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Structural chemistry and stability of anthocyanins

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Abstract

Anthocyanins, which are natural pigments, are accountable for the deep blue, red, and purple hues of many fruits and vegetables. These pigments, which are a part of the flavonoid family, have garnered significant attention due to their potential health benefits such as antioxidant, anti-inflammatory, and anticancer properties. The biological activity and bioavailability of anthocyanins are determined by their chemical structure and stability. Anthocyanins are composed of a flavylium cation and have various substituents such as sugar and acyl groups that can impact their stability and reactivity. At low pH levels, anthocyanins are in their flavylium form and exhibit vivid colouration, but at higher pH levels, they undergo structural changes into quinoidal bases that are less stable and less colourful. The stability of anthocyanins can be influenced by several factors such as light, temperature, pH, and the existence of metal ions. Exposure to light and high temperatures may lead to anthocyanin degradation, whereas metal ions can create complexes that hinder their stability and bioavailability. Heating, drying, and extraction procedures can all have an impact on anthocyanin stability. In order to create successful preservation and processing methods for foods and supplements high in anthocyanins, comprehending their chemical structure and stability is crucial. With this objective in mind, the purpose of this review paper is to furnish a comprehensive outline of current knowledge regarding anthocyanin's structural chemistry and chemical stability. Significant factors that influence the stability and reactivity of anthocyanins will also be emphasized.

Keywords: Anthocyanins, chemical stability, structure, encapsulation

Introduction

The most significant pigments in vascular plants are anthocyanins (from the Greek anthos, which means flower, and kianos, which means blue). Heterosides are the major type of anthocyanins found in nature. The structural basis for the aglycon forms of anthocyanins, also known as anthocyanidins, is the flavylium ion or 2-phenylbenzopyrylium, and they are composed of hydroxyl and methoxyl groups in various positions. More than 635 anthocyanins have been identified based on the quantity and arrangement of hydroxyl and methoxyl moieties. Pelargonidin, cyanidin, peonidin, delphinidin, petunidin, and malvidin are the six anthocyanidins in plants that are most commonly recognized. But the color and their stability are totally dependent upon certain environmental factors such as oxygen, temperature, pH, storage condition and amount of light. Anthocyanins are safe and easy to incorporate into aqueous media, making them suitable for use as natural water-soluble colorants^[1].

These pigments are also responsible to give some plants' flowers and fruits their brilliant orange, pink, red, violet, and blue hues. In a moderately acidic aqueous solution (pH 2), anthocyanins are often represented by their flavylium cation. Anthocyanins undergo equilibrium by acid-base, water addition-elimination, and isomerization reactions to transform into a variety of colourful and colorless forms at the pH conditions present in plants, food, and the digestive tract (between pH = 2 and pH = 8)^[2]. Anthocyanin molecules come in more than 250 different varieties, and they are found in foods including blueberries, grapes, black wolfberries, cherries, black rice, purple maize, red cabbage, broccoli, lettuce, canadaberry, junberry, sumacberry, black plums, cloudberry, pineberry and purple potatoes. The use of anthocyanins from natural sources as food colouring in foods and beverages is legal in many nations, including Europe (E163), Japan and the United States. According to toxicological tests on mutagenicity, reproductive toxicity, teratogenicity, acute and short-term toxicity, the Joint FAO/WHO Expert Committee on Food Additives (JECFA) found that extracts containing anthocyanins have very low toxicity^[3]. Anthocyanin colours may be used as a quantum satis in food items, with the exception of breakfast cereals, where a maximum

50

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quantity of 200 mg/l or mg/kg as suitable is 72 permitted (Regulation (EU) No 231/2012) [4]. Besides all these, some of the studies reported the relationship between the dietary intake of anthocyanins and the health-related benefits. Recent studies have shown that the intake of anthocyanins can help to protect against neurological diseases and cognitive functions related to age [5]. It also reduces the risk of heart diseases and chronic diseases like obesity and diabetes as it plays a significant role as an anti-inflammatory and anti-cancerous agent. But the biological use of these compound is limited due to their instability in the human digestive system which is because of the intestinal pH [6, 7]. According to some researchers, the absorption of anthocyanins majorly happens in the small intestine but many studies had reported that absorption of anthocyanins starts in the upper gastrointestinal tract [8, 9, 10, 11]. Recent studies have revealed that anthocyanins possess anti-inflammatory, anti-cancer, antimicrobial, and antioxidant properties, and can aid in reducing the occurrence of obesity, diabetes, and cardiovascular disease [12]. It is hence evident that anthocyanins are an excellent resource with vast potential for use in the food industry and medical field.

Anthocyanins, while beneficial, suffer from poor stability that can be impacted by various factors such as moisture, light, pH, temperature, sugar levels, vitamin C, oxygen, sulfur dioxide or sulfites, enzymes, co-pigments, and metal ions [13]. These variables can cause changes in the concentration and bioactivity of anthocyanins, which can ultimately affect consumer acceptance [14]. Recent studies have also highlighted that the bioavailability of anthocyanins is less than 1%. Anthocyanins' stability is subject to transformation through three methods: polymerization, cleavage, and derivatization. The outcome of anthocyanin cleavage is colorless compounds, whereas polymerization leads to browning. Meanwhile, derivatization reactions produce several molecules with different hues.

To maximize the benefits of anthocyanins, researchers have undertaken extensive investigations on how these parameters affect their stability. The focus has been on finding ways to overcome any shortcomings and improve stability, which in turn enhances the effectiveness of anthocyanins.

As a result, the goal of this paper is to offer an overview of anthocyanin structural chemistry as well as stability concerns. In this regard, the most significant factors influencing their stability were examined. Throughout this research, every aspect will be discussed in order to determine if it has a good or negative effect on anthocyanin stability. A set of figures and tables are also supplied to help readers comprehend their work. In this way, the prospect for future research into enhancing their stability and intense usage in the food industry and the medical area is given.

Structural Chemistry

Anthocyanin form	Molecular weight	Distribution in fruits and vegetables	Exhibited color	Structural difference		Molecular formula
				R1	R2	
Cyanidin (Cy)	287	50%	Brilliant red to orange	OH	H	C ₁₅ H ₁₁ O ₆
Malvidin (Mv)	331	7%	Bluish-purple	OCH ₃	OCH ₃	C ₁₇ H ₁₅ O ₇
Delphinidin (Dp)	303	12%	Violet	OH	OH	C ₁₅ H ₁₁ O ₇
Pelargonidin (Pg)	271	12%	Orange	H	H	C ₁₅ H ₁₁ O ₅
Petunidin (Pt)	317	7%	Red	OCH ₃	OH	C ₁₆ H ₁₃ O ₇

Stability of anthocyanins

The primary drawback of anthocyanin pigment is their

Anthocyanins are a type of flavonoid pigment that naturally occurs in hydro-soluble form. They are responsible for the striking red to blue hues seen in many plants. Structurally, these pigments possess a flavonoid skeleton with a C6-C3-C6 configuration, also known as a 2-phenyl-benzopyrylium cation or a flavylum. This skeleton consists of two aromatic rings, A and B, connected by a C-ring with two double bonds, which gives the C-ring a positive charge. Anthocyanins are usually bound to a glycosidic structure with an aglycone called anthocyanidin. Glucose is the most common sugar moiety attached to the molecule at either the C3-position of the C-ring or the C5- or C7-position of the A-ring, but other sugars like galactose, arabinose, rhamnose, and xylose may also be present. Nature contains 20 types of anthocyanidins, each with varying numbers and positions of hydroxyl or methyl ether groups. The main six main types of anthocyanidins present abundantly in nature are as shown in Figure 1: malvidin (Mv), pelargonidin (Pg), petunidin (Pt), delphinidin (Dp), cyaniding (Cy) and peonidin (Pn) [15]. The amount of hydroxyl groups, the degree of glycosylation and acylation, the catechol residue on the B ring, and the oxonium ion on the C ring all have a direct impact on their biological potential [16].

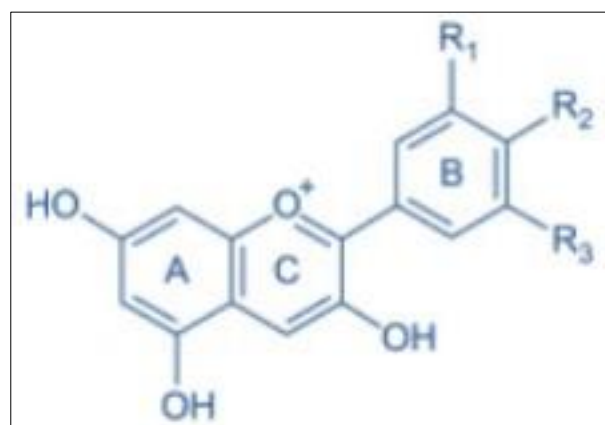


Fig 1: Basic Structure of Anthocyanin

As a result, anthocyanins are classified based on (i) the number, position, and degree of methylation of the hydroxyl groups; (ii) the number and nature of the sugar moieties bonded to the aglycone; and (iii) the position of the aliphatic and/or aromatic carboxylate acids on the sugar molecule [17]. The storage and processing conditions, temperature, and cooking, as well as exposure to light and oxygen, the presence of enzymes, other phenolic compounds, metal ions, ascorbic acid, hydrogen peroxide (H₂O₂), water, and/or sulphites, all impact the stability of anthocyanins.

incredibly low stability, which is easily influenced by a wide range of factors that includes the relative humidity, light,

basic or acidic range of pH, high temperature,

acylated and non-acylated sugars, vitamin C, oxygen levels, compounds of sulphur dioxide, enzyme activity, co-pigmentation, and metallic ions ^[13].

As a result, presence of these variables predicts different changes in anthocyanin content and their bioactivity, those influences that how well consumers will accept a product. Thus, polymerization, cleavage, and derivatization are three strategies to modify the stability of anthocyanins. Anthocyanin cleavage yields colorless chemicals, polymerization results in browning, and derivatization processes yield a variety of colour-changing molecules ^[18]. The stability of anthocyanins is frequently influenced by intrinsic and extrinsic factors such as pH, pigmentation, light, and temperature.

Factors affecting stability of anthocyanins

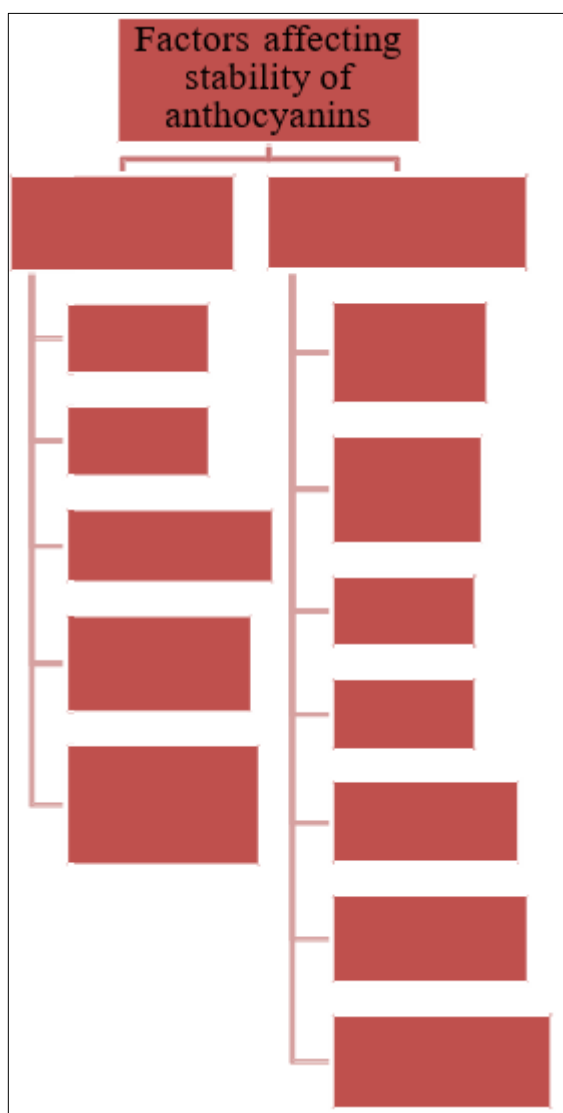


Fig 2: Intrinsic and Extrinsic factors affecting the stability of anthocyanins

Structure

The shade of monoacylated and nonacylated anthocyanins is majorly influenced by the substitution pattern of the aglycone

B-ring. A surge in hydroxyl groups (from pelargonidin to cyanidin to delphinidin) results in a shift towards longer wavelengths. Conversely, a rise in methylation (from cyanidin to peonidin to malvidin) brings about a shift towards shorter wavelengths. When cinnamic acids are acylated, the pigment is bathochromically shifted and produces blue hues. However, the type of acylating agent used can also play a role.

The coloring and spectral traits of moieties rely heavily on the position of the acyl group on the saccharide. When cinnamic acids are acylated, the visual thresholds are typically lower, which implies stronger pigmentation. Referred to as the hyperchromic effect, this phenomenon has been observed in both isolated anthocyanins and pigments found within plant extracts ^[19]. The colour of youthful red wines is primarily attributed to monomeric anthocyanins, which comprise between 57% and 69% of the coloration. However, the same cannot be said for aged red wines, as the production of oligomeric and polymeric derivatives during storage results in the negligible contribution of monomeric anthocyanins to color. It was found that monoglucosides contain the highest levels of colour intensity, which can be derived from the lowest visual detection thresholds. Meanwhile, higher detection thresholds are observed when a second saccharide moiety is present on the aglycone or the saccharide moiety is acylated, especially at the natural pH of red wine.

Copigmentation

Only anthocyanins exhibit copigmentation phenomena, making it a unique characteristic to this class of compounds. There has been no recorded instance of any other subclass of polyphenols or non-phenolic compounds exhibiting the same characteristics. Typically, copigmentation phenomena are accompanied by a shift towards longer wavelengths in the absorption spectrum of either the plant extract or anthocyanin, and a greater absorption capacity ^[20]. Furthermore, the use of 1H nuclear magnetic resonance techniques has revealed the vertical stacking of anthocyanidins and their copigments, providing concrete evidence for copigmentation. In addition, intramolecular copigmentation has been noted, where a single molecule contains two or more chromophores, resulting in a heightened color intensity.

The interaction between the anthocyanidin backbone and a copigment that is an integral component of the anthocyanin is what brings about the development of color. This process is realized through the alignment of the aromatic acyl moieties of acylated anthocyanins with the core structure of the anthocyanidin. This alignment causes steric hindrance, which in turn limits the attack of water at positions 2 or 4 of the anthocyanidin, thereby resulting in the formation of hemiacetal forms that are colorless. Furthermore, anthocyanin stabilisation driven by a process known as self-association. That is, the aforementioned steric barrier of anthocyanidin aglycone hydration at position 2 is achieved by the connection of multiple anthocyanin molecules via hydrophobic contacts of their aromatic nuclei. By implication, this effect is concentration-dependent; rising anthocyanin concentrations cause a bathochromic shift ^[21].

pH

The stability and degradation of anthocyanins also depends upon the pH, as anthocyanins also act as the pH indicators. In acidic conditions at pH 1, anthocyanins present in the form of flavylium cation that exhibits red and purple color, which

makes them particularly soluble in water [22]. Quinoidal blue species are prevalent when the pH rises to 2 to 4, whereas colourless chalcone and carbinol pseudobase start to develop when the pH rises to 5 to 6 [23]. The anthocyanins finally breaks down in accordance with the substituent groups at a pH greater than 7. However, at pH 4 to 6, four-anthocyanin forms can co-exist, with the flavylium cation preserving the balance of these forms. In the neutral pH anthocyanins shows the violet or purple color and in the alkaline pH anthocyanins shows the blue color. This happens because of the presence of flavylium cation in the anthocyanin structure. Both color and intensity can be affected due to the anthocyanin degradation that is caused because of the elevated pH [24]. Consequently, it is possible to conclude that the loss of anthocyanins has affected by the rise in temperature, heating duration, and pH.

Metal complexation

Anthocyanins having two or more vicinal hydroxyl functionalities (mostly cyanidin, delphinidin, and petunidin glycosides) can form complexes with divalent or trivalent cations like Fe³⁺, Al³⁺, Mg²⁺, Sn²⁺, or Cu²⁺. This complex formation is associated not only with anthocyanin stabilisation, but also with a considerable bathochromic change in the absorption spectrum. Tin, copper, iron, aluminium, magnesium, and potassium are the most prevalent metals found in anthocyanin complexes [21].

Interaction with food matrices

Analytical problems in analysing such events, as well as a more precise characterisation of the polymeric molecules engaged in such interactions, have prevented thorough and clear results. Recent research on the interaction of polysaccharides with anthocyanins indicated that sodium alginate, pectin, and maize starch had a stabilising effect when added to specific anthocyanin solutions [25]. Meanwhile, much more detailed studies have been conducted, revealing the stabilising potential of pectins when added to black currant anthocyanins in model solutions, with amidated pectins exhibiting the most pronounced effects and citrus pectins outperforming apple pectins in terms of anthocyanin retention after storage [26].

Processing and Storage

Anthocyanins are distinguished by their high reactivity and, as a result, vulnerability to hydration and oxidation. Furthermore, they interact with and react with other dietary components such as ascorbic acid, sulphur dioxide, saccharides, and their breakdown products. Furthermore, their vulnerability to enzymatic degradation makes it difficult to stabilise anthocyanins in plant-based meals or use them as food colourants as an alternative to synthetic colours. There are several factors that play a significant role in altering the true anthocyanin profile, including the creation of new molecules and loss of pigments during postharvest treatment and food processing. Some of these factors include winemaking, wine ageing and storage, postharvest ripening, cold storage, thermal treatment, comminution and pressing techniques, filtration and concentration, enzymatic treatment, extraction, fermentation, and various pre and postharvest treatments such as spraying, ultraviolet irradiation, and controlled molecular techniques [27].

Light

The impact of light on anthocyanins and their stability is twofold. In living tissues, light plays a crucial role in the synthesis of anthocyanins, promoting the accumulation of pigments. This phenomenon has also been observed in plant tissue cultures when evaluating the production of anthocyanins. Therefore, light is a significant factor in the stability of these compounds [28]. However, the effect of light on anthocyanins is two-fold. While light is necessary for the production of anthocyanins, it also accelerates their degradation. Furthermore, the presence of molecular oxygen affects the rate at which light-induced breakdown occurs. Notably, when exposed to fluorescent light, anthocyanins experience the most significant loss. These compounds are responsible for the vibrant colors of various plants, such as grapes and berries, as anthocyanins exhibit a high absorption capacity for visible light [29]. To reduce the detrimental influence of light on anthocyanins, packaging can be composed of materials that can block light from the visible spectrum, particularly the ultraviolet field, providing a protective barrier. Furthermore, glycosylation, acylation, and co-pigmentation all contribute to anthocyanins' light stability.

Temperature

The preservation and elongation of food shelf life, as well as the assurance of food safety, are often achieved through the utilization of heat processing. Depending on the desired shelf life and the functional parameters of the food, heat treatment can occur within a temperature range of 50-180 °C. Consequently, the application of high temperatures for specific durations during processing can lead to notable alterations such as changes in color, anthocyanin levels, and antioxidant capacity [14]. The degradation and loss of anthocyanins are caused by various mechanisms, including glycosylation, nucleophilic water attack, cleavage, and polymerization, all of which occur as a result of heat processing [30]. Temperature, therefore, plays a significant role in the stability of anthocyanin molecular structures, with higher temperatures leading to compound degradation and product browning in the presence of oxygen. Studies conducted on grape extracts have revealed that subjecting the extract to heat treatment at a temperature of 35 °C resulted in a reduction of more than 50% in the total anthocyanin content, compared to the same extract that underwent heat treatment at 25 °C.

Furthermore, the colour of the anthocyanins shifted from red to orange when exposed to temperatures of up to 40 °C, regardless of the pH level of the environment [31]. It is worth mentioning that thermal processes that require high temperatures, such as bleaching and pasteurization at 95 °C for 3 minutes to produce blueberry puree, led to a loss of 43% in total monomeric anthocyanins when compared to the amount present in the fresh fruit prior to heat treatment. It is important to note that while the number of anthocyanins decreased, the levels of polymer colours increased from 1% to 12%. This discovery suggests that heat-sensitive factors can contribute to the degradation of anthocyanin pigments, further supporting the theory that the destruction of pigments during juice processing is caused by endogenous enzymes present in fruits [32].

Ascorbic Acid

Ascorbic acid is one of the component that plays a major role in the human body as an antioxidant. This component plays

the major role in the food processing and during its storage because the amount of vitamin C levels shows the quality of food that has been deteriorated during and after the processing conditions^[33]. Some researchers analyzed that in the presence of ascorbic acid the anthocyanins degrades faster and loss of color was there^[34]. Anthocyanin nucleophilic sites believed to target by the few electrophilic molecules such as bisulphites, hydrogen peroxide and ascorbic acid.

Oxygen

Anthocyanins remain susceptible to the oxygen molecules due to their unsaturated chemical structure. It is the crucial factor that directly effects the stability of anthocyanins and increasing its rate of degradation by two ways: (i) by direct oxidative mechanism or (ii) by the action of oxidizing enzymes^[32]. It has been also demonstrated that for preventing the thermal degradation of anthocyanins, removal of oxygen molecules is necessary. It has been proven by several studies that high temperature and the presence of oxygen is the most harmful combination to affect the stability of anthocyanins^[21].

Sulfites

The usage of sulfites and sulfites is widespread in the preservation of fruit-based products, but it is important to note that these substances can lead to the depletion of anthocyanin pigment. Furthermore, anthocyanins can be restored through acidification to a lower pH, which releases sulfur dioxide (SO₂)^[21]. In the fruit and vegetable preservation industry, sulfur dioxide is commonly employed as a means to hinder microbial growth and prevent enzymatic and non-enzymatic browning. However, it is worth mentioning that high concentrations of sulfites (exceeding 10 g/kg) can result in irreversible degradation of anthocyanins^[21]. Sulfites find application in various areas of food processing, including as antioxidants and preservatives in the production of dried fruits and in winemaking. Nonetheless, their use is associated with the discoloration of anthocyanins, which occurs due to a reversible chemical reaction wherein sulfite is added to the anthocyanidin backbone, predominantly at the C4 position of the C-ring, resulting in colourless sulfonic acid derivatives. Consequently, anthocyanins that are "blocked" at the C4 position, such as vitisins, exhibit greater resilience to color loss caused by sulphites^[35]. The application of sulfite addition has frequently been employed to improve the extraction of pigments, specifically for the retrieval of oenocyanin (E 163) from grape pomace. This is due to the reversible nature of sulfonic acid formation and the fact that the resulting reaction products exhibit increased hydrophilicity compared to their corresponding anthocyanins.

Enzymes

Anthocyanases, which consist of glycosidases, peroxidases, and phenolases, are the enzymes primarily responsible for degrading anthocyanins. These enzymes can either be synthesized by the plant itself or found in its tissues or occur as a result of microbial contamination. It is important to note that glycosidases directly impact anthocyanins, whereas peroxidases and phenolases indirectly affect their stability. Specifically, glycosidases break the covalent bond between the glycosyl residue and the aglycone of an anthocyanin, resulting in the formation of unstable anthocyanidins. This process ultimately influences the color of the compound^[36].

^{37]}. One can make the assumption that the initial enzyme responsible for impacting the stability of anthocyanins is β -glucosidase. This enzyme generates anthocyanidins, which can then undergo further oxidation by polyphenol oxidase and/or peroxidase. As a result of these enzymatic actions, the solubility of anthocyanins decreases, leading to their conversion into colorless compounds and the subsequent loss of colour intensity in these pigments.

Encapsulation of anthocyanins

Encapsulation, a process in which a bioactive agent of natural origin (whether it be in solid, liquid, or gaseous form) is enveloped by a polymeric material or integrated into a matrix, serves to safeguard the agent from detrimental environmental factors. By means of encapsulation, various parameters such as the site and timing of delivery can be regulated to achieve optimal effectiveness.^[38,39] The size of the vesicles produced through this technique can vary significantly, ranging from 1 to 1000 μm .^[40]

Over the past few years, there has been a significant advancement in the development and refinement of various methods aimed at encapsulating anthocyanins within micro- and nanocarriers. There are many carriers in which the bioactive material can be encapsulated and their stability can be enhanced such as liposomes, lipid particles, emulsions, spray-drying and freeze drying.^[41, 42] There have been numerous methods documented for the design of micro- and nanocarriers that are used to encapsulate anthocyanins. The initial category of carriers consists of those that require specialized equipment for production, such as spray-drying, freeze-drying, and electro- spinning/spraying^[43]. Furthermore, lipid-based carriers, which are formulated using fats and oils like emulsions and liposomes, have also proven to be effective in the encapsulation process.

Anthocyanins can be derived from various sources. Lastly, another significant category consists of nano/microcarriers that are created through a process called ionic gelation. This encapsulation method involves utilizing atomization, dripping (coextrusion, extrusion), or electrostatic spray techniques. Lipid-based micro/nanocarriers can be divided into two distinct groups. The first group is comprised of emulsions, which consist of oil, water, and surfactants. These emulsions can take the form of single oil in water or water in oil emulsions, as well as double oil in water in oil or water in oil in water emulsions^[44].

Liposomes

Liposomes are spherical vesicles made up of one or more concentric lipid bilayers and contain an aqueous space^[45]. These phospholipid structures have the ability to encapsulate and protect hydrophilic substances, making them ideal for encapsulating anthocyanins. By incorporating these polyphenols, liposomes provide a protective barrier against degrading environmental factors. Additionally, liposomes have the ability to enhance the absorption and bioavailability of anthocyanins due to their biocompatibility, amphiphilicity, nontoxicity, and non-immunogenicity^[40, 47]. These advantageous properties have sparked significant interest in the biomedical, food, and cosmetic industries, as liposomes have a wide range of applications. However, it is important to note that liposomes can undergo oxidation processes, resulting in the formation of hydroperoxides, due to the

presence of unsaturated fatty acids in their membrane component^[40].



Fig 2: Different methods to encapsulate the anthocyanins

Emulsions

Emulsions are composed of at least two liquids that are unable to mix together, with the most common combination being water and oil. These liquids are held together by surfactants, and the smaller of the two is dispersed into spherical droplets within the larger one. There are various types of emulsions based on the dispersed liquid, including simple emulsions such as oil in water (O/W) or water in oil (W/O), as well as double emulsions like oil in water in oil (O/W/O) or water in oil in water (W/O/W)^[38, 46]. Double emulsions, specifically water in oil in water, offer a suitable technique for encapsulating hydrophilic substances like anthocyanins. This allows for easy incorporation of anthocyanins into the dispersed phase of an emulsion, providing protection against environmental damage and degradation^[40]. Moreover, this encapsulation system enables controlled release of anthocyanins at specific times or locations, while also enhancing their bioavailability in the gastrointestinal tract^[46].

Freeze drying

The process described here employs a contrasting approach to spray-drying by utilizing lower temperatures to achieve dehydration. Consequently, freeze-drying, or lyophilization as it is commonly referred to, proves to be an effective method for encapsulating compounds that are sensitive to high temperatures, such as anthocyanins. The procedure involves a series of steps including freezing, sublimation (primary drying), desorption (secondary drying), and ultimately the preservation of the resulting dry material^[47].

Freeze-drying offers several benefits that stem from its straightforward procedure, conducted in a low-temperature, air-free environment. This ensures that the resulting compounds are impervious to oxidation or chemical alteration^[47]. In particular, this technique is employed to enhance the thermal and color stability of anthocyanins, utilizing various wall materials^[46]. However, it is important to note that

freeze-drying does come with drawbacks, including the high expenses associated with vacuum technology and the lengthy dehydration process, which can take approximately 20 hours.

Spray drying

This particular methodology presents several advantages, including its efficiency, adaptability, cost-effectiveness, and scalability. It is also characterized by a high encapsulation efficiency and relatively good storage stability^[40]. Furthermore, a wide range of encapsulating agents, such as lipids, proteins, and polysaccharides, can be utilized depending on the specific compound being incorporated^[46]. The selection of appropriate wall material for microencapsulation via spray drying plays a crucial role in the overall efficiency of this technique. However, there are limitations in terms of the compounds that can be chosen for this method, as they must meet certain criteria, such as low viscosity at high concentrations, acceptable solubility, film-forming capacity, and emulsifying properties. Considering these criteria, the most commonly employed compounds for the spray-drying encapsulation of anthocyanins are polysaccharides. This is due to their low viscosity, desirable solubility, suitable emulsification characteristics, and high capacity to retain volatile compounds^[38]. Through this technique of encapsulation particles of various sizes can be obtained.

Conclusion

In conclusion, this review paper delved into the fascinating field of structural chemistry and the factors influencing the stability of anthocyanins, as well as the encapsulation methods employed for their stabilization. Anthocyanins, the vibrant plant pigments responsible for the brilliant hues seen in various fruits, vegetables, and flowers, have gained significant attention due to their potential health benefits and applications in food and pharmaceutical industries. Through a

comprehensive analysis of the structural chemistry of anthocyanins, it became evident that their stability is influenced by a multitude of factors. These factors include pH, temperature, light, oxygen, metal ions, and enzymatic degradation. By understanding the chemical properties and structural features of anthocyanins, researchers can employ strategies to enhance their stability and extend their shelf life. Various techniques for encapsulation have surfaced in recent times. As viable strategies for establishing a state of stability preserving the color, flavor, and bioactive properties of anthocyanins is a critical task. To achieve this, various encapsulation techniques have been developed, including microencapsulation, nanoencapsulation, and inclusion complex formation. These techniques create protective barriers that shield anthocyanins from external factors, preventing degradation and enhancing overall stability. As a result, the storage and handling characteristics of anthocyanin-rich products are improved, and their potential applications in different industries are expanded through controlled release. The choice of encapsulation materials and techniques is vital in determining the stability and bioavailability of encapsulated anthocyanins. Natural polymers, such as proteins, polysaccharides, and lipids, have gained recognition as ideal encapsulating agents due to their biocompatibility, biodegradability, and ability to form stable matrices. Additionally, advancements in encapsulation technologies, such as spray drying, freeze drying, and electrospinning, have facilitated the development of innovative encapsulation systems for anthocyanins.

Overall, this review highlights the importance of understanding the structural chemistry of anthocyanins and the factors influencing their stability. The utilization of encapsulation methods provides a promising avenue for the stabilization of these valuable plant pigments. Further research in this area will undoubtedly contribute to the development of improved encapsulation techniques, leading to enhanced stability and increased utilization of anthocyanins in various applications, including food, nutraceuticals, and pharmaceuticals. By harnessing the potential of anthocyanins and their stabilized forms, we can unlock their numerous benefits, promoting a healthier and more vibrant future.

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