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Lipid-based nanoencapsulation of anthocyanins: Strategies to enhance stability, bioavailability, and functional efficacy

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Abstract

Anthocyanins, natural pigments with potent antioxidant and therapeutic properties, have demonstrated significant health benefits, including cardiovascular protection, neuroprotection, anti-inflammatory effects, and metabolic disorder management. However, their low stability and poor bioavailability hinder their full potential in food, pharmaceutical, and nutraceutical applications. Lipid-based nanoencapsulation has emerged as an effective strategy to enhance anthocyanin stability, protect against environmental degradation, and improve their controlled release and absorption. Various lipid-based delivery systems, such as liposomes, nanoemulsions, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs), have been developed to optimize anthocyanin bioefficacy. These systems offer improved solubility, sustained release, and enhanced cellular uptake. This review explores the different lipid-based nanoencapsulation techniques, their mechanisms of action, and their potential applications in improving anthocyanin delivery. Additionally, it highlights the challenges and future perspectives in developing efficient lipid-based delivery systems for maximizing anthocyanins' therapeutic potential.

1. Introduction

Anthocyanins, a subclass of flavonoids responsible for the red, blue, and purple pigmentation in numerous fruits, vegetables, and grains, have gained significant scientific interest due to their substantial health benefits. These bioactive compounds are found in high concentrations in berries such as blueberries, blackberries, and raspberries, as well as in grapes, red cabbage, purple sweet potatoes, and certain grains like black rice (Khoo *et al.*, 2017). Their powerful antioxidant and anti-inflammatory properties contribute to disease prevention by modulating cellular pathways involved in oxidative stress, metabolic regulation, and immune function, which are essential in reducing the risk of chronic diseases like cardiovascular disorders, diabetes, neurodegenerative conditions, and even certain cancers (Wallace *et al.*, 2021). The internal production of free radicals and reactive oxygen species (ROS) because of aerobic metabolism is thought to be a major factor in the onset of degenerative diseases such as cirrhosis, Alzheimer's disease, cancer, aging, and arthritis (Mounika *et al.*, 2024). Extensive research suggests that the consumption of antioxidant-rich foods in the diet reduces the risk of many diseases and anthocyanins significantly improve cardiovascular health by enhancing endothelial function, reducing arterial stiffness, and lowering blood pressure, which collectively contributes to a decreased risk of heart disease (Aswany *et al.*, 2023). Additionally, their anti-inflammatory effects mitigate the chronic inflammation commonly associated with heart disease and metabolic syndrome, positioning anthocyanins as an essential component in heart-healthy diets. Furthermore, emerging evidence underscores the neuroprotective benefits (Vauzour, 2014), improved memory and cognitive performances (Zhu *et al.*, 2023), improved eye health (Liu *et al.*, 2021), and remarkable potential in managing metabolic disorders, particularly diabetes (Zhang *et al.*, 2019). Research indicates that anthocyanins inhibit key enzymes involved in carbohydrate digestion, thereby reducing postprandial glucose spikes, which makes them highly beneficial for individuals with type 2 diabetes or those at risk of developing the condition. It also exhibits anticancerous and antioxidant properties (Kumar and Pandey, 2013) by preventing DNA damage (a primary factor in the development of various cancers). In addition to these systemic benefits, anthocyanins also support gut health by acting as prebiotics, fostering the growth of beneficial bacteria, and inhibiting harmful pathogens. Recent findings indicate that they enhance the production of short-chain fatty acids (SCFAs), which play a crucial role in maintaining gut barrier integrity, reducing inflammation, and supporting overall digestive health (Zhu *et al.*, 2023).

Additionally, anthocyanin-based dietary supplements in the form of capsules, powders, and gummies are gaining traction. However, despite the clear health benefits, one of the primary challenges with anthocyanin supplementation is its relatively low bioavailability. Nanoencapsulation has revolutionized the delivery of anthocyanins by protecting them from environmental degradation, improving their bioavailability, and allowing for controlled release in food, pharmaceutical, and nutraceutical applications (Castañeda-Ovando *et al.*, 2023). Beyond lipid-based, polymer-based, cyclodextrin complexation, electrospinning, and inorganic nanocarriers, several emerging nanoencapsulation techniques have been developed to

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further enhance the stability and functionality of anthocyanins (McClements, 2021). These include nanocoacervation, spray-drying nanoencapsulation, supercritical fluid technology, dendrimers, micelle-based encapsulation, and nanohydrogels, each offering unique advantages for anthocyanin stabilization and controlled release (Zhang *et al*., 2022).

This review summarizes the health-promoting and disease preventing effects, factors affecting stability and bioavailability of anthocyanins. It also provides a brief insight on various techniques of nanoencapsulation; lipid-based encapsulation and future trends related to encapsulation.

2. Chemistry of anthocyanins

Anthocyanins are water-soluble flavonoid pigments responsible for the red, blue, and purple hues in plants, with structural diversity arising from different anthocyanidin cores, glycosylation, and acylation patterns (Khoo *et al*., 2017). Chemically, they are classified as glycosylated polyphenols, derived from the basic flavylium (2-phenylbenzopyrylium) cation structure (Khoo *et al*., 2017). Their structure consists of an anthocyanidin core, which is a chromophore containing hydroxyl and methoxy groups, conjugated with sugar moieties such as glucose, galactose, or arabinose at the C-3 position (He and Giusti, 2020). The degree of hydroxylation, methylation, and acylation influences their colour expression, stability, and antioxidant activity (Castañeda-Ovando *et al*., 2023). The six most common anthocyanidins are cyanidin, delphinidin, pelargonidin, peonidin, malvidin, and petunidin which differ in hydroxyl (-OH) and methoxy ($-OCH_2$) group substitutions, which influence their stability, antioxidant capacity, and colour expression (He and Giusti, 2020). Their chemical behavior is pH-dependent, with the red flavylium cation form predominating in acidic conditions (pH<3), shifting to purple quinoidal bases at neutral pH and degrading into colourless chalcones in alkaline environments (pH>7) (Zhang *et al*., 2022). Various stabilization strategies, such as co-pigmentation with polyphenols, acylation with organic acids, and metal complexation with Fe^{2}z or Mg^{2}z ions, enhance anthocyanin colour retention and oxidative resistance (Castañeda Ovando *et al*., 2023).

Table 1: Colour and sources of common anthocyanins along with their substituents

Anthocyanidin	R1($-OH/-OCH_2$) at C-3'	R2($-OH/-OCH_2$) at C-4'	R3($-OH/-OCH_2$) at C-5'	Colour hue	Natural sources
Cyanidin	-OH	-OH	-H	Reddish-purple	Berries, apples, red cabbage (Khoo *et al*., 2017)
Delphinidin	-OH	-OH	-OH	Blue	Blueberries, eggplant, and grapes (He and Giusti, 2020)
Pelargonidin	-H	-OH	-H	Orange-red	Strawberries, radishes, kidney beans (Zhang *et al*., 2022)
Peonidin	$-OCH_2$	-OH	-H	Pinkish-red	Cranberries, cherries, plums (Castañeda-Ovando *et al*., 2023)
Malvidin	$-OCH_2$	-OH	$-OCH_2$	Deep purple	Grapes, wine, and black rice (McClements, 2021)
Petunidin	-OH	-OH	$-OCH_2$	Bluish-purple	Blackcurrants, eggplant, blackberries (Fang and Bhandari, 2022)
Hirsutidin	$-OCH_2$	$-OCH_2$	-H	Deep red	Black rice, blood oranges (Ribeiro *et al*., 2022)
Europinidin	-OH	-OH	-OH	Dark blue	Rare in plants; found in some flowers (Varona *et al*., 2023)
Rosinidin	$-OCH_2$	-OH	-H	Reddish-pink	Anthurium flowers, certain fruits (Cruz *et al*., 2023)
Luteolinidin	-OH	-OH	-H	Yellow-orange	Sorghum, millet (He *et al*., 2023)
Apigeninidin	-H	-OH	-H	Yellow	Sorghum, cereals (Khoo *et al*., 2017)

3. Beneficial effects of anthocyanins

Anthocyanins are potent phytochemicals which has shown a significant role in preventing cardiovascular diseases, and metabolic diseases such as type 2 diabetes mellitus, promoting eye health, scavenging free radicals (antioxidant effects), and anticancerous and anti-inflammation effects.

3.1 Antioxidant effects

Anthocyanins exhibit potent antioxidant properties that help protect cells from oxidative stress. These compounds neutralize free radicals, reducing cellular damage and the risk of chronic diseases such as cardiovascular disease, cancer, and neurodegenerative disorders (Li *et al*., 2021). Studies indicate that anthocyanins enhance the activity of endogenous antioxidant enzymes, including superoxide dismutase and glutathione peroxidase, thereby strengthening the body's defense system against oxidative damage (Zhao *et al*., 2020). Additionally, they contribute to maintaining vascular health by preventing lipid peroxidation, which is a key factor in atherosclerosis development (Huang *et al*., 2019). Their ability to modulate oxidative stress also plays a role in reducing inflammation and improving metabolic health. Consuming anthocyanin-rich foods, such as berries, red cabbage, and purple sweet potatoes, may thus offer significant health benefits (Wang and Xu, 2022).

3.2 Cardioprotective effects

Recent studies have reinforced the significant role of anthocyanins in promoting heart health. A meta-analysis of randomized controlled trials demonstrated that purified anthocyanin supplementation effectively improves lipid profiles by reducing low-density lipoprotein (LDL) cholesterol and triglyceride levels, while increasing high-density lipoprotein (HDL) cholesterol concentrations (Zhu *et al*., 2021). Additionally, dietary anthocyanin intake has been associated with a decreased risk of coronary heart disease and overall cardiovascular disease incidence (Zhu *et al*., 2021). The cardioprotective effects of anthocyanins are attributed to their potent antioxidant and anti-inflammatory properties, which help mitigate oxidative stress and inflammation which are key contributors to cardiovascular diseases (Zhu *et al*., 2021). Incorporating anthocyanin-rich foods, such as berries, red cabbage, and purple sweet potatoes, into one's diet may thus offer substantial benefits for heart health.

3.3 Neuroprotective effects

Anthocyanins have been linked to improved cognitive function and brain health. Research suggests that anthocyanins exhibit neuroprotective effects by reducing oxidative stress and neuroinflammation, which are major contributors to neurodegenerative diseases such as Alzheimer's and Parkinson's (Ahles *et al*., 2021). These compounds also enhance synaptic plasticity and promote neurogenesis, thereby supporting learning and memory processes (Zhu *et al*., 2021). A meta-analysis of randomized controlled trials found that anthocyanin-rich supplementation significantly improved processing speed in older adults, suggesting potential benefits in daily cognitive functioning (Kent *et al*., 2017). Additionally, blueberry supplementation has been shown to enhance memory performance in older adults (Krikorian *et al*., 2010), and a single dose of a flavonoid-rich blueberry drink improved memory in children (Whyte and Williams, 2015). Consuming anthocyanin-rich foods such as blueberries, blackberries, and purple sweet potatoes may thus offer substantial cognitive benefits.

3.4 Anti-inflammatory effects

Anthocyanins have demonstrated potent anti-inflammatory properties. These compounds regulate inflammatory responses by inhibiting key pro-inflammatory cytokines, such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and nuclear factor-kappa B (NF-κB) (Caruso *et al*., 2021). Studies have shown that anthocyanins can suppress oxidative stress-induced inflammation by scavenging reactive oxygen species (ROS), thereby protecting tissues from chronic inflammation-related damage (Kowalska *et al*., 2023). Clinical trials suggest that anthocyanin-rich diets reduce systemic inflammation and alleviate symptoms in conditions such as rheumatoid arthritis and inflammatory bowel disease (Pojer *et al*., 2013). Furthermore, anthocyanins have been linked to improved gut microbiota composition, which plays a crucial role in modulating immune responses and reducing intestinal inflammation (Wallace and Giusti, 2015). Regular consumption of anthocyanin-rich foods may thus provide protective benefits against chronic inflammatory diseases and oxidative stress-related disorders.

3.5 Eye health

Anthocyanins, the pigments responsible for the vibrant colours in various fruits and vegetables, have been shown to promote eye health through multiple mechanisms. *In vitro* studies indicate that anthocyanins enhance rhodopsin regeneration, a crucial protein for low-light vision, thereby potentially improving night vision (Matsumoto *et al*., 2019). Additionally, these compounds exhibit antioxidative properties, protecting ocular tissues from oxidative stress and inflammation, which are implicated in various eye diseases (Matsumoto *et al*., 2019). Clinical studies have demonstrated that anthocyanin supplementation can improve visual functions; for instance, a randomized controlled trial reported that oral consumption of 240 mg of standardized bilberry extract for 12 weeks alleviated ciliary muscle fatigue associated with prolonged visual tasks (Matsumoto *et al*., 2019). Moreover, anthocyanins have been observed to improve retinal blood circulation, which may benefit individuals with normal-tension glaucoma (Matsumoto *et al*., 2019). Regular consumption of anthocyanin-rich foods, such as blueberries, bilberries, and blackcurrants, may thus offer substantial benefits for maintaining and enhancing eye health.

3.6 Prevention and management of diabetes mellitus

The bioactive compounds (anthocyanins) enhance insulin sensitivity and modulate glucose metabolism through various mechanisms. Clinical studies have shown that anthocyanin-rich diets can improve glycemic control; for instance, a meta-analysis reported that a median daily intake of 320 mg of anthocyanins over eight weeks significantly reduced fasting blood glucose levels and HbA1c in individuals with T2DM (Zhu *et al*., 2023). The anti-diabetic effects of anthocyanins are attributed to their ability to activate AMP-activated protein kinase (AMPK), leading to improved insulin sensitivity and glucose uptake in peripheral tissues (Guo *et al*., 2017). Additionally, anthocyanins exhibit anti-inflammatory and antioxidant properties, which further contribute to their protective role against insulin resistance and pancreatic β-cell dysfunction (Ró¿añska and Regulska-Ilow, 2018). Regular consumption of anthocyanin-rich foods, such as berries, red cabbage, and purple sweet potatoes, may thus offer a dietary strategy for the prevention and management of T2DM.

3.7 Anticancerous properties

Anthocyanins have demonstrated potential anticancer properties through various mechanisms. *In vitro* studies have shown that anthocyanins can inhibit the proliferation of cancer cells by interfering with kinase signaling pathways, thereby blocking uncontrolled cell division (Zhang *et al*., 2015). For instance, delphinidin has been found to inhibit hepatocyte growth factor-induced phosphorylation, blocking the Ras-ERK MAPK and PI3K/Akt pathways, which are crucial for cell proliferation (Syed *et al*., 2008). Additionally, anthocyanins can induce apoptosis in malignant cells via both intrinsic and extrinsic pathways, promoting programmed cell death in tumors (Zhang *et al*., 2015). Mulberry anthocyanins, for example, have been reported to induce apoptosis in gastric cancer cells through the p38/Fas/FasL/Caspase-8 pathway (Huang *et al*., 2012). Moreover, these compounds exhibit anti-inflammatory effects by downregulating pro-inflammatory mediators, which are often associated with cancer progression (Zhang *et al*., 2015). Their antioxidant properties also help neutralize free radicals, reducing oxidative stress that can lead to DNA damage and subsequent carcinogenesis (Zhang *et al*., 2015). Epidemiological evidence suggests that diets rich in anthocyanin-containing foods, such as berries, grapes, and red cabbage, may be associated with a lower risk of certain cancers (Zhang *et al*., 2015).

4. Stability and bioavailability: Factors affecting

Anthocyanins are water-soluble pigments, known for their antioxidant and health-promoting properties. Their stability and bioavailability are influenced by several factors:

4.1 pH

Anthocyanin stability is highly dependent on pH, as these pigments undergo structural transformations that influence their colour and degradation rate. In acidic conditions (pH<3), anthocyanins exist primarily in their flavylium cation form, which is red and relatively stable. As pH increases to neutral (pH 4-6), they transition into colourless carbinol or chalcone forms, leading to reduced pigment intensity and bioactivity (Castañeda-Ovando *et al*., 2009; He and Giusti, 2010). At alkaline pH (above 7), anthocyanins degrade rapidly, shifting to blue or green due to the formation of quinoidal bases, which are less stable and more susceptible to oxidation and polymerization (Khoo *et al*., 2017; Wallace and Giusti, 2019). This pH sensitivity significantly impacts their use in food and pharmaceutical applications, requiring careful formulation strategies to maintain their functional properties. Studies suggest that co-pigmentation with other phenolic compounds, interaction with metal ions, and encapsulation techniques such as nanoemulsions and liposomes can enhance anthocyanin stability under varying pH conditions (Patras *et al*., 2010; Nankar *et al*., 2020).

4.2 Temperature

Temperature plays a critical role in the stability of anthocyanins, as higher temperatures accelerate their degradation through oxidation, polymerization, and cleavage of glycosidic bonds. Thermal degradation is influenced by factors such as heating duration, pH, and the presence of co-pigments or metal ions (Patras *et al*., 2010). Studies indicate that anthocyanins degrade more rapidly at temperatures above 50°C, with significant losses occurring during food processing methods such as pasteurization, drying, and extrusion (Sadilova *et al*., 2007; Cisse *et al*., 2009). Additionally, heating can lead to structural modifications, converting anthocyanins into brown polymeric compounds with reduced bioactivity (Torskangerpoll and Andersen, 2005). However, encapsulation techniques such as microencapsulation and nanoemulsions have been explored to improve thermal stability and retain anthocyanin functionality in processed foods (Bakowska-Barczak and Kolodziejczyk, 2011). Therefore, optimizing temperature conditions during processing and storage is crucial for maintaining anthocyanin integrity and maximizing its health benefits.

4.3 Light exposure

Light exposure significantly affects the stability of anthocyanins, leading to their degradation through photochemical reactions such as oxidation and cleavage of glycosidic bonds. Ultraviolet (UV) and visible light can accelerate the breakdown of anthocyanins, causing colour fading and loss of bioactivity (Kýrca *et al*., 2007). The rate of degradation depends on factors such as light intensity, wavelength, and the presence of oxygen or other reactive species (Reque *et al*., 2014). Studies have shown that anthocyanins stored in transparent containers degrade faster compared to those kept in opaque or UV-blocking materials, highlighting the importance of proper packaging in preserving their stability (Zhao *et al*., 2019). Additionally, co-pigmentation with other polyphenols, encapsulation, and the use of antioxidants such as ascorbic acid have been explored as strategies to mitigate light-induced degradation (Niu *et al*., 2017). Proper storage conditions, including protection from direct light exposure, are essential for maintaining anthocyanin stability in food and pharmaceutical applications.

4.4 Oxygen

Oxygen plays a crucial role in anthocyanin stability, as its presence accelerates oxidative degradation, leading to colour loss and reduced bioactivity. Oxidation occurs through enzymatic and non-enzymatic pathways, with polyphenol oxidase (PPO) and peroxidase (POD) playing a significant role in anthocyanin breakdown, especially in fresh plant materials (Reque *et al*., 2014). Non-enzymatic oxidation is influenced by factors such as temperature, pH, and light exposure, which can generate reactive oxygen species that degrade anthocyanins (Zhao *et al*., 2019). Studies have shown that oxygen-rich environments contribute to anthocyanin polymerization, forming brownish degradation products that negatively impact food quality (Cisse *et al*., 2009). To enhance anthocyanin stability, strategies such as oxygen barrier packaging, antioxidant addition (*e.g*., ascorbic acid), and encapsulation techniques have been explored (Bakowska-Barczak and Kolodziejczyk, 2011). Minimizing oxygen exposure during food processing and storage is essential for preserving anthocyanin colour and functionality in various applications.

4.5 Metal ions

Metal ions play a significant role in anthocyanin stability, either enhancing or accelerating their degradation depending on the type and concentration of the metal. Divalent and trivalent metal ions such as **$Fe^{3}z$, $Cu^{2}z$, and $Al^{3}z$** can interact with anthocyanins, forming complexes that alter their colour and stability (Fenger *et al*., 2019). While some metal-anthocyanin complexes can enhance pigment stability and contribute to blue colouration, excessive metal ion concentrations often promote oxidative degradation through Fenton-like reactions, leading to anthocyanin breakdown and browning (Fang, 2014). The pH and presence of co-pigments influence the extent of metal complexation and its effects on anthocyanin stability (Zhang *et al*., 2020). To minimize degradation, strategies such as chelating agents (*e.g*., EDTA), pH control, and encapsulation techniques have been explored in food formulations (Castro-Alves *et al*., 2021). Understanding metal ion interactions is essential for optimizing anthocyanin stability in food and pharmaceutical applications.

4.6 Enzymes

Enzymes play a crucial role in the degradation of anthocyanins, significantly affecting their stability in plant-based foods and beverages. Polyphenol oxidase (PPO) and peroxidase (POD) are the primary enzymes responsible for anthocyanin degradation, catalyzing oxidation reactions that lead to pigment browning and loss of bioactivity (García-Pérez *et al*., 2019). PPO promotes anthocyanin oxidation in the presence of oxygen, forming quinones that react with other phenolic compounds, resulting in polymerization and discolouration (Queiroz *et al*., 2008). Similarly, POD accelerates anthocyanin breakdown in the presence of hydrogen peroxide, further compromising pigment stability (Cai *et al*., 2020). The rate of enzymatic degradation is influenced by factors such as temperature, pH, and substrate availability (Rawson *et al*., 2010). Strategies to mitigate enzymatic degradation include thermal and non-thermal processing methods such as blanching, high-pressure processing, and enzyme inhibitors (Nair *et al*., 2018). Controlling enzymatic activity is essential for preserving anthocyanin stability in food products and extending shelf-life.

4.7 Co-pigmentation

Co-pigmentation plays a crucial role in enhancing the stability and colour intensity of anthocyanins by forming non-covalent interactions with other organic molecules such as flavonoids, phenolic acids, amino acids, and metal ions. This phenomenon helps protect anthocyanins from degradation caused by pH fluctuations, light exposure, and oxidation (Boulton, 2001). Co-pigments stabilize anthocyanins by stacking against their planar structure, reducing water interaction and preventing colour loss (He *et al*., 2016). Studies have shown that phenolic acids like caffeic and ferulic acid, as well as flavones and flavonols, are effective co-pigments that improve anthocyanin retention in food products (Castañeda-Ovando *et al*., 2009). Additionally, co-pigmentation can shift anthocyanin colour expression, often resulting in a more intense red or blue hue depending on the pH and molecular arrangement (Torskangerpoll and Andersen, 2005). Understanding co-pigmentation mechanisms has practical applications in food and beverage industries, where anthocyanins are used as natural colourants, requiring stability for extended shelf-life.

5. Lipid-based system used for nanoencapsulation

Lipid-based nanoencapsulation systems for anthocyanins can be categorized into specific classes based on their composition, structure, and functionality. Below is a refined classification:

5.1 Vesicular Systems

Vesicular systems are among the most effective lipid-based carriers for anthocyanins, offering improved protection, controlled release, and enhanced bioavailability. Various forms of the vesicular system include liposomes, phytosomes, niosomes (non-ionic surfactant vesicles), ethosomes, and transfersomes (ultra-deformable vesicles). The detailed description is given below:

5.1.1 Liposomes

Liposomes, phospholipid-based vesicular structures, have been widely studied for anthocyanin encapsulation due to their biocompatibility, high encapsulation efficiency, and ability to protect anthocyanins from environmental degradation (Mozafari *et al*., 2021). The hydrophilic core of liposomes allows efficient loading of anthocyanins, while the lipid bilayers shield them from oxidative stress, pH variations, and enzymatic degradation, thereby improving their stability and bioavailability (Zhang *et al*., 2022). The incorporation of cholesterol into liposomal formulations has been shown to enhance membrane rigidity, reducing leakage and improving long-term stability (Parris *et al*., 2020). Additionally, surface modifications such as PEGylation extend circulation time and minimize clearance by the reticuloendothelial system, further enhancing the delivery potential of anthocyanin-loaded liposomes (Li *et al*., 2019).

Beyond conventional liposomes, ethosomes-vesicular carriers enriched with ethanol-have emerged as promising systems for anthocyanin delivery, particularly in transdermal and topical applications (Wang *et al*., 2021). The ethanol content in ethosomes enhances membrane flexibility, allowing deeper penetration through biological barriers and improving the bioavailability of encapsulated anthocyanins (Tan *et al*., 2022). Recent studies suggest that ethosomes exhibit superior encapsulation efficiency compared to traditional liposomes, making them a viable alternative for functional food and pharmaceutical applications (Santos *et al*., 2023). Advanced formulations, including pH-sensitive and thermosensitive liposomes, are also being explored for controlled anthocyanin release in gastrointestinal and biomedical settings, positioning lipid-based vesicular systems as essential tools for optimizing anthocyanin delivery (Wang *et al*., 2021).

5.1.2 Phytosomes

Phytosomes, a specialized form of lipid-based vesicular systems, have gained significant attention for encapsulating anthocyanins due to their ability to enhance bioavailability and stability (Kashyap *et al*., 2021). Unlike conventional liposomes, phytosomes are formed by the complexation of bioactive compounds with phospholipids, primarily phosphatidylcholine, which increases their solubility and facilitates better absorption across biological membranes (Manna *et al*., 2022). The amphiphilic nature of phospholipids enables the formation of a stable molecular complex where anthocyanins are embedded within the hydrophilic head, improving their stability against oxidative degradation and gastrointestinal conditions (Riva *et al*., 2020). Recent studies have demonstrated that anthocyanin-loaded phytosomes exhibit higher encapsulation efficiency (70-95%) and prolonged retention in systemic circulation compared to free anthocyanins, leading to improved therapeutic efficacy (Mukherjee *et al*., 2023). Additionally, the enhanced permeability of phytosomes enables superior uptake in the small intestine, preventing rapid excretion and degradation in the digestive tract (Patel *et al*., 2022). Modified phytosome formulations, such as polymer-coated and bioadhesive phytosomes, have further improved the controlled release and targeted delivery of anthocyanins, particularly in functional food and nutraceutical applications (Singh *et al*., 2023). These advancements highlight the potential of phytosomes as an efficient nanoencapsulation strategy for anthocyanins, addressing limitations associated with their poor solubility and instability in conventional formulations (Das *et al*., 2021).

5.1.3 Niosomes

Niosomes also referred to as neosomes, are non-ionic surfactant-based vesicular systems that have gained attention for encapsulating bioactive compounds, including anthocyanins, due to their enhanced stability, biocompatibility, and controlled release properties (Mahmoud *et al*., 2022). Unlike phospholipid-based liposomes, niosomes are composed of non-ionic surfactants such as Span, Tween, and Brij, which contribute to their superior chemical stability and cost-effectiveness in large-scale production (Khan *et al*., 2021). The hydrophilic-lipophilic balance (HLB) of surfactants plays a crucial role in determining the encapsulation efficiency and release profile of anthocyanins, with higher HLB values favoring aqueous solubility and prolonged retention time (Ghaffar *et al*., 2023). Studies have demonstrated that anthocyanin-loaded niosomes exhibit an encapsulation efficiency of 65-90 per cent, significantly improving their resistance to oxidative degradation and gastrointestinal instability (Chaves *et al*., 2022). Furthermore, niosomes provide controlled and targeted delivery, particularly in functional foods and pharmaceutical applications, by modulating vesicle size and surface charge, which enhances cellular uptake and absorption in the intestines (Singh *et al*., 2023). Advanced modifications such as PEGylated niosomes and chitosan-coated niosomes have been investigated to further enhance anthocyanin bioavailability and sustain their release under physiological conditions (Al-Mahallawi *et al*., 2021). These developments highlight niosomes as a promising alternative to traditional lipid-based carriers, addressing key challenges related to anthocyanin solubility, stability, and bioavailability (Gupta *et al*., 2020).

5.1.4 Ethosomes

Ethosomes, advanced lipid-based vesicular systems enriched with ethanol, have emerged as a promising strategy for enhancing the stability, permeability, and bioavailability of bioactive compounds, including anthocyanins (Touitou *et al*., 2021). Unlike conventional liposomes, ethosomes contain a high ethanol concentration, which increases membrane fluidity, allowing deeper penetration through biological barriers, such as the skin and intestinal epithelium (Beloqui *et al*., 2022). This unique structure enables ethosomes to improve the systemic absorption of anthocyanins, which are otherwise prone to degradation in the gastrointestinal tract (Gonçalves *et al*., 2023). Studies have demonstrated that anthocyanin-loaded ethosomes exhibit encapsulation efficiencies ranging from 75 to 95 per cent, significantly improving their resistance to oxidation and enzymatic degradation (Sadeghi-Ghadi *et al*., 2022). Additionally, ethosomes provide sustained release, ensuring prolonged circulation and enhanced bioavailability of anthocyanins in functional food and nutraceutical applications (Mirzaie *et al*., 2021). Recent advancements in polymer-coated ethosomes and pH-responsive ethosomal formulations have further optimized the controlled release and targeted delivery of anthocyanins, particularly for dermal, oral, and biomedical applications (Aqil *et al*., 2020). These findings highlight ethosomes as a superior nanoencapsulation system for anthocyanins, addressing critical challenges related to their poor solubility and low stability in conventional formulations (Dubey *et al*., 2023).

5.1.5 Transfersomes

Transfersomes are ultra-deformable vesicular carriers composed of phospholipids and edge activators, making them highly efficient for transdermal and oral delivery of bioactive compounds, including anthocyanins (Cevc and Blume, 2021). The presence of edge activators, such as Tween, Span, and sodium cholate, provides flexibility to the vesicles, allowing them to penetrate through tight intercellular spaces and biological membranes with minimal resistance (Elsayed *et al*., 2022). This structural advantage enhances the absorption and bioavailability of anthocyanins, which are otherwise susceptible to enzymatic degradation and poor intestinal uptake (Gharib *et al*., 2023). Recent studies have reported that transfersomal encapsulation of anthocyanins results in an encapsulation efficiency of 80-95 per cent, significantly protecting them from oxidation and light-induced degradation (Ma *et al*., 2021). Moreover, the ability of transfersomes to respond to osmotic gradients allows for a sustained and controlled release profile, making them highly effective for targeted delivery in nutraceutical, cosmetic, and pharmaceutical applications (Sadeghi *et al*., 2022). Advances in chitosan-coated and pH-sensitive transfersomes have further improved anthocyanin stability in gastrointestinal conditions, increasing their retention and systemic absorption (Moghimipour *et al*., 2020). These developments position transfersomes as a cutting-edge nanoencapsulation technology, overcoming the traditional challenges associated with anthocyanin solubility, degradation, and bioavailability (Al-Mahallawi *et al*., 2023).

5.2 Lipid nanoparticles

Lipid nanoparticles (LNPs) are advanced nanocarrier systems composed of biocompatible and biodegradable lipids, making them highly effective for encapsulating and delivering bioactive compounds, including drugs, proteins, and antioxidants (Puri *et al*., 2021). These nanoparticles offer several advantages over conventional delivery systems, including enhanced stability, controlled release, improved solubility, and increased bioavailability (Ghasemiyeh and Mohammadi-Samani, 2020). Structurally, LNPs can be classified into two main types: solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs). SLNs are composed of a single solid lipid matrix, whereas NLCs incorporate both solid and liquid lipids, enhancing drug loading capacity and stability (Naseri *et al*., 2015). The small size (50-1000 nm) and lipid-based composition allow LNPs to efficiently penetrate biological membranes, making them particularly useful in pharmaceutical, cosmetic, and nutraceutical applications (Shah *et al*., 2022).

LNPs are typically produced using high-pressure homogenization, microemulsion techniques, solvent evaporation, or nanoprecipitation methods, each influencing the particle size, stability, and encapsulation efficiency (Müller *et al*., 2011). One of the most significant advancements in LNP technology has been their role in mRNA-based vaccines, where ionizable lipid formulations enable efficient RNA encapsulation and intracellular delivery (Hou *et al*., 2021). In addition to vaccines, LNPs are widely explored for oral, dermal, and parenteral drug delivery, demonstrating superior targeted delivery and reduced systemic toxicity compared to traditional carriers (Witzigmann *et al*., 2020).

Lipid nanoparticles are also gaining traction in functional food and nutraceutical industries, particularly for encapsulating antioxidants like curcumin, resveratrol, and anthocyanins, which are prone to degradation under physiological conditions (Puglia *et al*., 2022). Studies have shown that anthocyanin-loaded LNPs exhibit enhanced stability, increased gastrointestinal absorption, and prolonged circulation time, making them a promising vehicle for delivering flavonoids and other polyphenolic compounds (Silva *et al*., 2023). Furthermore, surface modifications such as PEGylation, ligand conjugation, and pH-responsive coatings have been explored to improve targeted drug delivery and cellular uptake (Makhmalzadeh *et al*., 2019).

Despite their numerous advantages, challenges such as lipid oxidation, potential cytotoxicity at high concentrations, and limited large-scale production feasibility remain critical areas for further research (Yingchoncharoen *et al*., 2016). Nevertheless, continuous advancements in formulation techniques, lipid compositions, and drug-loading strategies are expected to enhance the efficiency and applicability of LNPs in diverse biomedical and industrial fields (Zhao *et al*., 2022).

5.3 Emulsion-based systems

Nanoencapsulation using emulsion-based systems has emerged as a promising strategy for enhancing the stability, bioavailability, and controlled release of bioactive compounds, including polyphenols, essential oils, vitamins, and flavonoids like anthocyanins (McClements, 2021). Emulsions are thermodynamically or kinetically stable heterogeneous mixtures consisting of two immiscible liquids, typically oil and water, stabilized by surfactants or emulsifiers (Jafari *et al*., 2018). These systems can be classified into oil-in-water (O/W), water-in-oil (W/O), and multiple emulsions (W/O/W or O/W/O) based on their dispersed and continuous phases (Gupta *et al*., 2022). Among these, O/W emulsions are widely used for encapsulating hydrophobic compounds, whereas W/O systems are suitable for water-soluble bioactives (Ghasemi *et al*., 2019).

Nanoemulsions, a subcategory of emulsion-based systems, are characterized by droplet sizes ranging from 20 to 200 nm, offering superior optical clarity, physical stability, and enhanced bioactive delivery compared to conventional emulsions (Taha *et al*., 2020). The nanoemulsion method is the most efficient drug delivery approach for the majority of medicines since it maximizes effectiveness while minimizing toxicity (Tamizharasi *et al*., 2023). The small droplet size increases the surface area-to-volume ratio, improving interfacial interactions and solubility of encapsulated compounds (Solans and Izquierdo, 2022). These nanoemulsions are produced using high-energy (high-pressure homogenization, ultrasonication) or low-energy (spontaneous emulsification, phase inversion) techniques, depending on formulation requirements (Qian and McClements, 2019).

Emulsion-based nanoencapsulation of anthocyanins has demonstrated significant improvements in protecting anthocyanins from degradation, enhancing intestinal absorption, and prolonging their release profile. Research has shown that anthocyanin-loaded nanoemulsions prepared with food-grade emulsifiers (*e.g.*, lecithin, whey protein, polysorbates) exhibit higher encapsulation efficiency (85-95%) and improved bioavailability compared to free anthocyanins (Zhang *et al*., 2020).

Advancements in solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), and Pickering emulsions have further optimized anthocyanin encapsulation by enhancing colloidal stability and reducing lipid oxidation (Pascuta *et al*., 2022). Recent studies have explored chitosan-coated nanoemulsions and pH-responsive biopolymer-stabilized emulsions for targeted and controlled release of anthocyanins, demonstrating potential applications in functional foods, nutraceuticals, and pharmaceutical formulations (Wang *et al*., 2023).

Despite their advantages, challenges such as phase separation, Ostwald ripening, and instability under extreme processing conditions remain areas of active research. However, innovations in co-encapsulation strategies (*e.g.*, anthocyanins with lipophilic antioxidants) and interfacial engineering are expected to further enhance the efficacy, shelf-life, and industrial applicability of emulsion-based nanoencapsulation systems (Ribeiro *et al*., 2023).

5.4 Self-emulsifying systems

Self-emulsifying drug delivery systems (SEDDS) are isotropic mixtures of oils, surfactants, co-surfactants, and sometimes co-solvents, which spontaneously form fine emulsions or nanoemulsions when exposed to gastrointestinal fluids, without requiring external energy (Kommuru *et al*., 2022). These systems have gained significant attention in pharmaceutical and nutraceutical applications due to their ability to enhance the solubility, bioavailability, and stability of lipophilic and hydrophilic bioactive compounds (Shakeel and Haq, 2021). The particle size of self-emulsified droplets typically ranges from 20 to 200 nm, with smaller sizes offering greater absorption, enhanced permeability, and improved therapeutic efficacy (Pouton, 2020).

Self-emulsifying systems can be classified into three main categories based on the droplet size after dispersion:

i. Self-emulsifying drug delivery systems (SEDDS): Forms emulsions with droplet sizes >200 nm.

ii. Self-nanoemulsifying drug delivery systems (SNEDDS): Produces nanoemulsions with droplet sizes between 20-200 nm, leading to improved drug absorption.

iii. Self-microemulsifying drug delivery systems (SMEDDS): Forms transparent microemulsions (<20 nm) with thermodynamic stability (Porter *et al*., 2021).

The effectiveness of self-emulsifying systems depends on oil phase selection, as it determines the solubilization capacity of bioactives, while surfactants (*e.g.*, polysorbates, lecithin, Cremophor EL) and co-surfactants (*e.g.*, ethanol, propylene glycol, polyethylene glycol) aid in reducing interfacial tension and stabilizing the emulsion (Gursoy and Benita, 2020). These systems have been widely explored for oral, topical, and parenteral delivery, demonstrating enhanced gastrointestinal absorption and lymphatic transport (Kazi *et al*., 2023).

Self-emulsifying systems of anthocyanins have been investigated as effective carriers to protect anthocyanins from degradation, improve their solubility, and enhance intestinal absorption (Guo *et al*., 2022). Studies have shown that SNEDDS loaded with anthocyanins significantly increase their intestinal permeability and bioavailability compared to free anthocyanins, demonstrating a 2 to 5-fold enhancement in plasma concentration (Liu *et al*., 2021). The incorporation of medium-chain triglycerides (MCTs) and long-chain lipids (*e.g.*, oleic acid, linoleic acid) in SEDDS formulations further enhances anthocyanin solubilization and absorption via the lymphatic transport system (Zhang *et al*., 2023). Additionally, chitosan-coated SNEDDS have been developed for targeted and sustained release of anthocyanins in the small intestine, offering superior stability and bioavailability (Li *et al*., 2022).

Recent advancements in pH-responsive SNEDDS and antioxidant-enriched formulations (*e.g.*, co-encapsulation with vitamin C, quercetin) have further optimized anthocyanin delivery by preventing degradation in acidic gastric environments and ensuring controlled release in the intestinal tract (Fang *et al*., 2023). This makes self-emulsifying systems highly promising for functional food, nutraceutical, and pharmaceutical applications. Despite their advantages, challenges such as precipitation upon dilution, drug leakage, and surfactant-induced toxicity remain areas of active research (Singh *et al*., 2022). However, continued advancements in lipid-based formulations, polymeric coatings, and hybrid emulsification strategies are expected to further enhance the effectiveness and commercial viability of self-emulsifying nanoencapsulation systems (Huang *et al*., 2023).

5.5 Hybrid systems

Hybrid nanoencapsulation systems are advanced delivery platforms that integrate two or more encapsulation techniques to achieve synergistic advantages in terms of stability, bioavailability, targeted delivery, and controlled release of bioactive compounds (Gupta *et al*., 2022). These systems are particularly beneficial for encapsulating sensitive and hydrophilic bioactives like anthocyanins, which are prone to degradation due to pH, temperature, light, and oxygen exposure (Lyu *et al*., 2023). Hybrid encapsulation combines different polymeric, lipid, or inorganic nanocarriers to optimize physicochemical properties and overcome limitations associated with single-system encapsulation (Zhang *et al*., 2023).

There are several types of hybrid systems, including:

i. Lipid-polymer hybrid nanoparticles (LPHNs): These systems incorporate a polymeric core (*e.g.*, chitosan, polylactic acid) surrounded by a lipid layer to enhance drug loading, biocompatibility, and sustained release (Fang *et al*., 2023).

ii. Lipid-inorganic hybrid nanoparticles: These nanocarriers integrate silica, gold, or calcium phosphate nanoparticles within a lipid matrix for improved stability, targeted drug release, and imaging applications (Zhou *et al*., 2022).

iii. Lipid-protein hybrid systems: Combining lipid-based carriers with protein-based coatings (*e.g.*, whey protein, zein, casein) enhances structural integrity, bioactive retention, and gastrointestinal stability (Chen *et al*., 2021).

iv. Polysaccharide-lipid hybrid systems: These use natural biopolymers (*e.g.*, alginate, chitosan, pectin) with lipid nanoparticles, providing improved mucoadhesion, enzymatic resistance, and bioavailability (Wang *et al*., 2023).

Hybrid systems have gained popularity in pharmaceuticals, nutraceuticals, and functional foods, as they offer multifunctional capabilities such as targeted drug delivery, pH-responsive release, and co-encapsulation of multiple bioactives (Kumar *et al*., 2022).

Anthocyanins, exhibit low chemical stability and poor bioavailability, necessitating hybrid nanoencapsulation strategies (Pascuta *et al*., 2022). Recent studies have demonstrated that lipid-polymer hybrid nanoparticles (LPHNs) significantly enhance anthocyanin stability, preventing degradation under gastric conditions (Lyu *et al*., 2023). Additionally, chitosan-coated lipid nanoparticles have shown a 3- to 5-fold increase in anthocyanin bioavailability, attributed to their mucoadhesive properties and controlled release profile (Zhang *et al*., 2023).

Moreover, hybrid systems integrating inorganic nanocarriers (*e.g.*, mesoporous silica, calcium phosphate) have exhibited high encapsulation efficiency (>90%) and sustained release over 48 hours, ensuring prolonged anthocyanin bioactivity (Zhou *et al*., 2022). Zein-stabilized lipid nanoparticles have also been explored for enhanced anthocyanin protection, enabling their application in functional foods (Chen *et al*., 2021).

Recent advancements include dual-responsive hybrid nanoparticles (*e.g.*, pH- and enzyme-sensitive carriers), which release anthocyanins selectively in the small intestine, maximizing absorption while reducing degradation in acidic gastric environments (Fang *et al*., 2023). This hybrid approach has significantly improved anthocyanin applications in functional foods, cosmetics, and pharmaceutical formulations (Kumar *et al*., 2022).

Despite their advantages, scalability, cost, and regulatory approval remain key challenges for hybrid nanoencapsulation systems. However, continuous research in biodegradable materials, food-grade hybrid carriers, and precision formulation techniques is expected to drive their industrial adoption and commercial viability (Wang *et al*., 2023).

Table 2: Research progress on common methods for the preparation of ACNs-lipid nanoparticles

Method	Steps	Embedding material	Advantages	Limitations	Stability improvement effects	References
High-pressure homogenization (HPH)	i. Melt the lipid phase and dissolve anthocyanins in the aqueous phase. ii. Form a pre-emulsion with high-speed stirring. iii. Pass through a high-pressure homogenizer (100-1500 bar). iv. Cool to solidify nanoparticles.	Lecithin, Glyceryl monostearate, Phospholipids, Stearic acid	Produces uniform, stable nanoparticles. Scalable for industrial production highpressure .	Requires expensive equipment. Possible anthocyanin degradation due to ability .	Reduces particle size, enhancing encapsulation and bioavail-	Lohcharoenkal *et al.*, 2021; Pando *et al.*, 2022; Müller *et al.*, 2023 . .
Solvent evaporation	i. Dissolve lipids and anthocyanins in an organic solvent (*e.g.*, ethanol, acetone). ii. Add solution to the aqueous phase under stirring. iii. Evaporate solvent using rotary evaporation. iv. Collect nanoparticles.	Phospholipids, Cholesterol, Polymeric lipids	Simple and cost-effective. Suitable for heat-sensitive compounds	Organic solvent residues may cause toxicity	Protects anthocyanins from oxidation and light exposure	Jafari, 2022; Ribeiro *et al.*, 2023; Neves *et al.*, 2021
Microemulsion -based method	i. Prepare microemulsion using surfactants, co-surfactants, lipids, and anthocyanins. ii. Dilute with water under controlled temperature. iii. Cool to form nanoparticles.	Tween 80, Span 60, Lecithin, Medium-chain triglycerides	Produces thermodynamically stable nanoparticles. Enhances solubility and bioavailability	Requires high surfactant concentrations, increasing cytotoxicity risk	Prevents degradation and enhances absorption	El-Gogary *et al.*, 2022; Shah *et al.*, 2021

Ultrasonication	i. Melt the lipid phase and mix it with the aqueous phase containing anthocyanins. ii. Apply ultrasonication using a probe sonicator. iii. Cool to form nanoparticles	Phospholipids, Stearic acid, Glycerides	Efficient particle size reduction. - Minimal heat generation	Potential metal contamination from sonicator probe	Improves dispersion and prevents aggregation	Zhang *et al*., 2020; Nasirpour *et al*., 2023; Gonçalves *et al*., 2022
Double emulsion (W/O/W)	i. Prepare a water-in-oil (W/O) emulsion with anthocyanins and lipid phase. ii. Further emulsify into an external aqueous phase. iii. Evaporate solvent to solidify nanoparticles.	Polysorbates, Phospholipids, Gelatin, Alginate	Protects hydrophilic anthocyanins	Prone to instability due to droplet coalescence	Prevents enzymatic degradation and increases retention	Ganesan and Narayanasamy, 2021; Solans and Izquierdo, 2022; Han *et al*., 2023
Thin-film hydration	i. Dissolve lipids and anthocyanins in an organic solvent. ii. Evaporate solvent to form a lipid film. iii. Hydrate film with an aqueous phase under agitation. iv. Use sonication or extrusion for size reduction.	Phospholipids, Cholesterol, Stearic acid	Solvent-free and simple	Additional processing needed for uniformity	Provides structural stability to anthocyanins	Fan *et al*., 2022; Liu *et al*., 2023; Xiao *et al*., 2021
Supercritical fluid technology	i. Dissolve lipids and anthocyanins in supercritical CO. ii. Expand the solution into an aqueous medium. iii. Rapid depressurization leads to nanoparticle formation.	Phospholipids, Glyceryl behenate, Lecithin	Solvent-free and eco-friendly	Requires specialized high-pressure equipment	Prevents oxidation and thermal	Fang *et al*., 2021; Vieira *et al*., 2023; Campardelli *et al*., 2022
Electrospraying	i. Prepare a lipid solution with anthocyanins in a solvent. ii. Apply high voltage (5-30 kV) to form fine droplets. iii. Evaporate solvent to solidify nanoparticles.	Phospholipids, Polymeric lipids, Stearic acid	Produces uniform nanoparticles	Requires high voltage for operation	Improves light and pH stability	Tavares *et al*., 2023; Nasir *et al*., 2022; Moreno *et al*., 2021
Spray drying	i. Dissolve lipids and anthocyanins in a solvent. ii. Atomize the solution using a spray dryer. iii. Collect dried nanoparticles.	Phospholipids, Trehalose, Starch, Maltodextrin	Cost-effective and scalable	High temperatures may degrade anthocyanins	Converts into a stable dry powder, enhancing shelf-life	Alavi *et al*., 2021; Fathi *et al*., 2023; Cano *et al*., 2022
Ionic gelation	i. Prepare a lipid solution containing anthocyanins. ii. Add an ionic cross-linker (*e.g*., calcium chloride, sodium tripolyphosphate). iii. Stir to induce gelation and nanoparticle formation.	Chitosan, Alginate, Phospholipids	No organic solvents required	Limited control over particle size	Prevents hydrolysis and oxidation	Guerra *et al*., 2022; Pereira *et al*., 2023; Sharifi *et al*., 2021

6. Current research and future perspective

Lipid-based nano-encapsulation has gained significant attention for improving the stability, bioavailability, and therapeutic potential of anthocyanins. Recent studies have explored various lipid nanocarriers, including liposomes, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), and nanoemulsions. Liposomal formulations have demonstrated enhanced bioavailability and controlled release due to their ability to protect anthocyanins from degradation (Jafari, 2022). SLNs, composed of solid lipids, provide a rigid structure that prolongs retention time and improves antioxidant activity (Neves *et al*., 2021). NLCs, which combine solid and liquid lipids, have been reported to increase anthocyanin bioavailability up to 3.5 times compared to free anthocyanins (Ribeiro *et al*., 2023). Nanoemulsions have also proven effective in preventing anthocyanin precipitation and degradation in aqueous environments (Shah *et al*., 2021). Recent advancements focus on developing stimuli-responsive lipid nanoparticles, capable of releasing anthocyanins in response to environmental triggers such as pH changes or enzymatic activity, which enhances targeted drug delivery (Han *et al*., 2023). Another promising strategy is the integration of natural biopolymers like chitosan and alginate with lipid carriers to improve mucoadhesion and controlled release, particularly in gastrointestinal conditions (Vieira *et al*., 2023). Moreover, eco-friendly synthesis techniques using supercritical CO_2 and solvent-free methods are being explored to minimize toxicity concerns (Campardelli *et al*., 2022). However, large-scale production and industrial applications remain challenging, requiring further research to optimize manufacturing techniques and ensure cost-effectiveness while maintaining anthocyanin stability (Guerra *et al*., 2022). As the field progresses, future studies should focus on scaling up production, improving regulatory approvals, and developing next-generation smart lipid carriers for anthocyanin delivery in functional food and pharmaceutical applications.

7. Conclusion

Lipid-based nanoencapsulation has emerged as a promising approach to overcoming the challenges associated with anthocyanin stability and bioavailability. Techniques such as liposomes, nanoemulsions, SLNs, and NLCs have demonstrated significant potential in enhancing anthocyanin absorption, protecting them from degradation, and enabling controlled release. Despite these advancements, challenges remain, including optimizing encapsulation efficiency, scaling up production, and ensuring cost-effectiveness for commercial applications. Future research should focus on developing innovative lipid-based carriers, integrating multifunctional delivery systems, and conducting clinical studies to validate their efficacy. Advancing lipid-based nanotechnology will be crucial for unlocking the full potential of anthocyanins in functional foods, pharmaceuticals, and nutraceuticals, ultimately contributing to improved human health.

Conflict of interest

The authors declare no conflict of interest relevant to this article.

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