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Review

Advances in the Preservation of Plant-Based Pigments via Spray Drying—A Systematic Review

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Abstract: Natural pigments derived from plant sources are notable not only for their vibrant colors but also for their nutritional value and proven biological activities. Spray drying has emerged as an efficient and cost-effective encapsulation technique, offering significant advantages such as enhanced stability, improved handling properties, and protection against degradation. The diverse range of natural wall materials (e.g., polysaccharides, proteins, and lipids) and the variability in spray drying operating conditions provide numerous possibilities to optimize encapsulation processes. The aim of this systematic review was to evaluate and compare the key factors influencing spray drying encapsulation of plant-based pigments. ResearchGate, Scopus, and Google Scholar were searched between July and December 2024. Data extraction was performed manually using a standardized form to collect information on plant source, pigment type, wall materials (type and concentration), spray drying conditions (in-let/outlet temperatures and feed flow rate), and process results (encapsulation efficiency, process yield, and total pigment content). Future advances in spray drying should focus on the optimization of spray drying conditions. Furthermore, innovations in spray drying formulations, such as customized combinations of polysaccharides and proteins or the incorporation of emulsifiers, could lead to more effective and scalable encapsulation processes, supporting the development of high-performance stable pigments for food, cosmetic, and pharmaceutical applications.

Keywords: plant-based pigments; encapsulation techniques; spray drying; process optimization; wall materials; natural colorants

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1. Introduction

Pigments have a long history in human civilization, as the first records of their use date back to prehistoric times, when they were used to paint caves, create rock art, and decorate ceramics. These pigments were derived from sources, including minerals and colored earths such as iron oxide (ochre), manganese dioxide (black), titanium dioxide (white), and various clays with diverse shades [1].

Beginning in the 19th century, the creation of synthetic dyes revolutionized their use in various industries, offering advantages such as greater availability, enhanced color stability, and lower production costs [2]. However, growing concerns about the health risks associated with synthetic dyes such as allergic reactions, hyperactivity in children, and potential carcinogenicity, have driven the demand for natural alternatives [3].

In the modern food industry, plant-based pigments and colorants play a critical role not only in imparting color but also in providing essential functional characteristics. The color of both natural and processed foods serves a key indicator of freshness, quality and safety while strongly influencing consumer preferences due to its psychological impact [4].

Plant-based pigments have emerged as a promising alternative to synthetic dyes due to their bioactive properties, including antioxidant, anti-inflammatory, and photoprotective effects [5,6]. Among the most studied natural pigments are anthocyanins, carotenoids, chlorophylls, and betalains, which not only provide color but also offer functional benefits in food, pharmaceutical, and cosmetic applications. However, their widespread use is hampered by their susceptibility to degradation under environmental factors such as light, heat, oxygen, and pH changes [7–13].

Encapsulation is a well-studied strategy that has focused on improving the stability and bioavailability of plant-based pigments, and among the various encapsulation techniques, spray drying stands out as the most versatile for industrial applications [14–16]. This process allows the transformation of liquid pigment dispersions into stable powders, offering advantages such as longer shelf life, better handling, and increased protection against oxidation [14,17].

Despite the extensive use of spray drying to encapsulate plant-based pigments, significant gaps remain in the understanding of optimal operating parameters. Current research lacks a comprehensive analysis of the most effective wall materials, the influence of processing conditions on encapsulation efficiency, and the impact of spray drying on pigment bioactivity.

The aim of this systematic review was to evaluate and compare the key factors influencing spray drying encapsulation of plant-based pigments. Specifically, this review aims to:

1. Compare spray drying with other encapsulation techniques, such as freeze drying, coacervation, and fluidized bed coating to highlight its advantages and limitations in industrial applications.
2. Identify the most commonly used wall materials and their impact on plant-based pigment stability.
3. Evaluate the optimal spray drying process conditions (e.g., inlet/outlet temperature and feed flow) to maximize encapsulation efficiency and plant-based pigment retention.

By synthesizing recent advances in the field, this review provides insights into best practices for the stabilization and retention of plant-based pigments, facilitating their broader application in the food, cosmetic and pharmaceutical industries.

2. Methodology

2.1. Research Questions

The research questions addressed by this study are:

1. What makes spray drying the preferred method for encapsulating plant-based pigments compared to other encapsulation techniques?
2. What are the main wall materials used in spray-drying encapsulation of plant-based pigments, and how do they influence the stability and retention of these pigments?
3. What are the optimal spray drying process conditions (inlet/outlet temperature and feed flow rate) for different plant-based pigments to maximize encapsulation efficiency and pigment retention?

2.2. Search Strategy

The search process was conducted in ResearchGate, Scopus, and Google Scholar between July and December 2024. The search strategy followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The keywords used were: “encapsulation”, “spray dried”, “spray cooling”, “ultrasonics”, “inclusion”, “fluidized bed coating”, “coacervation”, “freeze drying”, “co-crystallization”, “extrusion”,

"wall material", "chlorophylls", "carotenoids", "anthocyanins", and "betalains". The search terms were used individually and in combination using Boolean operators to refine the search (e.g., "spray AND drying" or "spray AND drying AND carotenoids"). Filters were applied to include only peer-reviewed studies published in English.

2.3. Inclusion/Exclusion Criteria

The selection process was conducted in three phases. In Phase 1, studies were included if the title contained the term "encapsulation" and the abstract referred to spray drying applied to food products. In Phase 2, only studies using spray drying as the encapsulation method were selected, and publication years were restricted to post-2010 for book chapters and post-2017 for review and original articles. These years were chosen to ensure the inclusion of the most recent advances in the field. In Phase 3, full texts were reviewed, and studies were excluded if they lacked methodological details (e.g., missing encapsulation conditions), did not provide data on encapsulation efficiency, pigment retention, or stability data), or were not accessible through institutional databases or official sources.

A PRISMA flowchart (Figure 1) outlines the study selection process. Initially, 950 documents were identified across the databases. After applying the inclusion/exclusion criteria, the final dataset included 10 book chapters, 34 review articles, and 137 original articles.

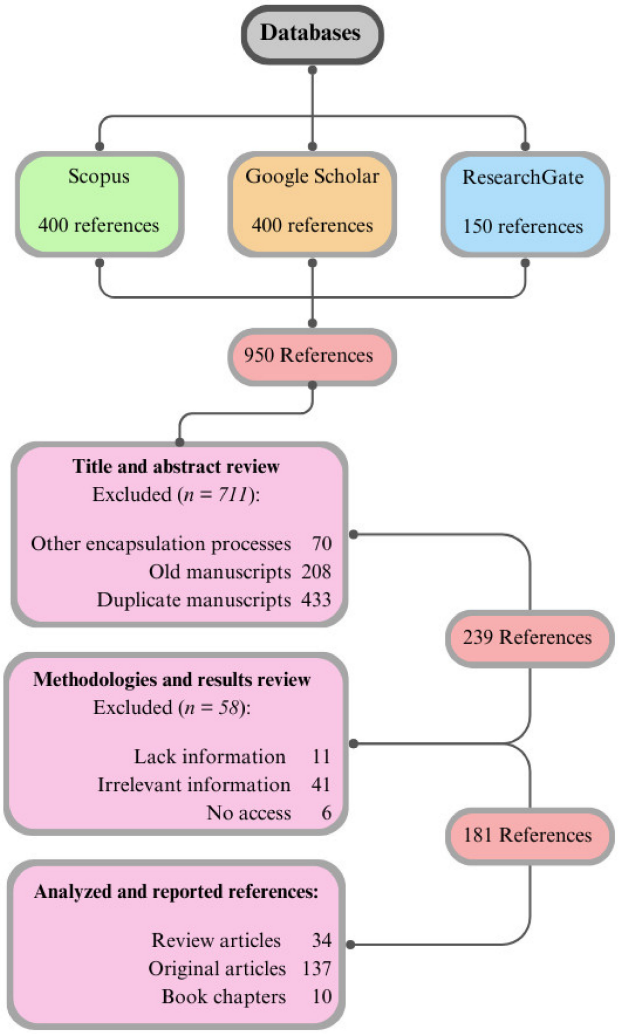


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart of the study selection process.

2.4. Selection Process

Data extraction was performed manually, collecting information on plant source, pigment type, wall materials (type and concentration), spray drying conditions (inlet/outlet temperatures and feed flow rate), and process results (encapsulation efficiency, process yield, and total pigment content). Data from each study was recorded in a structured table to facilitate comparison and synthesis.

3. Results

This section summarizes the results of the study.

3.1. Spray Drying Process

Encapsulation is a process designed to store, manage, preserve the stability, prevent degradation, and release core materials (e.g., substances, particles, enzymes, or compounds) under controlled conditions. During encapsulation, the core material is entrapped within a polymeric matrix known as the wall material, which can be composed of carbohydrates (e.g., starch, alginate, and maltodextrin (MD)), gums (e.g., Arabic (GA), karaya, and pectin), proteins (e.g., gelatin, whey (WPI), and gluten), lipids (e.g., beeswax and carnauba), or combinations of these materials [14–16].

Encapsulation processes can be physical, mechanical, or chemical methods, for example, extrusion, freeze drying, vacuum drying, spray cooling, fluidized bed coating, and spray drying, as specified in Table 1.

Table 1. Characteristics of encapsulation techniques used for conservation of antioxidants compounds.

Encapsulation Techniques	Characteristics	Examples of Encapsulated Components	References
Physical/Mechanical Techniques			
Spray drying	Process that atomizes a dispersion through heated air to evaporate water and produce a powder	Pigments, flavors, and sweeteners	[15]
Extrusion	Process that forces a material to flow through a hole to produce capsules	Flavors, extracts, and polymers	[18]
Freeze drying	Process that vacuums sublimate a frozen emulsion to produce a powder	Oils, extracts, and flavors	[19]
Spray cooling	Process that solidifies dispersion through cold air to generate particles	Pharmaceuticals, cosmetics, and food ingredients	[20]
Fluidized bed coating	Process that coated particles by spraying an encapsulating agent onto a fluidized powder bed	Vitamins, nutrients, and colorants	[21]
Ultrasonics	Process that generates capsules through acoustic cavitation from water-oil dispersions	Vitamins, fats, and lipids	[22]
Chemical Techniques			
Coacervation	Process that uses the electrostatic interactions of an emulsion to precipitate components	Oils, carotenoids, and nutraceuticals	[23]

Table 1. *Cont.*

Encapsulation Techniques	Characteristics	Examples of Encapsulated Components	References
Co crystallization	Process that incorporates a component in a solution supersaturated with sugar to crystallize it simultaneously	Flavors, oils, and spices	[24]
Inclusion	Process uses hydrophilicity-hydrophobicity of materials to trap components	Flavors, pigments, and spices	[25]

Spray drying is a unitary operation that converts liquid substances into solids in a continuous process consisting of three consecutive stages [14,26]. Prior to the spray drying process, the core material (component or substance to be encapsulated) must be dispersed with the wall material and additives (if required). The most used wall materials in spray drying processes are usually high molecular weight polymers such as starch, MD, and GA. The function of these materials is to increase the glass transition temperature of the dispersion to protect the core material, while reducing adhesion to the wall of the equipment during drying to minimize product losses [14,17]. The process starts with spraying the dispersion into the drying chamber at a controlled speed. The sprayed dispersion then comes into contact with the hot air that enters the drying chamber at a controlled flow rate and temperature. In this step, heat transfer occurs, causing the water in the dispersion to evaporate, resulting in the formation of a fine powder. Finally, the powder travels through the collection tunnel to the final container [14].

This process is fast, reproducible, scalable, and energy-efficient, making it cost-effective and economical. Furthermore, it has been shown to be useful for a broad spectrum of substances, including thermosensitive components (e.g., vitamins and antioxidant compounds) [14]. Therefore, it has been used at laboratory, pilot, and industrial scale (e.g., food, cosmetics, and pharmaceutical) [27,28], as it is intended to preserve, manipulate, store and transport the core materials in a simpler way [29].

3.2. Natural Pigments from Plant Sources

Plant-based pigments are primary and secondary metabolites generated as part of the plant's metabolism, performing functions such as defense, photoprotection, metabolic regulation, and light harvesting [6]. Pigments can be classified into four main groups: chlorophylls, carotenoids, betalains, and flavonoids. Each group has a unique chemical structure, but their subgroups have structural modifications that lead to functional differences, which are described in the following sections.

3.2.1. Chlorophylls

Chlorophylls are the pigments associated with the green color found in photosynthetic organisms such as cyanobacteria, algae, and plants. Their function is to transform light energy into chemical energy during photosynthesis [7]. Chlorophylls are found mainly in the green leaves of plants, but are also present in fruits, stems, and shoots. Not all green foods contain the same amount of chlorophylls or necessarily the same types. The levels can vary depending on the species and factors such as the plant's age and the growing conditions [30]. There are four types of chlorophylls (a, b, c and d); however, chlorophylls a and b are the only ones present in plants [31]. Typically, the ratio of chlorophyll a to b is 3:1, but this can vary depending on the light conditions in which the plant is growing. That is, the proportion of chlorophyll a increases with greater exposure to light [30]. The structural difference between chlorophylls a and b is only at carbon 7, the first has a methyl group

($-CH_3$) and the second an aldehyde group (-CHO), as shown in Figure 2. This difference allows for variations in the colors they represent, while chlorophyll a shows a blue-green color, while chlorophyll b shows a blue-yellow color [30].

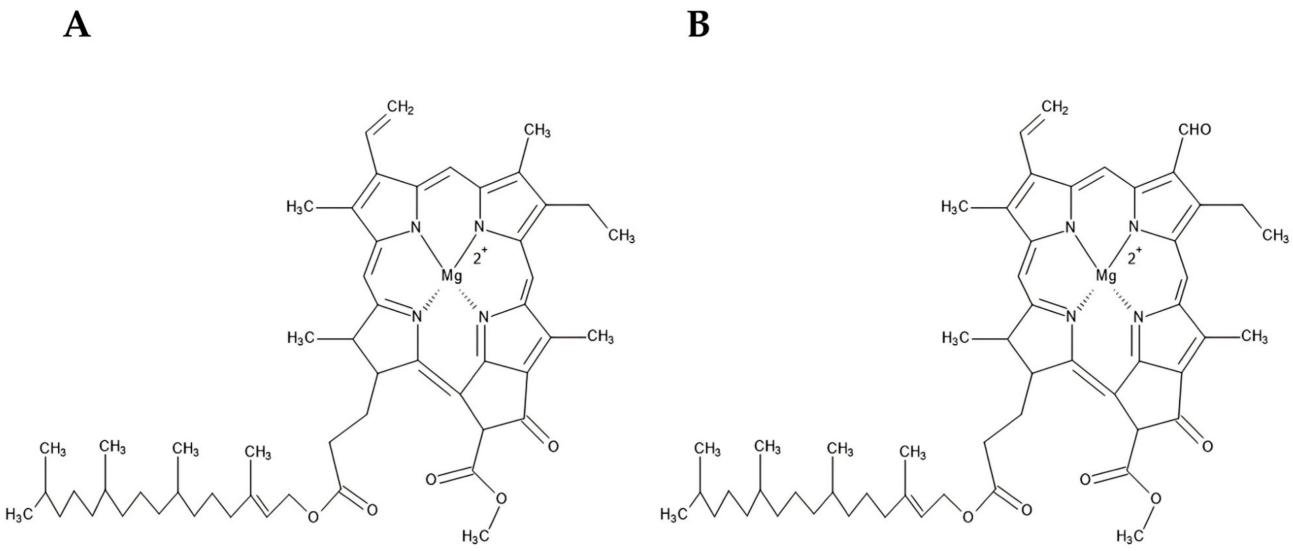


Figure 2. Chemical structure of (**A**) chlorophyll a and (**B**) chlorophyll b.

From a commercial perspective, chlorophylls and their derivatives are mainly used in the food industry as colorants, known for their ability to intensify and improve the color of food products [32]. Nutritionally, chlorophylls are a valuable source of vitamins A, C, E, and K; as well as essential minerals such as magnesium, iron, and calcium [30]. From a functional perspective, chlorophylls exhibit antioxidant properties, which make them the potential preventive and therapeutic agents in various diseases, including those associated with oxidative stress, such as inflammation, modulation of the intestinal microbiota, liver diseases, and even in the reduction in cancer cell proliferation [33,34].

3.2.2. Carotenoids

Carotenoids are a group of pigments found in plants, algae, and some photosynthetic microorganisms. In addition to their role in photosynthesis, they can attract insects for pollination and seed dispersal. Carotenoids are grouped into two main classes: carotenes and xanthophylls [8].

Carotenes are found in plant sources with colors ranging from deep orange to deep red, such as papaya, pomegranate, tomato, chili pepper, and watermelon [35,36]. The most common carotenes are α-carotene, β-carotene, and lycopene, which have a basic structure (Figure 3) composed only of carbon (-C) and hydrogen (-H) [8].

On the other hand, xanthophylls are found in marigold flowers, potatoes, lettuce, guava, corn, and other plant species with colors ranging from bright yellow to orange [36,37]. The basic structure of xanthophylls (Figure 3) includes hydroxyl groups (-OH), for example, β-cryptoxanthin, capsanthin, lutein, and zeaxanthin [38].

Carotenoids are used in the food and cosmetic industries in products such as fruit juices, tomato sauces, sweets, sunscreens, and tanning lotions, due to their accessibility, variety of colors, and their pigmenting power [39]. Additionally, β-carotene is a precursor of vitamin A, which is essential for nutrition, eye health, and strengthening the immune system [40]. Furthermore, carotenoids are known for their antioxidant activity, which is related to multiple neurodegenerative diseases (e.g., Parkinson's and Alzheimer's). They have been studied for their anti-inflammatory, anti-cancer, and cardiovascular potential, as well as their role in controlling obesity, diabetes, and hypertension [35,41].

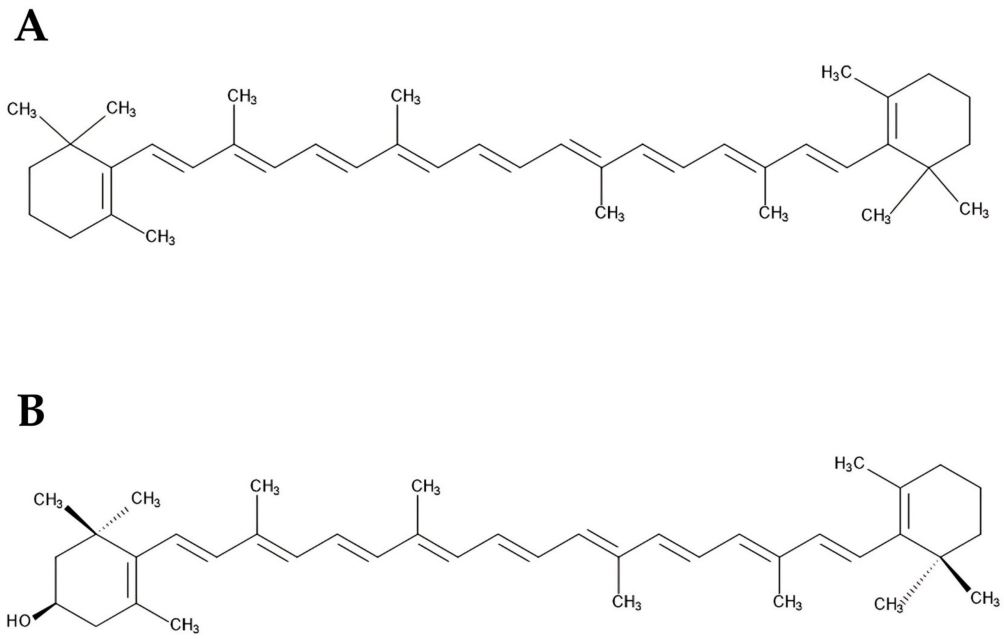


Figure 3. Basic chemical structure of (**A**) carotenes and (**B**) xanthophylls.

3.2.3. Betalains

Betalains are pigments found exclusively in the order Caryophyllales (families: Aizaceae, Amaranthaceae, Basellaceae, Cactaceae, Nyctaginaceae, Phytolaccaceae, Phytolaccaceae, and Portulacaceae) and in Basidiomycetes (higher fungi). Betalains are grouped into two main classes: the betacyanins and the betaxanthins, whose basic structure resembles betalamic acid (Figure 4). Betalains are primarily found in flowers, leaves, and stems with purple-red colorations, such as red beets, strawberries, dragon fruit, and prickly pears. The most common betacyanins are amaranthin, betanin, celosianin II, lampranthin I, and phyllocactin. On the other hand, betaxanthins are found in vegetables with yellow-orange colors, such as yellow beet, moss rose, Swiss chard, red goosefoot, and yellow prickly pear. The most common betaxanthins are dopaxanthin, indicaxanthin, purtulacaxanthin I, vulgaxanthin I, and vulgaxanthin II [9–12].

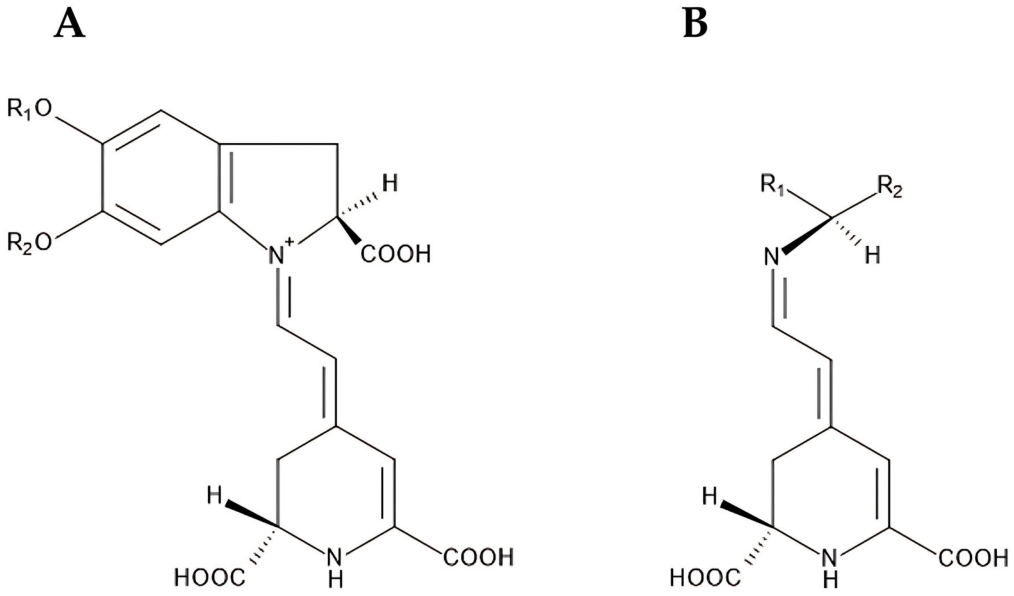


Figure 4. Basic chemical structure of (**A**) betacyanins and (**B**) betaxanthins.

Betalains have gained attention due to their potential use as natural colorants in the food and cosmetics industries [42]. In recent years, studies have emerged exploring the application of betalains in smart packaging formulations, which indicate changes in the atmosphere within the packaging [43].

Betalains are also valuable for their nitrate content, which has a positive impact on the intestinal tract and plays a role in cardiovascular diseases [44]. Ample evidence has demonstrated their anti-inflammatory, antioxidant, and antispasmodic activity. Additionally, betalains appear to be beneficial in treating diseases such as diabetes, cancer, hypertension, and atherosclerosis [44–46].

3.2.4. Flavonoids

Flavonoids are a broad class of polyphenolic pigments that act as secondary metabolites in various plants, including fruits, vegetables, leaves, flowers, and roots [47]. They are characterized by a chemical structure composed of two phenolic rings and a central three-carbon ring that form a chromophore structure (Figure 5). More than 9000 types of flavonoids have been reported, classified into subclasses such as flavonols, flavones, flavonones, flavanol, isoflavones, and anthocyanins [13]. The most common flavonols are kaempferol, quercetin, myricetin, and tamarixetin, which provide yellow to greenish-yellow colors from sources such as onions, broccoli, olive oil, and berries. Flavones such as chrysin, apigenin, rutin, luteolin, and tangeretin found in buckwheat, red pepper, tomato skin, parsley, thyme, and other vegetables provide pale yellow to colorless colors. Flavanols such as catechin, epicatechin, epigallocatechin, glausan-3-epicatechin, proanthocyanidins from apples, and tea provide yellow to dark brown colors. Anthocyanidins such as apigenidin, cyanidin, delphinidin, pelargonidin, malvidin are found in cherries, blueberries, strawberries, grapes, and other red, purple, and blue fruits. Flavanones (e.g., naringin, naringenin, taxifolin, and hesperidin) found in citrus fruits—grapefruits, lemons, and oranges—and isoflavones (e.g., genistein and daidzein) from soybeans and legumes are not typically pigments, as they have other important functions in plants, such as protection against pathogens, interaction with soil microorganisms, and regulation of plant growth [13,48,49].

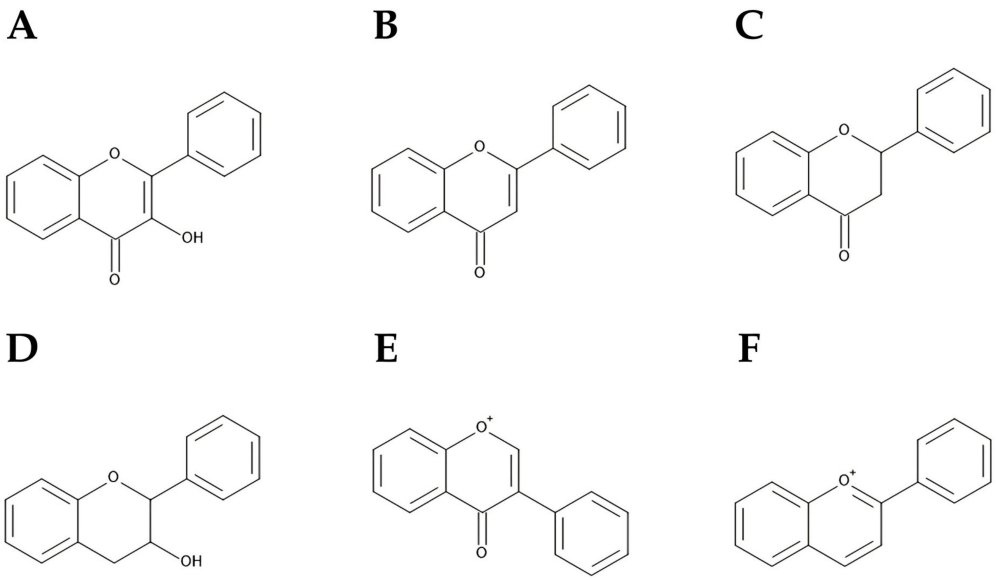


Figure 5. Basic chemical structure of (**A**) flavonols, (**B**) flavones, (**C**) flavonones, (**D**) flavanol, (**E**) isoflavones, and (**F**) anthocyanins.

Flavonoids are widely used in the food industry due to their coloring and aromatic properties. They are used as food additives, dietary supplements, and as agents to improve the stability and flavor of foods and beverages [48]. Furthermore, they are attractive to the pharmaceutical industry due to their diverse biological properties, including antioxidant, anti-inflammatory, antimicrobial, antitumor, and cardioprotective activities. Therefore, it has been suggested that regular consumption of flavonoids may be associated with reduced risk of chronic diseases such as cardiovascular disease, cancer, and neurodegenerative diseases [49].

3.3. Encapsulation of Plant-Based Pigments

Several studies have used advanced techniques, such as spray drying, to encapsulate plant-based pigments and improve their stability and bioavailability, as listed in Table 2. The results of the process, in terms of total pigment content (TPC), are related to the initial content of the core material. In other words, each plant material contains varying concentrations depending on the plant source, species, maturity, environmental conditions, cultivation practices, etc. [50,51]. Furthermore, the analysis of the reviewed studies reveals that the choice of wall material and its concentrations, as well as the drying conditions, significantly impact the encapsulation efficiency (EE%) and pigment content retention (Table 2). The selection of an appropriate wall material for pigment encapsulation depends on the properties (hydrophilic or hydrophobic) of these bioactive compounds, the purpose of encapsulation (protection, controlled release, etc.), and the conditions of the spray drying process [52,53].

Table 2. Encapsulation by spray drying of plant-based pigments.

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (μg/g)	
Chlorophylls										
Barley grass	--	MD	10–20%	140–170	90–105	1.80	nr.	nr.	3270–7290	[54]
Kale	--	WPI	5–15%	215	65	0.72	nr.	98–99	86–259	[55]
Kale	--	WPI	0–20%	120–180	70–90	0.72	nr.	95–99	nr.	[56]
Katuk	--	WPI	nr.	160	nr.	nr.	nr.	nr.	690–1350	[57]
Katuk	--	WPI	7%	150	nr.	nr.	nr.	23–32	785–1081	[58]
Moringa	--	MD	5.5–22.5%	116–144	nr.	2.30	3–40	nr.	350–1250	[59]
Spinach	--	GA+MD	0–8.75:18.75–35 *w*/*w*	170	85	0.30	62–94	45–81	nr.	[60]
Spinach	--	WPI	7.8%	132	85	1744	nr.	68	298	[4]
Spinach	--	WPI, SPI	6%, 6%	140	75–77	0.60	nr.	nr.	723–1160	[61]
Spinach	--	nr.	nr.	120	72–75	0.60	nr.	nr.	32,000–68,000	[62]
Spinach	--	FOS, MD	0.5–1.5%, 0.5–1.5%	180–190	80	nr.	nr.	nr.	5190–18,140	[63]
Spinach	--	GA+MD	0–5:5–10 *w*/*w*	145	95	0.09	nr.	62–77	35–47	[64]
Spinach	--	MD	nr.	160–200	80–100	1.54	nr.	nr.	262–579	[65]
Carotenoids										
Carrot	α-Carotene	GA+MD	15:15% *w*/*v*	190	80	nr.	nr.	nr.	366	[66]
Carrot	β-Carotene	GA+MD	15:15% *w*/*v*	190	80	nr.	nr.	nr.	730	[66]
Carrot	Carotenoids	MD+GA, MD+MG	10:5–10% *w*/*v*, 10:5–10% *w*/*v*	160	60–87	0.60	nr.	40–100	nr.	[67]
Carrot	Carotenoids	MD, GA, OSA	nr.	195	80	nr.	96–99	45–60	nr.	[68]
Carrot waste	β-Carotene	MD+WPI+IN	0–0.5:0–0.5:0–0.5% *w*/*v*	130	65	0.48	nr.	0–66	3.5–9.3	[69]

Table 2. *Cont.*

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (μg/g)	
Corn	Carotenoids	SC, SP, MD, IN	7% *w*/*v*	130	65	0.48	nr.	26–82	nr.	[70]
Cherry tomato	Lycopene	MD	10–20%	140–160	80	0.36–0.60	nr.	nr.	1.0–22	[71]
Gac fruit	β-Carotene	WPC+GA	7:3 *w*/*w*	160–180	nr.	0.18–0.36	nr.	nr.	334–674	[72]
Gogi berry by-products	Zeaxanthin	OSA, OSA+GA, OSA+SPI, OSA+GA+MD, OSA+GA+LPS	12–24% *w*/*w*, 12:12% *w*/*w*, 12:12% *w*/*w*, 13.5:7.5:3% *w*/*w*, 13.5:7.5:3% *w*/*w*	90	nr.	nr.	nr.	77–93	nr.	[73]
Golden berry	Carotenoids	MD, MS, GA, CB, IN, SA	3–20, 3–20, 13–20, 20, 20, 20	140	70	0.60	52–67	16–77	5569–1105	[74]
Guaraná by-product	Carotenoids	GA	20% *w*/*v*	140	nr.	0.60	nr.	90–100	nr.	[75]
Guaraná peels	Carotenoids	GA	20% *w*/*v*	100	nr.	0.60	nr.	97–100	41–96	[76]
Lupin seeds	Astaxanthin	MD	14–20%	140–160	nr.	nr.	nr.	37–93	50–1200	[77]
Lupin seeds	Astaxanthin	MD	15% *w*/*v*	120–160	nr.	0.24	nr.	88–97	nr.	[78]
Mamey	Carotenoids	MD+GA, MD+MG	10:5–10% *w*/*v*, 10:5–10% *w*/*v*	160	60–87	0.60	nr.	20–100	nr.	[67]
Mandarin	α-Carotene	MD	30–70%	140	80	0.30	20–60	nr.	5–30	[79]
Mandarin	Lutein	MD	30–70%	140	80	0.30	20–60	nr.	5–35	[79]
Mandarin	β-Cryptoxanthin	MD	30–70%	140	80	0.30	20–60	nr.	3–100	[79]
Marigold flower	Lutein	MD+GA	60:40 *w*/*w*	160–170	nr.	nr.	nr.	nr.	1046	[80]

Table 2. *Cont.*

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (μg/g)	
Marigold flower	Zeaxanthin	MD+GA	60:40 *w*/*w*	160–170	nr.	nr.	nr.	nr.	400	[80]
Marigold flower	Lutein	MD+GA	60:40 *w*/*w*	160–170	nr.	nr.	nr.	nr.	255	[80]
Marigold flower	Zeaxanthin	MD+GA	60:40 *w*/*w*	160–170	nr.	nr.	nr.	nr.	160	[80]
Marigold flowers	Lutein	MD+GA	50–70:30–50% *w*/*w*	150–190	nr.	0.05	50–73	42–78	660–1280	[81]
Marigold flower	Lutein	MD+GAc	6–7.5:14–17.5% *w*/*w*	170	nr.	0.20	62–70	35–83	5–6	[82]
Palm fiber	β-Carotene	GA	20–40%	130–202	nr.	nr.	nr.	61–86	nr.	[83]
Peach palm residues	β-Carotene	MD+GA	7.6:7.6% *w*/*v*	160	70	0.19	nr.	65–90	nr.	[84]
Pequi fruit	Lycopene	WPI, WPI+MD, WPI+IN	40% *w*/*v*, 20:20% *w*/*v*, 20:20% *w*/*v*	170	110	0.80	nr.	nr.	72–90	[85]
Pink guava	Lycopene	OFCM, AVM	1.2% *w*/*v*, 0.4% *w*/*v*	120	nr.	0.35	nr.	nr.	4104–4155	[86]
Pumpkin by-products	Carotenoids	GA	20% *w*/*w*	130	nr.	0.60	nr.	95–100	9–29	[87]
Pumpkin peels	Carotenoids	GA	20% *w*/*w*	130	nr.	0.60	nr.	46–54	105–368	[88]
Spinach	β-Carotene	WPI, SPI	6% *w*/*v*	140	75–77	0.60	nr.	nr.	130–170	[61]
Spinach	β-Carotene	nr.	nr.	132	65	0.42	nr.	nr.	800–2800	[89]
Spinach	Lutein	nr.	nr.	132	65	0.42	nr.	nr.	1000–2600	[89]
Spinach	α-Tocopherol	nr.	nr.	132	65	0.42	nr.	nr.	400–1200	[89]

Table 2. *Cont.*

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (µg/g)	
Tamarillo	Carotenoids	MD, GA, OSA, RMD	20% *w*/*w*	140–170	60–90	nr.	59–89	85–95	nr.	[90]
Tamarillo	Carotenoids	MD	13–38% *w*/*w*	130–180	nr.	0.49	nr.	nr.	1–48	[91]
Tomato	Lycopene	GA, IN	5–30%, 5–25%	110–200	nr.	0.22	15–50	3–26	nr.	[92]
Tomato	Lycopene	GA	12% *w*/*v*	160–180	nr.	0.24–0.72	nr.	nr.	40–110	[93]
Tomato waste	Lycopene	MD	22–78% *w*/*w*	35–65	nr.	0.45	nr.	nr.	700–1553	[94]
Tucuma coproduct	Carotenoids	MD+GA	5%:10% *w*/*v*	100	nr.	0.45	nr.	77	2559	[95]
Tucuma	Carotenoids	GA	8.5% *w*/*w*	120	nr.	0.60	nr.	80	2500	[96]
Tucuma oil	Carotenoids	GA	30% *w*/*w*	120–180	nr.	0.60	nr.	44–91	55–158	[97]
				Betalains						
Amaranth seeds	Betacyanin	MD+ClM	10% *w*/*v*:0–1% *w*/*v*	150	85	0.36	63–68	nr.	434–891	[98]
Amaranth seeds	Betaxanthin	MD+ClM	10% *w*/*v*:0–1% *w*/*v*	150	85	0.36	63–68	nr.	226–449	[98]
Beetroot	Betanin	MD, MD+XG	30%, 29.85:0.15	180	90	0.60	nr.	nr.	nr.	[99]
Beetroot	Betanin	MD, MD+XG	30%, 29.85:0.15 *w*/*w*	150	90	0.60	48–62	64–72	nr.	[100]
Beetroot	Betanin	MD, CM, MD+CM, MD+GA	10–15%, 10–15%, 5–10:5 *w*/*w*, 5–10:5 *w*/*w*	150	90	0.60	41–44	nr.	1415–2122	[101]
Beetroot	Betacyanin	MD, OF, IN, NU	1%, 1%, 1%, 1%	180	100	0.30	nr.	nr.	nr.	[102]

Table 2. *Cont.*

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (μg/g)	
Beetroot	Betaxanthin	MD, OF, IN, NU	1%, 1%, 1%, 1% *w*/*v*	180	100	0.30	nr.	nr.	nr.	[102]
Beetroot	Betanin	PPI	20% *w*/*v*	130	70	0.44	nr.	nr.	248	[103]
Beetroot	Vulgaxanthin-I	PPI	20% *w*/*v*	130	70	0.44	nr.	nr.	296	[103]
Beetroot	Betanin	IN+WPI	1–2:1–2 *w*/*w*	130–170	95–108	0.80	nr.	80–94	1578–1931	[104]
Beetroot	Vulgaxanthin-I	IN+WPI	1–2:1–2 *w*/*w*	130–170	95–108	0.80	nr.	80–94	1858–2218	[104]
Beetroot	Betacyanin	MD	15–35% *w*/*v*	150	nr.	0.3	60–70	nr.	nr.	[105]
Beetroot	Betacyanin	MD	15–35% *w*/*v*	110–170	nr.	0.30	50–70	nr.	nr.	[105]
Beetroot	Betanin	GA+TH+MD	4:4:2	120	85	0.47	nr.	62–70	45–80	[106]
Beetroot	Betacyanin	PP	3.5–7% *w*/*v*	125–150	50	0.54	28–42	40–55	8450–9810	[107]
Beetroot	Betacyanin	PP	3.5–7% *w*/*v*	125–150	50	0.54	28–42	15–60	4330–5060	[107]
Beetroot	Betanin	MD	34% v/w	175	82–85	nr.	55–95	nr.	2900–3000	[108]
Beetroot	Betanin	MD	nr.	nr.	nr.	nr.	nr.	nr.	10–150	[109]
Beetroot	Isobetanin	MD	nr.	nr.	nr.	nr.	nr.	nr.	10–120	[109]
Beetroot	Neobetanin	MD	nr.	nr.	nr.	nr.	nr.	nr.	10–45	[109]
Beetroot	Batalain	MD	4–8% *w*/*v*	140–148	nr.	0.15	11–18	nr.	13,710–18,280	[110]
Beetroot	Vulgaxanthin	MD	10% *w*/*v*	160	70	nr.	nr.	nr.	3–23	[111]
Beetroot	Betanin derivated	MD	10% *w*/*v*	160	70	nr.	nr.	nr.	55–94	[111]
Beetroot	Betanin	MD	10% *w*/*v*	160	70	nr.	nr.	nr.	3352–4084	[111]
Beetroot	Betacyanins derivated	MD	10% *w*/*v*	160	70	nr.	nr.	nr.	7–137	[111]

Table 2. *Cont.*

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (µg/g)	
Beetroot	Isobetanin	MD	10% *w*/*v*	160	70	nr.	nr.	nr.	981–1563	[111]
Beetroot	Betanidin	MD	10% *w*/*v*	160	70	nr.	nr.	nr.	9–63	[111]
Beetroot	Neobetanin	MD	10% *w*/*v*	160	70	nr.	nr.	nr.	60–82	[111]
Beetroot	Betalain	MP, NU, MD, KT	nr.	90–130	55–80	0.72	55–76	77–84	5271–5811	[112]
Beetroot	Betanin	MP, NU, MD, KT	nr.	90–130	55–80	0.72	55–76	79–87	3119–3421	[112]
Beetroot	Vulgaxanthin	MP, NU, MD, KT	nr.	90–130	55–80	0.72	55–76	73–84	2153–2469	[112]
Beetroots	Betanin	MD	nr.	140	73	0.27	nr.	nr.	nr.	[113]
Bougainvillea	Betacyanin	PD, IN, PD+IN, IN+ALB	15% *w*/*w*, 15% *w*/*w*, 7.5:7.5 *w*/*w*	160	nr.	0.60	52–78	98–100	nr.	[114]
Bougainvillea	Betaxanthin	PD, IN, PD+IN, IN+ALB	15% *w*/*w*, 15% *w*/*w*, 7.5:7.5 *w*/*w*	160	nr.	0.60	28–51	93–99	nr.	[114]
Cactus	Betaxanthin	MD, ClM	1:0.225 *w*/*w*	170	77	0.49	nr.	60–100	340	[115]
Globe amaranth	Gomphrenin I	MD	20 *w*/*w*	140	72	0.36	nr.	nr.	6900	[116]
Globe amaranth	Gomphrenin II	MD	20 *w*/*w*	140	72	0.36	nr.	nr.	45,250	[116]
Globe amaranth	Gomphrenin III	MD	20 *w*/*w*	140	72	0.36	nr.	nr.	19,800	[116]
Globe amaranth	Isogomphrenin I	MD	20 *w*/*w*	140	72	0.36	nr.	nr.	3300	[116]

Table 2. *Cont.*

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (μg/g)	
Globe amaranth	Gomphrenin III isomer	MD	20 *w*/*w*	140	72	0.36	nr.	nr.	42,000	[116]
Globe amaranth	Isogomphrenin III isomer	MD	20 *w*/*w*	140	72	0.36	nr.	nr.	16,000	[116]
Jiotilla	Betacyanin	ClM	1 g	140	70	0.33	24–69	nr.	285–1719	[117]
Jiotilla	Betaxanthin	ClM	1 g	140	70	0.33	24–69	nr.	628–2055	[117]
Pitahaya	Betaxanthin	MD, PPM	1 g, 1 g	170	nr.	0.35	25–50	nr.	85–87	[118]
Pitahaya	Betanin	MD, FL	25% *w*/*w*, 25% *w*/*w*	150	75	0.60	nr.	82–98	nr.	[119]
Pitahaya	Betacyanin	MD, WPI	20–40% *w*/*v*, 20–40% *w*/*v*	100	nr.	0.15	30–75	95–99	nr.	[120]
Pitahaya	Betacyanin	ClM	1 g	140	70	0.33	42–67	nr.	380–1708	[117]
Pitahaya	Betaxanthin	ClM	1 g	140	70	0.33	42–67	nr.	444–2218	[117]
Pitahaya	Betacyanin	MD	30%	140–180	nr.	1.37	nr.	nr.	80–412	[121]
Pitahaya	Betacyanin	NST, SST, PST	10% *w*/*w*, 10% *w*/*w*, 10% *w*/*w*	140	80	0.20	nr.	94–97	346–553	[122]
Pitahaya	Betaxanthin	NST, SST, PST	10% *w*/*w*, 10% *w*/*w*, 10% *w*/*w*	140	80	0.20	nr.	94–97	403–538	[122]
Pitahaya	Betacyanin	MD	15%	165	80	0.60	17	46	500	[123]
Pitahaya	Betaxanthin	MD	15%	165	80	0.60	17	10	50	[123]
Prickly pear	Betacyanin	MD	30% *w*/*w*	160–180	70–80	nr.	70–100	65–95	217–410	[124]
Prickly pear	Betaxanthin	MD	30% *w*/*w*	160–180	70–80	nr.	70–100	65–95	150–320	[124]
Prickly pear	Betaxanthin	MD	6–30 g	110–180	nr.	0.18	40–62	92–99	180–198	[125]
Prickly pear	Indicaxanthin	MD	1% *w*/*v*	150	nr.	0.18	nr.	87–100	nr.	[125]
Prickly pear	Betacyanin	MD	10% *w*/*v*	120–140	nr.	nr.	nr.	nr.	56–803	[126]

Table 2. *Cont.*

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (μg/g)	
Prickly pear	Betaxanthin	MD	10% *w*/*v*	120–140	nr.	nr.	nr.	nr.	39–385	[126]
Prickly pear	Betaxanthin	MD	15% *w*/*v*	160	75	0.30	nr.	58–99	nr.	[127]
Prickly pear	Betanin	ST	0.5–15% *w*/*v*.	120	72	0.30	29–61	nr.	3500–6800	[128]
Quinoa	Betacyanin	MD	10–30% *w*/*v*	140–180	nr.	0.40	17–43	nr.	199	[129]
				Flavonoids						
Andean blueberry	Anthocyanin	GA, MD, MD+GA	20% *w*/*w*, 20% *w*/*w*, 10:10% *w*/*w*	170	80	0.48	nr.	81–96	700–880	[130]
Andean blueberry	Anthocyanins	PPPM, GA	6% *w*/*v*, 6.2% *w*/*v*	170	nr.	0.35	24–69	nr.	216–10,822	[131]
Banana flowers	Anthocyanin	MD	14% *w*/*v*	170	80	0.36	nr.	96	576	[132]
Bayberry	Flavonoids	MD	nr.	160	90	0.90	nr.	nr.	640–950	[133]
Blackcurrant	Anthocyanin	MD	20% *w*/*w*	130	nr.	0.48	nr.	nr.	900	[134]
Blackcurrant pomace	Anthocyanin	BP, CPP	14% *w*/*v*, 14% *w*/*v*	160	80–84	0.60	nr.	nr.	18,000–22,000	[135]
Blood orange by-product	Anthocyanin	SA, β-CD	1–2% *w*/*v*. 1–2% *w*/*v*	120	68–71	0.30	nr.	nr.	8100	[136]
Blackcurrant juice	Anthocyanins	MD, IN, MD+IN	30–40% *w*/*v*, 30–40% *w*/*v*, 20–26:10–13% *w*/*v*, 23–30:7.5–10% *w*/*v*	180	70	nr.	nr.	nr.	2184–7273	[137]
Blackcurrant juice	Flavonols	MD, IN, MD+IN	30–40% *w*/*v*, 30–40% *w*/*v*, 20–26:10–13% *w*/*v*, 23–30:7.5–10% *w*/*v*	180	70	nr.	nr.	nr.	219–342	[137]
Blue corn	Anthocyanins	AF	6–12% *w*/*v*	150	85	nr.	nr.	10–23	900–12,000	[138]

Table 2. *Cont.*

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (μg/g)	
Blueberry fruit	Quercetin	MD	10–30% *w*/*v*	170–210	nr.	nr.	0–11	0–14	0–2	[139]
Blueberry waste	Anthocyanins	IN, SA	2% *w*/*v*, 2% *w*/*v*	150	80	0.72	60–72	nr.	16,920–19,540	[140]
Calafate	Flavonoids	MD	10–30 g	100–140	nr.	0.06	57–61	41–57	11,900–14,800	[141]
Centella asiatica	Quercetin	MD+CD	68:12 g	140–160	nr.	0.33	nr.	50–99	nr.	[142]
Chokeberry	Flavonoids	MD, SM	5% *w*/*v*	130	56	0.48	nr.	73–97	nr.	[143]
Chokeberry	Flavonoids	GA	5% *w*/*v*	130	56	0.48	nr.	84	nr.	[144]
Cinnamon	Flavonoids	MD+AG	5–12.5:5–15% *w*/*w*	160	nr.	0.60	nr.	nr.	34,000–85,000	[145]
Citrus by-product	Flavonoids	MD, MD+SP, MD+Car	1 g, 5:1 g, 9:1 g	125	55	0.24	35–45	58	340	[146]
Corn	Anthocyanin	Hβ-CD	20% *w*/*w*	140	80	0.60	nr.	nr.	1191	[147]
Cranberry	Anthocyanins	MD, GA, MD+GA	15% *w*/*v*, 15% *w*/*v*, 7.5:7.5% *w*/*v*	185	105	nr.	nr.	59–70	749–1028	[148]
Cranberry juice	Flavonols	MD	15% *w*/*v*	180	71	nr.	nr.	nr.	435–3727	[149]
Cranberry juice	Flavanols	MD	15% *w*/*v*	180	71	nr.	nr.	nr.	125–926	[149]
Cranberry juice	Anthocyanins	MD	15% *w*/*v*	180	71	nr.	nr.	nr.	57,425	[149]
Cupuassu	Flavonoids	MD	5–10% *w*/*v*	nr.	nr.	nr.	12–19	45–82	5890–13,160	[150]
Elderberry	Anthocyanin	MD	20% *w*/*w*	130	nr.	0.48	nr.	nr.	2500	[134]
Firethorn	Flavonoids	MD+GA	1–4:1–4% *w*/*w*	130–150	nr.	0.36	nr.	nr.	40–280	[151]
Grape by-product	Anthocyanin	nr.	nr.	120–160	68–98	0.60–0.84	5–19	60–73	16	[152]

Table 2. *Cont.*

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (μg/g)	
Grapefruit integro pectin	Hesperidinc	nr.	nr.	110	nr.	0.20	95	nr.	13,400	[153]
Grapefruit integro pectin	Naringinc	nr.	nr.	110	nr.	0.20	95	nr.	28,700	[153]
Italian black rice	Anthocyanins	MD, GA, MD+GA		150	nr.	0.42	nr.	nr.	81,300–93,600	[154]
Laurel leaves	Flavonoids	β-CD, β-CD+MD, β-CD+GA	4–14 g	120–180	70–90	nr.	66–84	45–92	11,428–13,932	[155]
Lemongrass	Flavonoids	GA, MD, GA+MD	10% *w*/*v*, 10% *w*/*v*, nr.	110–150	nr.	0.28	nr.	nr.	2500–5500	[17]
Lippia citriodora	Flavonoids	MD, IN	2–7 g	135–195	60–90	0.12	26–75	86–89	6719	[156]
Manilkara zapota	Flavonoids	MD	21% *w*/*v*	130	60	0.55	nr.	nr.	1847	[157]
Maize waste	Flavonoids	MD	10 g	nr.	nr.	nr.	76	99	nr.	[158]
Moldavian balm	Flavonoids	MD+AP	1–3:10 g	120–180	nr.	0.96	64–90	nr.	200–400	[159]
Moringa leaves	Flavonoids	LBG, TG, CMC, LBG+TG, TG+CMC, CMC+LBG	1%, 1%, 1%, 0.5:0.5%, 0.5:0.5%	120	68–71	0.12	56–68	24–36	14,270–26,820	[160]
Moringa leaves	Flavonoids	MD+HMP	9–10:0–1% *w*/*v*	120–160	nr.	0.48	nr.	nr.	32,000–48,130	[161]

Table 2. *Cont.*

Source	Pigment Type	Wall Materials		Spray Drying Conditions		Process Results				Reference
		Type	Proportion or Concentration	Tin (°C)	Tout (°C)	FFR (L/h)	PY (%)	EE (%)	TPC (μg/g)	
Nettle leaves	Flavonoids	MD, MD+GA, CD, CD+GA	nr., 1–3:1 *w*/*w*, nr., 1–3:1 *w*/*w*	120–200	70–100	nr.	68–83	96–99	1157	[162]
Rabbiteye blueberries	Anthocyanins	WPI, SPI, WPI+HMP, SPI+HMP,	10% *w*/*v*, 4% *w*/*v*, 10:1–4% *w*/*v*, 4:1–4% *w*/*v*	165	70	0.24	nr.	75–93	nr.	[163]
Phyllanthus niruri	Quercetin	MD, WPI, MD+WPI	20% *w*/*w*, 20% *w*/*w*, 2:18% *w*/*w*	180	nr.	nr.	nr.	75–85	nr.	[164]
Purple potato	Anthocyanins	MD	5–20 g	92–180	nr.	0.18	20–81	59–93	1340	[165]
Rabbiteye blueberries	Anthocyanins	WPI, SPI, WPI+HMP, SPI+HMP,	10% *w*/*v*, 4% *w*/*v*, 10:1–4% *w*/*v*, 4:1–4% *w*/*v*	165	70	0.24	nr.	75–93	nr.	[163]
Raspberry	Anthocyanin	MD	20% *w*/*w*	130	nr.	0.48	nr.	nr.	500	[134]
Roselle	Anthocyanins	MD	50–100 g	150–170	91–99	0.50	nr.	5–25	6000–11,000	[166]
Spent coffee grounds	Flavonoids	MD, GA, MD+GA	20 g, 20 g, 10:10 g	100	nr.	0.11	20–60	nr.	360–788	[167]
Tintorera grape waste	Anthocyanin	MD	10–30% *w*/*v*	90–120	50–80	0.24	nr.	nr.	880–1770	[168]

nr.: not reported; AF: agave fructan; AG: acacia gum; ALB: albumin; AP: apple pectin; AVM: aloe vera mucilage; BP: buckwheat protein; CB: cellobiose; CD: cyclodextrin; CM: chia mucilage; CMC: carboxymethyl-cellulose; CPP: chia pea protein; Car: carrageenan; ClM: cladode mucilage; EE: encapsulation efficiency; FFR: feed flow rate; FL: fibersol; FOS: fructans; GA: gum Arabic; GAc: gum acacia; HMP: high methyl pectin; Hβ-CD: hydroxypropyl β-cyclodextrin; IN: inulin; KT: kleptose; LBG: locust bean gum; LPS: L. barbarum polysaccharide; MD: maltodextrin; MG: mesquite gum; MP: milk powder; MS: modified starch; NST: modified starch; NU: nutriose; OF: oligofructose; OFCM: Opuntia ficus-indica cladodes mucilage; OSA: octenyl succinic anhydride starch; PD: polydextrose; PP: pea protein; PPI: pumpkin protein isolate; PPM: pitahaya peel mucilage; PPPP: prickly pear peel mucilage; PST: phosphorylated starch; PY: process yield; RMD: resistant maltodextrin; SA: sodium alginate; SC: sodium caseinate; SP: soy protein; SPI: soy protein isolate; SST: succinylated starch; ST: starch; TPC: total pigment content; TG: tragacanth gum; TH: tehalose; Tin: inlet temperature; Tout: outlet temperature; WPC: whey protein concentrate; WPI: whey protein isolate; XG: xanthan gum; nr.: not reported; β-CD: β-cyclodextrin.

4. Discussion

In this section, we discuss the answers to our research questions.

4.1. Versatility of Spray Drying for Encapsulating Plant-Based Pigments

The encapsulation of bioactive compounds and pigments can be achieved by various physical, mechanical and chemical techniques, each influencing the stability, functionality and applicability of the encapsulated compounds. Compared to other physical and mechanical techniques, spray drying offers advantages for encapsulating plant-based pigments.

Extrusion, although effective for encapsulating flavors and polymers, has limitations in preserving thermosensitive compounds due to the high pressures involved in the process [18]. Freeze drying provides excellent stability for oils and extracts, but its high cost and energy consumption make it less viable at an industrial level compared to spray drying [19]. Spray cooling, often used in the pharmaceutical and cosmetic industries, has limited efficiency in retaining hydrophilic pigments, such as anthocyanins and betalains [20]. Fluidized bed coating is suitable for vitamins and colorants but has lower capacity for encapsulating natural pigments due to the need for preformed particles [21]. Ultrasonic technology, although innovative and promising, is more oriented towards the encapsulation of fats and lipids, making it less effective for hydrophilic pigments like anthocyanins or carotenoids [22].

Chemical encapsulation techniques, such as coacervation, co-crystallization and inclusion, offer advantages for retaining oils and lipophilic compounds. However, their efficiency for encapsulating plant-based pigments may be limited, especially in those highly sensitive to oxidation. Coacervation effectively encapsulates carotenoids but poses challenges in controlling particle size and ensuring long-term stability [23]. Co-crystallization, commonly used for flavors and oils, is less suitable for pigments due to the need for supersaturated sugar solutions for simultaneous crystallization [24]. Finally, inclusion relies on hydrophobic and hydrophilic interactions to trap compounds within a matrix, but its applicability with spray drying depends on the interaction between the host and the encapsulated compound [25].

Spray drying stands out for its versatility and efficiency in encapsulating plant-based pigments, surpassing other techniques in scalability, cost, and industrial adaptability. This makes it suitable for applications in food, cosmetics and pharmaceutical products [14]. The growing number of scientific publications in recent years highlights its increasing use, not only for plant-based pigments but also for bioactive components in general (Figure 6).

4.2. Wall Materials Used for Spray Drying of Plant-Based Pigments

Water solubility is a crucial characteristic in encapsulation, as it facilitates the formation of homogeneous solutions or suspensions. Most polysaccharides used as wall materials are hydrophilic, meaning they have an affinity for water [169]. However, some modified or complex polysaccharides, such as cyclodextrins, may have hydrophobic properties, allowing for the encapsulation of liposoluble bioactive compounds [170].

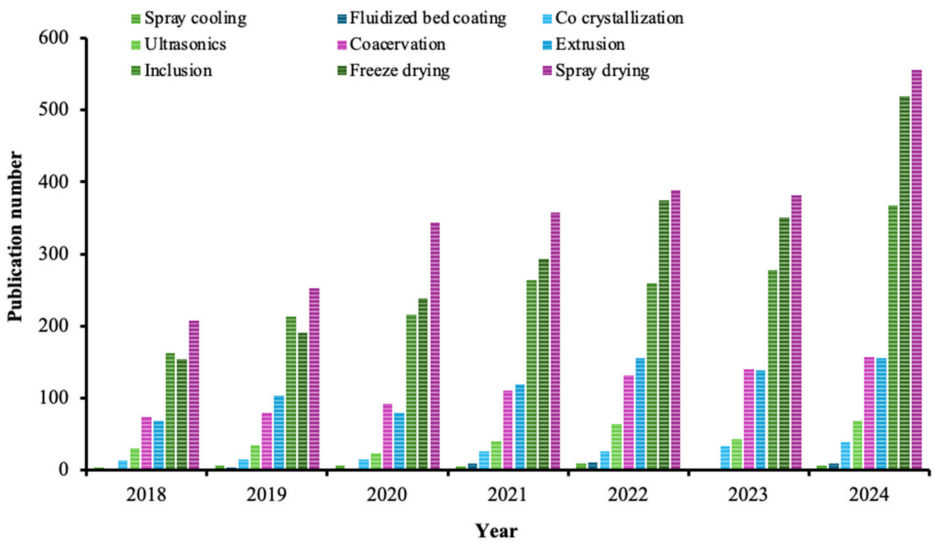


Figure 6. Number of publications related to the preservation of bioactive components by spray drying (source: Scopus; keywords: encapsulation, spray cooling, ultrasonics, inclusion, fluidized bed coating, coacervation, freeze drying, co crystallization, extrusion, and spray drying; accessed: 5 December 2024).

The most commonly used polysaccharides in spray drying of plant-based pigments include GA and MD (Table 2). These polysaccharides are frequently used in encapsulation due to their excellent film-forming properties and stability:

- For chlorophylls and carotenoids, polysaccharides alone may not be optimal due to their hydrophilic nature, but they can form emulsions that protect these pigments. Studies report that MD combined with GA (MD+GA) achieves high encapsulation efficiencies.
- For betalains and hydrophilic flavonoids (e.g., quercetin and catechin) [171,172], polysaccharides provide stable encapsulates. The combination of polysaccharides (e.g., MD+GA+Tehalose) does not always yield better results than using simple polysaccharides (MD).

Protein-based wall materials have amphipathic properties, interacting with both hydrophilic and hydrophobic compounds [173]. The hydrophilic region of proteins interacts with hydrophilic pigments such as betalains and hydrophilic flavonoids, while the hydrophobic region interacts with hydrophobic pigments such as chlorophylls, carotenoids [30,174], and hydrophobic flavonoids (e.g., apigenin and luteolin) [175]. Proteins can be used individually in spray drying processes [56–58], with WPI being the most commonly used in pigment encapsulation (Table 2). However, most studies report mixed formulations, where the protein mainly interacts with some polysaccharide [69,101,164], to enhance the characteristics of the encapsulates [98,108,164].

The success of spray drying in relation to wall material type can be visualized through the Process Yield (PY%), EE% and TPC (μg/g) parameters. Key findings include:

- MD alone shows high EE% for betacyanins (95–99%) [120] but variable results for astaxanthin (37–93%) [77].
- GA formulations significantly improve EE%, particularly for carotenoids, achieving up to 100% in guarana peels [76].
- Proteins (WPI, SPI) alone show high EE% for betacyanin (95–99% in pitahaya) and anthocyanins (75–93% in Rabbiteye blueberries) [120,163].
- Mixed systems (MD+GA, MD+Cyclodextrins, WPI+MD) often outperform single-component wall materials, improving both EE% and stability.

- PY values vary widely across studies due to differences in dryer type, feed rate, and formulation.
- Polysaccharides alone (MD) have PY% results up to 100% in betaxanthins [124], compared to mixed systems (MD+Soy protein: 35–45%) for flavonoids encapsulation [146].
- TPC is not necessarily correlated with EE% or PY%.
- TPC is the most relevant parameter for pigment encapsulation, as it reflects the amount of bioactive compound retained in the final powder.
- A high EE% does not guarantee high pigment retention if thermal degradation or losses occur during drying.

Combining different polysaccharides or blending them with proteins and lipids can optimize encapsulation properties, enhance pigment stability, and even enable controlled release (Table 2) [176].

4.3. Process Conditions for Spray-Drying of Plant-Based Pigments

Spray drying conditions are crucial for proper encapsulation, as they significantly influence the quality and stability of the final product [177]. Air inlet and outlet temperatures are among the most critical factors. On the one hand, high inlet temperatures (above 200 °C) can facilitate water evaporation and accelerate the spray drying process, but they can also cause collapsed, perforation [178,179], or even thermal degradation of heat-sensitive pigments [180]. In contrast, low inlet temperatures help maintain the stability of thermosensitive components but may result in sticky capsules due to insufficient drying [178]. Therefore, properly controlling the outlet temperature is crucial to ensure the resulting powder has adequate moisture content, preventing agglomeration, and maintaining the fluidity of the encapsulated powder.

According to the data compiled in Table 2, betalains have shown thermal stability at 70–90 °C, chlorophylls at 70–100 °C, flavonoids at 70–130 °C, and carotenoids at 90–190 °C.

The feed (or spray) speed in spray drying processes plays a crucial role. For example, an excessively fast speed can lead to insufficient water evaporation, resulting in larger and wetter particles, while a speed that is too slow can reduce process efficiency and increase operating costs. This effect is directly related to the contact time and heat transfer between the hot gas and the sprayed particles [26,181].

The type of sprayer and its nozzle (e.g., rotary, hydraulic, pneumatic, etc.) also influence the quality of the encapsulations. Nozzles that form finer droplets tend to achieve better encapsulation efficiency because they produce small, uniform particles with good dispersion and solubility of the final product, but although they require regular maintenance [26].

In addition, relative humidity and airflow in the spray drying chamber are additional factors to consider. Proper airflow ensures uniform heat distribution and efficient water vapor removal, while maintain low relative humidity in the drying chamber helps prevent moisture absorption by the encapsulated particles, preserving their stability and physical properties [26,181].

Optimizing these drying conditions results in encapsulates with improved properties, high encapsulation efficiency, and controlled release. However, the stability and functionality of any component, such as pigments, are maximized through the careful selection of the wall material. To carry out successful spray drying processes, it is necessary to consider the components to be encapsulated, wall material, the dryer type (model and scale), and the operating conditions tailored to these factors [14,16].

5. Concluding Remarks

Plant-based pigments from plant sources are not only notable for their vibrant colors but also for their nutritional value and proven biological activity. These compounds have shown potential in combating diseases such as diabetes, inflammation, hypertension, and certain types of cancer. Advances in science and technology have developed safe methods for extracting natural pigments with high levels of purity. However, their high reactivity remains a challenge for their application and utilization.

Spray drying is a highly effective technique for encapsulating plant-based pigments, with the choice of wall materials and process conditions playing a crucial role in determining encapsulation efficiency, pigment stability, and final product quality. Polysaccharides such as MD and GA remain widely used due to their film-forming properties, while proteins like WPI enhance interactions with both hydrophilic and hydrophobic compounds. Mixed systems, including polysaccharide-protein and polysaccharide-polysaccharide combinations, often yield superior encapsulation performance.

Optimizing spray drying parameters is essential for enhancing pigment stability, bioavailability, and overall product quality, with significant implications for the food, cosmetic, and pharmaceutical industries. In food applications, improved encapsulation can extend shelf life, maintain color integrity, and enhance functional properties. In cosmetics, stable pigment formulations can lead to more vibrant, long-lasting products, while in pharmaceuticals, controlled-release encapsulation can improve bioactive compound delivery.

Future advancements in spray drying should focus on developing novel wall materials, such as biopolymers, lipids, or proteins from non-conventional sources, to enhance pigment protection, solubility, and controlled release. Optimizing spray drying conditions—including temperature control, feed rate, and droplet size—will be key to improving encapsulation efficiency and pigment stability. Additionally, innovations in spray drying formulations, such as tailored polysaccharide-protein combinations or the incorporation of emulsifiers, could result in more effective and scalable encapsulation processes, supporting the development of high-performance, stable pigments for food, cosmetic, and pharmaceutical applications.

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