic ensures that the mixture loses moisture and the microcapsules do not get trapped on the cyclone wall when subjected to spray drying. The coating of modified chitosan is promising in terms of morphology, as it produces spherical microcapsules without wrinkles, with a regular surface and size of 5 μm (Ribeiro et al., 2021). Despite the advantages offered by modified chitosan, there is a faster release compared to its natural form (Carlan et al., 2021), so it is recommended to mix it with other materials to overcome this disadvantage.

4.1.4. Starch

The interaction of the helical forms of amylose and the branched structure of amylopectin is responsible for achieving favorable properties for microencapsulation (Hu et al., 2022). The slowing down of intermolecular interactions of amylose and a significant amount present in starch improves gelatinization fluidity and promotes the self-binding of starch with the microcapsule core; on the other hand, a higher content of amylopectin enhances the stability in freezing and thawing of the microcapsules (Zhao et al., 2023). The starch is easily accessible and can come from different sources such as amaranth, corn, taro, and those with modified chemical structures. Amaranth starch shows good thermal stability but low water-solubility; the 99 % amylopectin in its chemical

structure hinders its dissolution in high concentrations; however, subjecting amaranth starch to carboxymethylation processes (substitution of the hydroxyl group by carboxymethyl with negative charge) improves gelation, water solubility and achieves efficiencies ranging from 87.53 % and 98.47 % (Constantino and Garcia-Rojas, 2023). Taro starch exhibits different characteristics compared to other starches; it has a low amylose content and a significant amount of endogenous protein and phosphorus, causing emulsion effects (Fan et al., 2023); a high protein content leads to flocculation, hinders the spray-drying process and the formation of microcapsules. Proteins with positive charge can form coacervate complexes bound by negative starch chains; however, these complex formations are precipitated and unstable in aqueous conditions, resulting in an efficiency of 20.9 % (Hoyos-Leyva et al., 2018). On the other hand, the use of waxy corn starch produces a polymeric network that coats the vitamin, exhibits an amorphous shape, records low water activity, efficiency (90 %) and yield (58 %) (Panyoyai et al., 2017).

The industry modifies internal starch structures to enhance absorption, retention and binding with other coating materials (Leyva-López et al., 2019). The combination of modified starch and Arabic gum promoted the formation of vitamin D3-loaded microcapsules, due to its high viscosity and solid content, a firm and stable coating is formed to preserve the vitamin for three months (Bajaj et al., 2021). The combination of oxidized corn starch and gelatin improves the morphology and stability of ascorbic acid microcapsules. By binding hydroxyl and aldehyde groups with water molecules through hydrogen bonds, it achieves the production of smooth and compact microcapsules. This mechanism occurs within the internal cavities of starch polymers (Dang et al., 2017). Finally, starch processed by enzymatic hydrolysis produces maltodextrin, an oligosaccharide with unit's equivalent to dextrose; maltodextrin has the ability to form coating matrices (Jafari et al., 2019).

4.1.5. Maltodextrin

The preference for using maltodextrin is due to the equivalent units of dextrose (3 to 20), whose carbon chain can generate complex mixtures of high and low molecular weight (Garnero et al., 2013; Saavedra-Leos et al., 2015). The presence of helical structures and hydrophobic behavior in aqueous solutions gives it the ability to adapt to processes such as microencapsulation; a high content of dextrose results in a lower molecular weight, smooth surface and enhances the protection of the compound (Xiao et al., 2022). Using maltodextrin as the sole coating material results in slightly fractured microcapsules; however, when mixed with gelatin, it produces a rigid structure without breakage (Nami et al., 2023). Mixtures of maltodextrin and sodium caseinate achieve microencapsulation of α-tocopherol with efficiencies ranging from 59 to 71 %; however, due to the lipophilic nature of α-tocopherol and the hydro-solubility of maltodextrin, there is low oil retention and a reduced emulsifying capacity during the process (Selamat et al., 2018). The combination of maltodextrin and Arabic gum exhibits emulsifying capacity, forming denser but morphologically deficient particles (Bajaj et al., 2021; Jafari et al., 2019; Ribeiro et al., 2020).

4.1.6. Whey protein

The use of proteins as coating materials has garnered significant interest in the microencapsulation of vitamins; they have the ability to form stable emulsions and preserve the integrity of the active compound (Łopusiewicz et al., 2020). The amphiphilic nature of proteins and their good interfacial activity favor interaction at the oil–water interface, creating an emulsion (Fan et al., 2023). Whey proteins are a source of essential amino acids and have a branched chain (Jain et al., 2015); lactoglobulin and lactalbumin form stable emulsions; however, this capability is influenced by the pH and ionic strength of the microencapsulation process (Assadpour et al., 2017). Globular proteins of low molecular weight interact with lipid molecules of vitamin E, forming firm structures and stable microcapsules (Parthasarathi and Anandharamakrishnan, 2016). Additionally, the displacement of the protein in the water–air interaction and the formation of coating walls achieve a smooth and glassy surface, surpassing the coalescence of the core and preventing sticky interactions that occur in the drying chamber (Jafari et al., 2019). The complementation of proteins and polysaccharides improves the quality of the microcapsule in terms of yield and efficiency (Fig. 3); polysaccharides do not achieve proper absorption at the oil–-water interface due to the lack of lipophilic molecules, which, thanks to the thickening and stabilizing capabilities of polysaccharides, complement with proteins to obtain more stable microcapsules (Fan et al., 2023). The gelatin is a hydrocolloid that exhibits gelation properties at 37 °C, biocompatibility and bioadhesiveness, making it a suitable candidate for forming films and protective barriers (Dang et al., 2017; Milanovic et al., 2014).

4.1.7. Gelatin

The gelatin is a hydrocolloid that exhibits gelation properties at 37 °C, biocompatibility and bioadhesiveness, making it a suitable candidate for forming films and protective barriers (Dang et al., 2017; Milanovic et al., 2014). The formation of the gelatin and Arabic gum complex in a 6:1 ratio at pH 4.0 achieves an efficiency of 79.76 % and balances the positive charges of gelatin ($NH3^{+}$) with the negative charges of the gum (COO^{-}) through electrostatic interactions. Higher pH and an excess of both materials cause instability and phase separation (Santos et al., 2021). The use of sodium caseinate, gelatin, polyglycerol polyricinoleate and decaglycerol decaoleate forms spherical and slightly rough structures; the involvement of lipophilic emulsifiers stabilizes the microcapsule by insoluble compaction that occurs in the coating (Fraj et al., 2021). The viscosity in these cases is due to the electrostatic binding of negatively charged caseinate molecules and positively charged gelatin molecules. Additionally, the surfactant properties conferred by both proteins result from the presence of hydrophobic amino acids in gelatin and the flexibility of caseinate to absorb and unfold at the air/water and oil/water interfaces, forming an interfacial membrane (Milanovic et al., 2014).

4.1.8. Zein

Zein is a prolamin protein with high hydrophobic amino acid values, causing its insolubility in water but solubility in alcohols, alkaline solutions and anionic compounds (Coelho et al., 2021; Couto et al., 2023). Hydrophobic amino acids contain sulfur internally and polar amino acids; the interaction between zein's amine groups and the carboxylic groups of polysaccharides can form complex and stable microparticles (Shehzad et al., 2024). However, zein lacks stability under elevated thermal conditions due to the denaturation of its internal structure. Therefore, applications such as spray drying may result in low efficiency and performance values; meanwhile, in electrohydrodynamic processes at a temperature of 22 °C, zein achieves efficiency values of 93 % (Coelho et al., 2021, 2022).

4.1.9. Pectin

Pectin, a polysaccharide extracted through ionization of galacturonic acids, possesses gel-forming, stabilizing and thickening properties (Assadpour et al., 2017). It establishes electrostatic interaction with cationic biopolymers like alginate, forming more stable complexes that preserve the active compound (Li et al., 2021). This process is influenced by factors such as ionic strength, pH, biopolymer ratio, heat treatment, agitation and the degree of polysaccharide esterification (Rosales and Fabi, 2023); the lower the degree of esterification, the higher the number of free carboxylic acids, promoting the electrostatic binding of pectin with other compounds (Lara-Espinoza et al., 2018).

Microencapsulation of vitamins using natural biopolymers is an intriguing alternative for the food industry; they can form complexes with polysaccharides, proteins and lipid bases through covalent and electrostatic bonds, as well as some synergistic effects (α-D-glucopyranose and amino acids) (Nami et al., 2023; Singh et al., 2018). Fig. 3 highlights the efficiency and performance values resulting from binary

mixtures of lipid bases, polysaccharides, and proteins, proving to be viable and sustainable.

4.1.10. Lipid bases

Hydrophobic materials exhibit polymorphism, as they present the same chemical composition in different crystalline structures; this process originates from the liquid phase of the hydrophobic compound (melting), progresses through various forms: hexagonal (α), orthorhombic (β') and triclinic (β) and concludes with solid molecules (Fennema et al., 2017); polymorphic transformations are enhanced with a careful selection of raw materials and environmental conditions such as temperature, pressure and storage.

A successful microencapsulation process with these types of materials involves achieving the formation of β' crystals, as they are characterized by yielding flexible microcapsules with high retention of the active compound. The microencapsulation of ascorbic acid in neutral and hydrogenated palm oil succeeds in forming β' crystals; the presence of palmitic acid and triglycerides with 50 and 52 carbon atoms results in soft, spherical microcapsules with rough surfaces and adequate retention of ascorbic acid (dos Carvalho et al., 2019). One of the factors influencing the formation of lipid microcapsules is the solvent. Using water to dissolve ascorbic acid, interesterified fat and soy lecithin as the coating material produces microcapsules with smooth surfaces but with the presence of pores caused by the evaporation of water during spraying; this facilitates the entry of oxygen and, simultaneously, the degradation of the vitamin (de Matos-Jr et al., 2017). Solvent evaporation promotes the reduction of microcapsules when subjected to spray drying, while hydrophobic materials harden and maintain their original diameter during spray cooling (Alvim et al., 2016). A blend of soy lecithin (5 %) and vegetable fat (94 %) achieves the stability of vitamin B12 at 25 °C in the absence of light, preserving 92.46 % of the active compound for up to 4 months; in its free form, only 24.8 % is retained (Chalella Mazzocato et al., 2019). Hydrophobic materials offer a favorable alternative for the microencapsulation of vitamins. The low-temperature process promotes the formation of more stable solid particles over time, achieving promising physical characteristics such as efficiency (80 %) and yield (73 %) (Sartori et al., 2015).

4.1.11. Other materials

Polyelectrolytes and surfactants can be employed in the industry for the protection of active compounds, additionally, mixtures of polymers and surfactants have been established (Budinčić et al., 2021; Sharipova et al., 2016). Green tea is a rich source of epigallocatechin gallate and epicatechin, which possess the ability to absorb UV light; when mixed with ferrous sulfate, it forms phenol-metal complexes, the initial layer covers the entire surface of the vitamins. As a second layer, egg white can be utilized, as it enhances stability against heating, UV irradiation and humidity (Zhu et al., 2021). Natural biopolymers like *Lycopodium clavatum* sporopollenin are under investigation for the microencapsulation of vitamins, applying this compound as a coating material achieves good release and stability of folic acid (Mohammed et al., 2021).

4.2. PI02: What factors are involved in the controlled release of microencapsulated vitamins and how do they influence the release kinetics?

The release of active compounds has become a crucial assay before undergoing food fortification; the release process is the result of the rupture of the coating and detachment of the microencapsulated compound, consideration is given to the rate, release time and mathematical models that help predict the mechanism of microcapsule separation. These variables depend directly on the properties of the polymer and suspension medium conditions, such as pH (Uyen et al., 2020).

4.2.1. pH

The mouth, stomach and intestines have different pH values, allowing for the digestion and absorption of food. Therefore, the development and application of simulated assays enable the prediction of the behavior that foods would undergo in the body. The pH is a parameter that intervenes from the formation of microcapsules to complex coacervation processes (Table 4) and in the suspension medium where the release is evaluated. An optimal pH promotes the formation of coacervate complexes, consequently leading to efficient microcapsules with good yield, at a pH of 4.0, complexes of gelatin and Tara carboxymethyl cellulose are formed, showing a better balance between polysaccharide/protein charges and turbidity level, confirming the presence of complex coacervates. The optimization of this factor allows for efficiency values of 79.76 %, a zeta potential close to 0 mV and spherical microcapsules with an average size of 0.25 μm (Santos et al., 2021). At a pH of 4.5, the formation of complexes is higher, as the protonation of the wall material occurs at a pH of 4.2 (pKa of carboxylic groups), under this optimization, the efficiency and yield values depend directly on the material ratio (Jannasari et al., 2019; Constantino and Garcia-Rojas, 2023). When microcapsules undergo release tests, the suspension medium is responsible for altering the structure of the coating material, resulting in the protonation or deprotonation of the polymer; this causes a change in the shape, zeta potential, size, and release of the microcapsules.

The structure of polymers with amino groups such as chitosan can expand at a low pH due to the repulsions of the highly protonated group; meanwhile, exposed to a high pH, the structure will contract and/or become immiscible due to deprotonation and reduced repulsions (Safdar et al., 2019). When using calcium alginate as the sole coating material and neutral pH, the protonation of the carboxyl group (COOH) converts it into an ionized group (–COO-), causing electrostatic repulsion between negative charges along the entire structural chain of alginate; these repulsions result in swelling and larger pores on the surface of the microcapsule, leading to faster release (Eslami et al., 2018). In materials such as sporopollenin, simulated gastric fluid systems (SGF – pH 1.2) predict slow release and low solubility due to the protonation of carboxylic groups; meanwhile, in simulated intestinal fluid systems (SIF – pH 7.4), rapid release occurs through the deprotonation of carboxylic acids, the coating becomes highly soluble and forms carboxylic salts (Mohammed et al., 2021). An increase in the release rate in SIF (pH 7.0) is caused by the fragile electrostatic relationship of the coating materials and the presence of digestive enzymes, therefore, it is necessary to optimize this factor, considering the pH activation property, which will modify the release profile of microencapsulated nutrients (Constantino and Garcia-Rojas, 2023).

The release process of an active compound is controlled by the degradation of the coating, resulting in the diffusion of the compound from the encapsulating matrix. This behavior is reflected in current protective mechanisms such as nano/microencapsulation and pharmaceutical tablets. In this sense, the release mechanism that has been most developed for vitamins is the diffusion mechanism, the main characteristic of this behavior is the speed at which the polymer degrades from the outside to the inside, leading to a higher rate of water penetration and consequently a controlled release kinetics (Fu and Kao, 2010; Safdar et al., 2019). The diffusion mechanism of microencapsulated vitamins occurs through a biphasic pattern: a burst or explosion effect, followed by a slow and steady release. The burst effect is attributed to polymer degradation under extreme pH conditions and chemical alterations of the polymer (Carlan et al., 2018; Jain et al., 2015; Rodrigues da Cruz et al., 2019; Thakur et al., 2017). Another factor in the diffusion mechanism is the structural change that biopolymers undergo. The modification of functional groups makes the microcapsule more soluble, less stable and results in a burst release for modified chitosan (3.5 min), while in its natural form, a more prolonged release occurs (39.5 min) (Estevinho and Rocha, 2017).

4.2.2. Crosslinking agent

Crosslinkers are widely used in microencapsulation due to their rapid

and/or controlled release. The crosslinkers most frequently used and considered in this review include polyricinoleate polyglycerol, polysorbate, glycerol, genipin, sorbitan monooleate and glutaraldehyde (Assadpour et al., 2017; Coelho et al., 2022; Comunian et al., 2013; Danarto et al., 2020; Jain et al., 2015; Rodrigues da Cruz et al., 2019; Sartori et al., 2015). Most crosslinkers are synthetic and in some cases, toxic, such as glutaraldehyde, so their use in food applications is avoided (Ehrmann, 2021). The crosslinking process is mainly employed for biocompatibility and strengthening of proteins and amino acids (Fraj et al., 2021). In double emulsion techniques, the crosslinker increases efficiency indices due to its oil retention capacity. The incorporation of glycerol and polysorbate reduces the release process to 10 s under SGF conditions (37 °C), while the release time without a crosslinker is typically 14 min (Coelho et al., 2022), this behavior is consistent when adding 5 % polyglycerol polyricinoleate, leading to a rapid release (Sartori et al., 2015). Folic acid microcapsules are not stable when using polyglycerol polyricinoleate, but they are stable when employing sorbitan monooleate. This leads to flocculation and coalescence of microparticles, resulting in reduced release under acidic conditions and 78 % release under alkaline conditions (Assadpour et al., 2017), when employing a chemical microencapsulation technique, it is necessary to optimize the active compound, coating material, crosslinker and process conditions to achieve an appropriate profile of controlled release, exceeding 2 mmol/g of genipin reduces the release rate, but with an equal concentration, complete release is achieved in 60 min. This effect is due to the formation of more compact coatings that slow down the diffusion of the microcapsule (Fraj et al., 2021).

4.2.3. Mathematical models of vitamin release

Mathematical models have fostered a widespread practice in fields such as engineering, biology, science, technology, and medicine. The purpose is to describe the relationship between process parameters and real-world characteristics (Dash et al., 2010). In terms of controlled release, mathematical models serve five objectives that help us understand the scope a release process should have using mathematical equations (Malekjani et al., 2021):

a) Optimize the release mechanism.
b) Create and design products using the release kinetics.
c) Determine the physical release process through values estimated by the employed models.
d) Predict the release profile and rate to avoid unnecessary studies.
e) Define the possible factors that influence total release, such as the characteristics of the coating material and the morphology of the microcapsules.

Despite the existence of empirical, semi-empirical and realistic models in the release, significant differences can be observed when putting them into practice. Realistic models play a clearer, more objective role in the processes and quantitatively predict the possible effects involved in total release better. Moreover, they implement the execution of the 5 objectives of the release process. In contrast, empirical and semi-empirical processes are not suitable for achieving accurate predictions (Mehrnia et al., 2017). The use of mathematical models helps predict the phenomena that occur during the diffusion process (Carlan et al., 2021). The diffusion mechanism consists of chained processes such as:

- Wetting of the microcapsule.
- Swelling of the coating material.
- Disintegration or erosion of the microcapsule.
- Dilution of the active compound.
- Permeation of the active compound into the coating phase.
- Permeation of the active compound into the food phase.

Each of these processes has the ability to control the release rate and the rate of the free compound (Malekjani and Jafari, 2021). The process that controls the release rate in a food matrix simultaneously defines the release kinetics, while the process that controls the rate is related to the active compound, physicochemical characteristics of the coating material, morphology of the microcapsule and the solution in which the microcapsules are placed (Vasisht, 2014). There are some tools that help simulate the release process, such as mathematical models; Table 9 describes the mathematical models most frequently used in the microencapsulation of vitamins.

The zero-order model describes that the concentration of the active compound is a factor unrelated to the release rate; an increase or decrease in the compound does not alter diffusion. It is considered a zero-order prediction due to various factors such as slow release, solubility of the microcapsule and surface activity (Vasisht, 2014). This model, along with the Higuchi model, is most applicable when lipid bases are used as coating material, showing increased hydrophobicity, better affinity and low release of the core (dos Carvalho et al., 2019). The Higuchi model focused on a pseudo-steady state, where the percentage of released compound is proportional to the square root of the released time. It assumes constant diffusion, occurring only in one dimension without swelling. These characteristics are directly related to the shape and surface of the microcapsules. The compound slides through the surface pores, avoiding a modification in the initial size and swelling of the microcapsule. Under this concept, the Higuchi and Korsmeyer-Peppas models achieved the highest correlation coefficient (Fraj et al., 2021). On the other hand, the Korsmeyer-Peppas model is associated with the release mechanism of the active compound, this mechanism can detect Fickian diffusion, which is controlled by the diffusion coefficient and non-Fickian diffusion, which is related to the constant velocity and swelling of the microcapsule (Vasisht, 2014). The models of zero order and Korsmeyer-Peppas are acceptable due to their

Table 9
Mathematical models used in the release of vitamins.

Mathematical models

Zero order $Q_t = Q_0 + K_0 t$

First order $lnQ_t = lnQ_0 + K_1 t$

- t = Time (min).
  - Q_t = Amount of bioactive compound released at time t.
  - Q_0 = The initial amount of the bioactive compound is considered to be $Q_0 = 0$
  - K_0 = Zero-order release constant.
  - K_1 = First order release constant.

Higuchi $Q_t = K_2\sqrt{t}$

Korsmeyer-Peppas $Q_0/Q_\infty = K_3 t^n$

- t = Time (min).
  - Q_t = Amount of bioactive compound released at time t.
  - Q_0 = The initial amount of the bioactive compound is considered to be $Q_0 = 0$
  - Q_∞ = Release of the bioactive compound in infinite time.
  - K_2 = Higuchi release constant.
  - K_3 = Korsmeyer-Peppas release constant.
  - n = Exponent of the release process (Fickian diffusion mechanism).
  - $n < 0.43$ = Case I, time-dependent transport $t^{-0.57}$.
  - $0.43 < n < 0.85$ = Case II; anomalous transport, diffusion by means of swelling t^{n-1}
  - $n = 0.85$; Transport II; as a function of time-release of zero order
  - $n > 0.85$ = Transport Supercase II as a function of time t^{n-1}

Weibull

$$Q_t = Q_\infty\left[1 - e^{-\left(\frac{t - t_0}{t_d}\right)^\beta}\right]$$

- t = Time (min).
  - t_0 = Delayed release time, it is considered $t_0 = 0$.
  - t_d = Time taken to release 63.2 % of the bioactive compound.
  - Q_t = Amount of bioactive compound released at time t.
  - Q_∞ = Release of the bioactive compound in infinite time.
  - β = Curve shape parameter.
  - $\beta = 1$; Curve with exponential profile.
  - $\beta > 1$; Sigmoidal curve with inflection point.
  - $\beta < 1$; Curve steeper than an exponential profile.

Adapted from Carlan et al. (2021); Gonçalves et al. (2022) and Mohammed et al. (2021).

Table 10
Behavior of microencapsulated vitamins in fortified foods.

Food	Microencapsulated Vitamin	Behavior	References
Yogurt	Vitamin D3	• Higher viscosity. No increase in pH and acidity. Less syneresis. Good textural properties.	Nami et al. (2023)
	Vitamin D2	• Bioavailability of 92.6 %, compared to free vitamin (67 %).	Moeller et al. (2018)
Bread	Vitamin D	• Thermally stable microcapsules.	Zhu et al. (2021)
Cookies	Ascorbic acid	• Conservation of ascorbic acid around 85 %, whereas in its free form, it was 70 % and caused dark spots on the cookie's body. Stronger breakage (4.25 kgf) Water activity lower than the control sample	Alvim et al. (2016)
Gummy candies	β-carotene	• Vitamin recovery was 67 %. Bioaccessibility of 28 %. Reduction in hardness, chewiness and gumminess.	Constantino and Garcia-Rojas, (2023)

good correlation values (0.831 to 0.957); however, they only manage to fit into the linear region of the release process and determine the diffusion coefficient (Table 9), which predicts the release mechanism from a physical perspective (Ribeiro et al., 2020). The most fitting model for predicting the release mechanism is the Weibull model, providing correlation coefficients ranging from 0.884 to 0.999, along with the β value indicating the shape of the curve and highlighting the exponential profile that the release has followed (Gonçalves et al., 2022). Under this premise, the behavior of the coating materials is verified. For Arabic gum and xanthan, the β values were higher than 1, indicating a sigmoidal curve with an inflection point. The resistance of the coating walls is evidenced by determining that 63.2 % of retinoic acid was released from xanthan gum in 11 min and from sodium alginate in 143 min. The mathematical models of release are important tools to foresee and optimize the controlled release of active compounds. They allow designing efficient and precise systems, not only do they save time and resources in production, but they also contribute to ensuring the stability and effectiveness of the microcapsules, thus improving the quality of the final products in the food industry (see Table 10).

4.3. PI03: Which foods are fortified with microencapsulated vitamins?

The fortification of foods with micronutrients is a challenge faced by the food industry; direct addition is the main cause of triggering negative reactions in their physical, chemical and organoleptic characteristics, limiting their intake (Muñoz-More et al., 2023). In response to this, this review encompasses studies on fortification in different food systems, as detailed below.

4.3.1. Dairy products

Nami et al. (2023), observed that gelatin halted the aqueous network of yogurt and hardened the casein micelle network, while maltodextrin promoted gelation throughout the yogurt structure, demonstrating that the intervention of these two coating materials better protected vitamin D. Meanwhile, Moeller et al. (2018), determined that heating at 85 °C under pH 4–4.3 caused precipitation and consequently, conglomerates of caseins and double encapsulation; showing that the coating of casein micelles is a highly protective material against acidic conditions and high temperatures, leading to slow and steady release.

4.3.2. Baked products

Zhu et al. (2021), regarding microencapsulated vitamin D in bread, whose thermal process at 220 °C for 15 min demonstrated stability and good recovery, being a good possibility to improve nutritional quality. Alvim et al., (2016), evidenced that the incorporation of the vitamin in its free form caused dark spots due to oxidation and degradation in the baking process; this effect significantly affects people's acceptance.

4.3.3. Gummy candies

Constantino and Garcia-Rojas, (2023), showed that the bioaccessibility of candies enriched with microencapsulated β-carotene was low, possibly due to the complex structure of the food.

5. Future perspectives in vitamin microencapsulation

The enrichment of foods with microencapsulated vitamins is a favorable alternative for the entire population, including vegetarians and vegans, as it contributes to the proper functioning of the body. The Subcommittee on Interpretation and Uses of Dietary Reference Intakes of the Institute of Medicine, (2000), establish that daily values of vitamins in the body should not exceed 120 mg, including some to a lesser extent such as the B-complex and fat-soluble vitamins, this would necessitate adding lipid microcapsules in smaller quantities to avoid consumer rejection. Authors such Chalella Mazzocato et al. (2019), mention that microcapsules composed of lipid bases would act positively in products with high fat content such as avocado, butter, chocolate and yogurt, aiming to preserve sensory conditions and make the microcapsules imperceptible. One of the difficulties observed in this review is the lack of sensory tests in fortified foods and the absence of evaluations of bioavailability and bioaccessibility. Consumer approval provides valuable information about the sensory perception of the product and plays an important role in palatability, overall acceptance of the food and the success of the product in the market, meanwhile, using gastrointestinal simulations such as bioavailability and bioaccessibility is necessary to determine if the microencapsulated compound is viable in the human body. Biodisponibility represents the amount available to be absorbed by the organism and bioaccessibility focuses on the fraction released during digestion; these estimates are crucial to ensure the efficient absorption of microencapsulated vitamins and functional compounds. Optimization of the formulation in the microencapsulation process is one of the essential factors for improving biodisponibility and bioaccessibility, ensuring that the benefits of microencapsulation are reflected in demonstrative biological results. Finally, microencapsulation of vitamins is a good alternative for use in pharmaceutical products and dietary supplements, as well as its incorporation into solid, semi-solid and liquid foods, being ingested directly (in powder form) as a food additive.

6. Conclusions

The vitamins are integral to the functioning and development of human health; however, there are still diseases caused by vitamin deficiencies that pose the risk of death. Fortification is a favorable strategy to supply the daily intake levels of vitamins that the body needs; however, it is necessary to understand that vitamins are sensitive compounds susceptible to degradation during the processes of food manufacturing, storage, and handling. Microencapsulation is a favorable alternative to

preserve the stability of vitamins. Optimal formulation and the selection of coating materials generate thermally stable microcapsules with high efficiency values, controlled release profiles, good retention, and suitable morphological characteristics. In this regard, their incorporation into foods would not only preserve the stability of vitamins but also provide a favorable alternative to contribute to public health and improve the nutritional quality of the food.

CRediT authorship contribution statement

Luis Alfredo Espinoza-Espinoza: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Henry Daniel Muñoz-More:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Juliana Maricielo Nole-Jaramillo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luis Alberto Ruiz-Flores:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nancy Maribel Arana-Torres:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luz Areliz Moreno-Quispe:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jaime Valdiviezo-Marcelo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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