Advancement of Protein- and Polysaccharide-Based Biopolymers for Anthocyanin Encapsulation

Jiahui Song¹, Yue Yu¹*, Minghuang Chen², Zhongyang Ren³, Lin Chen⁴, Caili Fu², Zhengfei Ma⁵* and Zhanming Li¹,²

¹ School of Grain Science and Technology, Jiangsu University of Science and Technology, Zhenjiang, China, ² National University of Singapore Suzhou Research Institute, Suzhou, China, ³ College of Ocean Food and Biological Engineering, Jimei University, Xiamen, China, ⁴ Food, Nutrition and Health, Faculty of Land and Food Systems, The University of British Columbia, Vancouver, BC, Canada, ⁵ Department of Health and Environmental Sciences, Xi’an Jiaotong-Liverpool University, Suzhou, China

Although evidence shows that anthocyanins present promising health benefits, their poor stability still limits their applications in the food industry. Increasing the stability of anthocyanins is necessary to promote their absorption and metabolism and improve their health benefits. Numerous encapsulation approaches have been developed for the targeted release of anthocyanins to retain their bioactivities and ameliorate their unsatisfactory stability. Generally, choosing suitable edible encapsulation materials based on biopolymers is important in achieving the expected goals. This paper presented an ambitious task of summarizing the current understanding and challenges of biopolymer-based anthocyanin encapsulation in detail. The food-grade edible microencapsulation materials, especially for proteins and polysaccharides, should be employed to improve the stability of anthocyanins for effective application in the food industry. The influence factors involved in anthocyanin stability were systematically reviewed and highlighted. Food-grade proteins, especially whey protein, caseinate, gelatin, and soy protein, are attractive in the food industry for encapsulation owing to the improvement of stability and their health benefits. Polysaccharides, such as starch, pectin, chitosan, cellulose, mucilages, and their derivatives, are used as encapsulation materials because of their satisfactory biocompatibility and biodegradability. Moreover, the challenges and perspectives for the application of anthocyanins in food products were presented based on current knowledge. The proposed perspective can provide new insights into the amelioration of anthocyanin bioavailability by edible biopolymer encapsulation.

Keywords: anthocyanins, biopolymer, polysaccharides, encapsulation, stability, bioavailability

HIGHLIGHTS
- The interactions between food matrix and anthocyanins were discussed in detail.
- The influence factors involved in the stability of anthocyanins were introduced.
- Performance of proteins or polysaccharides-based encapsulation was concluded.
- Advantages of protein-polysaccharide systems for encapsulation were summarized.
INTRODUCTION

Recently, numerous studies have updated the current understanding of the health-promoting effects of dietary polyphenols and related food products (1–3). As an important and well-considered type of polyphenol, non-toxic water-soluble anthocyanins contribute to food color and present a wide range of biological activities, including antibacterial, anti-inflammatory, anti-diabetic, anti-obesity, and anticancer effects (4–6). However, the low stability and non-targeted release of anthocyanins have become the main obstacles in realizing their biological benefits in food systems (7, 8).

The main challenges for the application of anthocyanins in the food industry are how to decrease anthocyanin loss and control anthocyanin reaction to obtain more products with high stability (9, 10). Encapsulation systems can introduce physical protection for anthocyanins to achieve the stimulus-responsive controlled release and site-specific delivery of anthocyanins (11, 12). Many encapsulation methods have been performed for the controlled release of anthocyanins to overcome the poor stability, oral bioavailability, and intestinal absorption of anthocyanins.

In addition to delivery techniques or carriers, various cross-linked biopolymers have also been studied for anthocyanin encapsulation (13, 14). Suitable encapsulation materials are important for achieving the expected performance of anthocyanins. Undoubtedly, only edible materials can be developed for the delivery of anthocyanins in food applications (10, 15). Edible biopolymer-based systems, including proteins and carbohydrates, are preferred for anthocyanin encapsulation (16, 17).

Encapsulated systems based on protein or polysaccharide particles can protect anthocyanins in food products during storage and retain the bioavailability of anthocyanins within the gastrointestinal tract (18, 19). In this perspective, the current understanding of biopolymer-based anthocyanin encapsulation is presented in this paper in detail. The influence factors involved in anthocyanin stability are introduced, and the properties and performances of anthocyanins encapsulated by proteins or polysaccharide-based systems are summarized in detail. Moreover, the challenges and future perspectives of the application of anthocyanins in food products are highlighted. Retaining the bioavailability of anthocyanins by means of edible biopolymers encapsulation can provide much information for the promising application of anthocyanins in food products.

STABILITY OF ANTHOCYANINS

Factors Affecting the Stability of Anthocyanins

Anthocyanins have a carbon skeleton made up of C6–C3–C6 unit (xanthine cation) and are composed of anthocyanidin (aglycone units) linked to sugar, which is usually located at the 3-position on the C-ring and methoxyl and hydroxyl groups (20), as shown in Figure 1. However, the stability of anthocyanins is strongly related to the substitution pattern in the B-ring; the stability can be improved with the increase in methoxyl group or deteriorate with the increase in hydroxyl group. Glycosylation and acylation can improve the stability of anthocyanins (21, 22).

In general, the application of anthocyanins as food additives is seriously limited by their instability. The absorption of anthocyanins is small in comparison with the dietary consumption of anthocyanins, indicating the low bioavailability of anthocyanins (28, 29). Anthocyanins may easily be degraded in vivo before reaching the target locations because of the harsh environment. As shown in Figure 1, anthocyanin stability can be easily impacted by pH, structure, enzymes, light, temperature, oxygen, solvents, concentrations, and other compounds that can interact with anthocyanins (12, 24). All of these factors restrict the wide applications of anthocyanins, because anthocyanins are extremely unstable and can easily degrade. Hence, the industrialized applications of anthocyanins in food products are challenging.

Edible Encapsulation Materials

To date, although evidence shows that anthocyanins present promising health benefits, their poor stability still limits their applications in food industry. Foods containing anthocyanins can only enter the bloodstream for further absorption and metabolism after reaching the gut lumen (30). Therefore, increasing the stability of anthocyanins is necessary to promote their absorption and metabolism and improve their health benefits. Encapsulated delivery systems have been reported to protect anthocyanins from adverse environmental conditions (31–34).

Although several wall materials can be employed for encapsulation, some properties, such as affinity, film-forming ability, degradability, intestinal resistance, and viscosity, should be optimized before the selection of wall materials (23, 35). Edible wall materials can be made from gum, protein, polysaccharides (natural or modified), and synthetic polymers (36, 37). The food-grade proteins and polysaccharides that are generally recognized as suitable materials for food products are shown in Table 1. Therefore, edible microencapsulation materials, especially for proteins and polysaccharides, should be clarified to improve the stability of anthocyanins for effective application in the food industry (Figure 2).

PROTEIN- AND POLYSACCHARIDE-BASED
ENCAPSULATION

Protein-Based Encapsulation

Food-grade proteins, especially whey protein, caseinate, gelatin, and soy protein, are attractive in the food industry owing to their health benefits. Their functional properties, including gelation, emulsification, and binding capacity, support their use as alternatives in the development of anthocyanin delivery systems (46, 47). In addition, proteins' hydrophobic region can interact with the benzene ring of anthocyanins. The carbonyl and amine groups of proteins form hydrogen bonds with the hydrophilic region of anthocyanins (48).
FIGURE 1 | Structures, main colors involved, and bioactivity of six important food anthocyanidins, as well as factors affecting the stability of anthocyanins. R$_1$, R$_2$ = H or OH; R$_3$ = H or glucose. The parameters were adapted from (12, 21, 23–27) with permission.

TABLE 1 | Properties of encapsulation materials for anthocyanins.

| Source of anthocyanins | Encapsulation materials | Properties | References |
|------------------------|-------------------------|------------|-----------|
| Extract from jaboticaba pomace | Maltodextrin, pectin, and soy protein isolate | Decreases the degradation caused by UV radiation | (38) |
| Black soybean seed coat extracts | Soy protein isolate | Decreases the degradation rate and improves stability | (39) |
| Powdered BRS violeta grape juice | Soy protein and whey protein | Increases stability for long shelf life | (40) |
| Elderberry (Sambucus nigra L.) | Whey protein and pectin | Increases encapsulation efficiency | (41) |
| Camelina sativa L. Crantz | Neutral polysaccharides and proteins | Increases stability | (42) |
| Black currant extract | Whey protein isolate, inulin, and chitosan | Increases stability | (43) |
| Sweet cherry skins | Whey proteins | Increases stability | (44) |
| Blueberry | Whey protein isolate | Improves bioactivity | (45) |

Whey proteins could be developed as wall materials to deliver anthocyanins with enhanced bioavailability (21, 35). Whey protein microgels as an anthocyanin encapsulation material can dissolve rapidly in the gastrointestinal tract and form liquid particles that impede anthocyanin release and degradation (49). The interactions between whey proteins and anthocyanins affect the color and heat/light stability of anthocyanins. The encapsulation of anthocyanins from blackcurrant using whey protein via spray drying or freeze drying has been suggested to develop nutritional food products (50). The encapsulation of anthocyanins from sour cherry skins using whey proteins with suitable encapsulation efficiency (over 70%) decreases gastric digestion and thus presents a potential as a functional matrix for food products (51).

Whey protein, casein, and soy protein isolates are efficient for improving anthocyanin bioavailability (Table 1). Casein
and whey protein have been used as wall materials to encapsulate blueberry anthocyanins using spray drying technique. Anthocyanin encapsulation is helpful in decreasing the rapid release and degradation of anthocyanin, especially during digestion in simulated gastric fluid. However, casein and whey protein showed different protection mechanisms as shown in Figure 3. The formation of casein–anthocyanin microparticles with poor solubility effectively inhibited the release and degradation of anthocyanins. The highly soluble whey protein–anthocyanin microparticles had decreased anthocyanin release. Casein and whey protein isolate could be employed to hinder the release of encapsulated anthocyanins, indicating that the proteins’ physicochemical properties and structural changes caused by digestion contributed to anthocyanin delivery. Obviously, the individual digestion behaviors of different proteins or composites as wall materials for anthocyanin encapsulation should be investigated in future research. The conformational change of the amphiphilic peptides of 18 amino acids (C6M1) from an $\alpha$-helical structure to a $\beta$-sheet structure was caused by co-assembly when used for anthocyanin encapsulation (Figure 4). The C6M1 peptide improved the resistance of anthocyanin to pH, high temperature, and metallic ions and improved the bioactivity for scavenging free radicals (52).

Although anthocyanin–protein interactions have been extensively studied, many parameters still need to be evaluated (53). The chemical structures of anthocyanins contribute to binding affinity. Moreover, different anthocyanins may produce different binding forces with proteins; hence, binding affinity to specific anthocyanins should be explored (54). The protein concentrations used in combination with anthocyanins still need to be optimized because they influence the rheological and sensory properties of anthocyanin–protein complexes, which are crucial parameters for food and beverage products (21).

**Polysaccharide-Based Encapsulation**

Polysaccharides, such as starch, pectin, chitosan, cellulose, mucilages, and their derivatives, are used as encapsulation materials because of their satisfactory biocompatibility and biodegradability (55). The performances of starch and its derivatives have been evaluated for anthocyanin encapsulation. Non-toxic and biodegradable chitosan has been widely utilized for anthocyanin encapsulation. Anthocyanin–chitosan nanoparticles are formed via non-covalent bonds (e.g., weak ionic binding and hydrogen binding) (56). As reported, dual coating with chitosan and polyionic polysaccharide to stabilize anthocyanins had high encapsulation efficacy and achieved resistance against auto-oxidation, heat, ascorbic acid, and neutral environment (57).

In addition, as the most widely reported cyclic oligosaccharide material, cyclodextrin can form complexes with anthocyanins through hydrogen bonding and hydrophobic interactions (58). Maltodextrin is also commonly introduced in the food industry as a wall material. The dextrose equivalent of maltodextrin is of paramount importance for retaining the stability and other properties of anthocyanins (59). Short-chain maltodextrin with high dextrose equivalent resulted in browning, hygroscopicity, and solubility. However, maltodextrin with a higher dextrose equivalent showed better performance in retarding anthocyanin degradation (60, 61).

The combination of xanthan gum and carboxymethyl starch produced a high encapsulation efficiency (over 96%) and contributed to the stability of blueberry anthocyanins (62). The co-encapsulation of blackberry juice and Lactobacillus acidophilus by gum arabic–maltodextrin could be effective to protect anthocyanins and probiotic bacteria (63). In addition, alginate–pectin hydrogel particles have been reported to encapsulate blueberry anthocyanins with high encapsulation efficiency (116%) (64).

**Combination of Proteins and Polysaccharides for Encapsulation**

Covalent interaction is the main pathway that contributes to the interactions between proteins and polysaccharides. Several factors affect covalent interactions, such as intrinsic factors, including free amino groups, carbonyl groups, molecular structure, hydrophilicity, and hydrophobicity. Similarly, extrinsic factors, such as pressure, temperature, processing methods (i.e., microwave, ultrasonic, and pulsed electric field), crosslinkers, and the molar ratio between biopolymers, affect the interactions between proteins and polysaccharides.

The covalent bonds formed by proteins and polysaccharides are involved in the enhancement of the stability and impediment of anthocyanin release in harsh environments (65). During this process, polysaccharides and proteins or peptides form electrostatic complexes by opposite charges under particular pH conditions. The covalent bonds can be achieved via chemical cross-linking or Maillard reactions. Anthocyanins interact with proteins via hydrophobic interactions and hydrogen bonds because of the high affinity between anthocyanins and proteins (13, 66). Afterward, the loaded proteins can be cross-linked by...
electrostatic interaction with oppositely charged polysaccharides to form double polymers (67, 68).

Electrostatic interactions between differently charged acrosome molecules lead to the formation of protein–polysaccharide complexes. This technique consists of two parts: the phase separation of biopolymer mixtures and the subsequent deposition of a cohesive phase near the active ingredients (69, 70). Three main steps, namely, the solubilization of biopolymers, mixing the biopolymers with appropriate proportions, and the acidification of the medium, are required to form complexes. Moreover, the acidification phase is critical because it strongly affects the complex dimensions of formation (32).

The biopolymers formed by proteins or peptides and polysaccharides are promising for anthocyanin encapsulation because they could achieve high loading capacity and encapsulation efficiency and controlled release (71). Whey protein, gum arabic, and maltodextrin have been employed for anthocyanin extract encapsulation using freeze drying with encapsulation efficiency over 82%; they could reduce anthocyanin degradation during heat processing (72). Moreover, the biopolymer particles fabricated with beet pectin and whey protein have been used to encapsulate anthocyanins to improve their heat stability (31). Anthocyanins from elderberry were encapsulated through whey proteins and pectin with high encapsulating efficiency (98%), and the remarkable antioxidation of the system highlighted the potential utilization of the microcapsules in food products (41).

As shown, the biopolymers of proteins and polysaccharides for anthocyanin encapsulation can be formed by covalent interactions and non-covalent complexations, and the possible factors that might be involved in the formation are summarized in previous studies (73). In comparison with the anthocyanin encapsulation based on proteins or polysaccharides, the protein-polysaccharide systems for anthocyanin encapsulation are comparable or more excellent for the improvement of stability in harsh environments and may overcome the limitation of single utilization (9, 74).

The strategy of anthocyanin encapsulation has presented functionalities in improving stability, increasing gastric residence time, and targeting release to enhance anthocyanin uptake and absorption by the formation of nanogels, microgels, microparticles, or emulsion systems (17, 75). The protein- and polysaccharide-based biopolymers for anthocyanin encapsulation (Figure 5) provide new insights for further research on how to protect anthocyanins against the external harsh environment by the utilization of environmentally friendly biopolymers.

**Interactions Between Proteins and/or Polysaccharides and Anthocyanins**

The absorption and excretion of anthocyanins are associated with many factors; among which, the food matrix’s effects are important to maintain the bioactivities of dietary anthocyanins (79, 80). As important parameters, the non-covalent interactions of anthocyanins with proteins, and/or carbohydrates have attracted intensive research attention (81). These interactions with macronutrients, which are driven by van der Waals interactions, hydrogen bond, and hydrophobic interaction, could...
affect anthocyanins’ properties, including bioavailability and radical scavenging (82).

Anthocyanin–protein complexes can be formed by crosslinking or aggregation via non-covalent binding. The hydroxyl and terminal galloyl groups of anthocyanins may contribute to the modulation of crosslinking owing to their molecular flexibility (82, 83). Moreover, anthocyanin–protein (non-enzyme) interactions may also be involved in subtle conformational changes (84). Non-covalent interactions may also occur between anthocyanins and carbohydrates (Figure 2).

Generally, the consumption of plant anthocyanins involves the ingestion of starch and fibers, which may help improve their stability by countering the pH variations in different in vivo digestion phases (85). The physical entrapping induced by these molecules restricts the mixing process between digestive fluids and anthocyanins to avoid their degradation to some extent and facilitate the biomolecules to reach the gut wall, which can improve their bioavailability and health-promotion benefits (12, 34).

Proteins, polysaccharides, and other components in the food matrix are commonly worked together to affect anthocyanin or macronutrient digestion. All ingredients work together to produce a final result, which highlights that the effects of the food matrix should be evaluated by taking into account all the ingredients or at least the main contributors. The observed effects and interactions of the matrix with anthocyanins remain elusive and require further investigation (77, 78, 86).

CURRENT UNDERSTANDING AND FUTURE PERSPECTIVES

The non-targeted release and low stability are the major obstacles of anthocyanins to present health benefits in food
systems (87–89). Recently, encapsulation approaches have been developed to address the low stability, low oral bioavailability, and poor intestinal absorption of anthocyanins. Several emerging micro/nanoencapsulation approaches are effective to some extent for improving anthocyanins’ stability against the harsh environment of the gastrointestinal tract with bio-efficacy enhancement (90, 91). In encapsulation, particle aggregation and particle size control, the sensitivity to pH and ionic strength of the prepared particles, as well as other related factors, should be optimized for the practice applications with satisfactory stability and bioavailability (92, 93). As above, the application of emerging micro/nanoencapsulation techniques in the food industry is still challenging.

Only food-grade biomaterials can be employed and accepted for delivering anthocyanins in the food industry. Regardless of nano/microcapsulation technique, food-grade materials, such as proteins, and polysaccharides, are utilized as wall materials for anthocyanin encapsulation with the promising performance of high encapsulated efficacy, enhanced stability, and excellent biocompatibility. The interactions between anthocyanins (e.g., proteins/peptides and polysaccharides) and biomaterials are important in designing delivery systems (Figure 6). The biomaterials properties, satisfactory stability, and the interactions between the biopolymers and anthocyanins should be considered when the edible biopolymers were selected for anthocyanin encapsulation. Although each method has advantages for specific applications, evaluating the requirements according to the advantages and disadvantages of encapsulation approaches is necessary before selection.

Bioderived colloidal particles, including protein–polysaccharide conjugates, micro/nanogels, and microfibers, provide new insights into the development of biopolymer interfaces to replace emulsifier layers (94). The potential of stabilized interface for particles has attracted great attention for food colloidal structure research (95). Complex coacervation, which has received a growing interest, presents excellent loading capacity, mild operating conditions, and controlled release (96). These controlled parameters for polysaccharide–protein complexes can enhance functional properties without enzymatic and chemical modifications and support the excellent encapsulation of anthocyanins.

Future recommendations include the utilization of microencapsulated anthocyanins with satisfactory bioavailability and stability as food fortification components (97). Developing more biopolymers with health benefits as wall materials is also crucial. New edible biomaterials or the new combinations of known biomaterials for the effective microencapsulation or nanoencapsulation of anthocyanins are important for the satisfactory design of micro/nanomaterials with novel characteristics (98). In particular, research interest on the microcapsules of anthocyanins and other polyphenols for biologically triggering their release in living cells is increasing (99, 100). Additionally, further research
Figure 6: Framework of the future trends or advantages of the micro-/nanoencapsulation of anthocyanins using edible biopolymers, including proteins or/and polysaccharides. PP, protein-polysaccharide.

is still suggested to combine the feasibility of different anthocyanin encapsulation techniques. However, seeking and strengthening the optimal techniques combined with environmental protection, high yield, and low cost are still needed.

The booming food industry will no longer be regarded as a low-profit commodity and will be a source of well-being and a revenue potential. The utilization of functional biopolymers via edible materials for food structure design provides new insights into the development of future foods with excellent sensory properties and health benefits, avoiding synthetic additives and negative nutrients. Importantly, investigating new edible biomaterials or creating new colloidal structures with underutilized edible biopolymers for future food design is an exciting and promising research direction.

**AUTHOR CONTRIBUTIONS**

JS, YY, ZL, and ZM designed the topic. JS and YY prepared the manuscript. JS, ZR, and ZL prepared the figures. YY, ZM, MC, ZR, LC, and CF reviewed and revised the manuscript. All authors contributed to the article and approved the submitted version.

**ACKNOWLEDGMENTS**

This work was financially supported by the National Natural Science Foundation of China (Grant No. 31902204), Natural Science Foundation of Fujian Province (2021J01835), National Key Research and Development Program of China (2021YFD2100200/2021YFD2100204), and Science and Technology project of Fujian health and Family Planning Commission (2021GGA054).

**REFERENCES**

1. Yu X, Chu M, Chu C, Du Y, Shi J, Liu X, et al. Wild rice (Zizania spp): a review of its nutritional constituents, phytochemicals, antioxidant activities, and health-promoting effects. Food Chem. (2020) 331:127293. doi: 10.1016/j.foodchem.2020.127293

2. Rabelo ACS, Borghesi J, Noratto GD. The role of dietary polyphenols in osteosarcoma: a possible clue about the molecular mechanisms involved in a process that is just in its infancy. J Food Biochem. (2022) 46:e14026. doi: 10.1111/jfbc.14026

3. Koch W. Dietary polyphenols—important non-nutrients in the prevention of chronic noncommunicable diseases: a systematic review. Nutrients. (2019) 11:1039. doi: 10.3390/nu11051039

4. Braga MB, Veggi PC, Codolo MC, Giaconia MA, Rodrigues CL, Braga ARC. Evaluation of freeze-dried milk-blackberry pulp mixture: influence of adjuvants over the physical properties of the powder, anthocyanin content and antioxidant activity. Int Food Res J. (2019) 125:108557. doi: 10.1016/j.foodres.2019.108557

5. Jia Y, Cai S, Muhoza B, Qi B, Li Y. Advance in dietary polyphenols as dipeptidyl peptidase-IV inhibitors to alleviate type 2 diabetes mellitus:
aspects from structure-activity relationship and characterization methods. *Crit Rev Food Sci Nutr.* (2021) 1–16. doi: 10.1080/10408398.2021.1989659

6. Yu Y, Li Z, Cao G, Huang S, Yang H. Bamboo leaf flavonoids extracts alleviate oxidative stress in HepG2 cells via naturally modulating reactive oxygen species production and Nrf2-mediated antioxidant defense responses. *J Food Sci.* (2019) 84:1609–20. doi: 10.1111/1750-3841.14609

7. Bendokas V, Skemiene K, Trumbeckaite S, Stany S, Passamonti S, Borutaita V, et al. Anthocyanins: from plant pigments to health benefits at mitochondrial level. *Crit Rev Food Sci Nutr.* (2020) 60:3352–65. doi: 10.1080/01924202.2019.1678421

8. Muche BM, Speers RA, Rupasinghe HP. Storage temperature impacts on anthocyanins degradation, color changes and haze development in juice of "Merlot" and "Ruby" grapes (*Vitis vinifera*). *Front Nutr.* (2018) 5:100. doi: 10.3389/fnut.2018.00100

9. Tan C, Dadmohammadi Y, Lee MC, Abbasspourd A. Combination of copigmentation and encapsulation strategies for the synergetic stabilization of anthocyanins. *Comp Rev Food Sci F.* (2021) 20:3164–91. doi: 10.1111/1541-4337.12772

10. de Oliveira Filho JG, Braga ARC, de Oliveira BR, Gomes FP, Moreira VL, PereiraVEC, et al. The potential of anthocyanins in smart, active, and bioactive eco-friendly polymer-based films: a review. *Food Res Int.* (2021) 142:110202. doi: 10.1016/j.foodres.2021.110202

11. Sun Y, Chi J, Ye X, Wang S, Liang J, Yue P, et al. Nanoliposomes as delivery system for anthocyanins: physicochemical characterization, cellular uptake, and antioxidant properties. LWT. (2021) 139:110554. doi: 10.1016/j.lwt.2020.110554

12. Rashwan AK, Karim N, Xu Y, Xie J, Cui H, Mozafari M, Chen W. Potential micro-/nano-encapsulation systems for improving stability and bioavailability of anthocyanins: an updated review. *Crit Rev Food Sci Nutr.* (2021) 1–24. doi: 10.1080/10408398.2021.1987858

13. Zhang X, Zeng Q, Liu Y, Cai Z. Enhancing the resistance of anthocyanins to environmental stress by constructing ovalbumin-propylene glycol alginate nanocarriers with novel configurations. *Food Hydrocoll.* (2021) 118:106668. doi: 10.1016/j.foodhydrocoll.2021.106668

14. Tan C, Arshadi M, Lee MC, Godec M, Azizi M, Yan B, et al. A robust aqueous core–shell–shell coconut-like nanostructure for stimuli-responsive delivery of hydrophilic cargo. *ACS Nano.* (2019) 13:9016–27. doi: 10.1021/acsnano.9b03049

15. Liu Y, Peng B. A novel hyaluronic acid-black rice anthocyanins nanocomposite: preparation, characterization, and its xanthine oxidase (XO)-inhibiting properties. *Front Nutr.* (2022) 9:879354. doi: 10.3389/fnut.2022.879354

16. Ribeiro JS, Veloso CM. Microencapsulation of natural dyes with biopolymers for application in food: A review. *Food Hydrocoll.* (2021) 112:106374. doi: 10.1016/j.foodhydrocoll.2021.106374

17. Sharif N, Khoshnoudi-Nia S, Jafari SM. Nano/microencapsulation of anthocyanins: a systematic review and meta-analysis. *Int Food Res J.* (2020) 132:109077. doi: 10.1016/j.ifrj.2020.109077

18. Nishimoto-Sauceda D, Romero-Robles LE, Antunes-Ricardo M. Biopolymer nanoparticles: a strategy to enhance stability, bioavailability, and biological effects of phenolic compounds as functional ingredients. *J Sci Food Agric.* (2022) 102:41–52. doi: 10.1002/jsfa.11512

19. Cai D, Li X, Chen J, Jiang X, Ma X, Sun J, et al. A comprehensive review on innovative and advanced stabilization approaches of anthocyanin by modifying structure and controlling environmental factors. *Food Chem.* (2022) 366:130611. doi: 10.1016/j.foodchem.2021.130611

20. Kalt W. Anthocyanins and their C6-C3-C6 metabolites in humans and animals. *Molecules.* (2019) 24:2042. doi: 10.3390/molecules24220424

21. Dini C, Zaro MJ, Viña SZ. Bioactivity and functionality of anthocyanins: a review. *Curr Bioact Compd.* (2019) 15:507–23. doi: 10.2174/157340721666180822115312

22. Chen B-H, Stephen Inbaraj B. Nanoemulsion and nanoliposome based strategies for improving anthocyanin stability and bioavailability. *Nutrients.* (2019) 11:1052. doi: 10.3390/n11051052

23. Mohammadalinejad S, Kurek MA. Microencapsulation of anthocyanins—Critical review of techniques and wall materials. *Appl Sci.* (2021) 11:3936. doi: 10.3390/app11093936

24. Cai D, Li X, Chen J, Jiang X, Ma X, Sun J, et al. A comprehensive review on innovative and advanced stabilization approaches of anthocyanin by modifying structure and controlling environmental factors. *Food Chem.* (2022) 366:130611. doi: 10.1016/j.foodchem.2021.130611

25. Stănicic N, Oancea AM, Aprodou I, Turturić M, Barbu V, Ionită E, et al. Investigations on binding mechanism of bioactives from elderberry...
Bioencapsulation for Anthocyanin Stability

Song et al. Biopolymers Encapsulation for Anthocyanin Stability

10 June 2022 | Volume 9 | Article 938829

(continued from previous page)

42. Ferron I, Milanesi C, Colombo R, Pugliese R, Papetti A. Selection and optimization of an innovative polysaccharide-based carrier to improve anthocyanins stability in purple corn cob extracts. Antioxidants. (2022) 11:916. doi: 10.3390/antiox11050916

43. Enache IM, Vasile AM, Enachi E, Barbu V, Stanciuc N, Vizireanu C. Co-microencapsulation of anthocyanins from black currant extract and lactic acid bacteria in biopolymeric matrices. Molecules. (2020) 25:1700. doi: 10.3390/molecules25071700

44. Milea AS, Vasile AM, Circiumaru A, Dumitraşcu L, Barbu V, Răpeanu G, et al. Valorizations of sweet cherries skins phytochemicals by extraction, microencapsulation and development of value-added food products. Foods. (2019) 8:188. doi: 10.3390/foods8060188

45. Zang Z, Chou S, Geng L, Si X, Ding Y, Lang Y, et al. Interactions of blueberry anthocyanins with whey protein isolate and bovine serum protein: color stability, antioxidant activity, in vitro simulation, and protein functionality. LWT. (2021) 152:112269. doi: 10.1016/j.lwt.2021.112269

46. Ju M, Zhu G, Huang G, Shen X, Zhang L, Jiang L, et al. A novel picking emulsion produced using soy protein-anthocyanin complex nanoparticles. Food Hydrocoll. (2020) 99:105329. doi: 10.1016/j.foodhyd.2019.105329

47. Shen Y, Zhang N, Tian J, Xin G, Liu L, Sun X, et al. Advanced approaches for improving bioavailability and controlled release of anthocyanins. J Control Release. (2022) 341:285–99. doi: 10.1016/j.jconrel.2021.11.031

48. Wu G, Hui X, Mu J, Brennan MA, Brennan CS. Functionalization of lactic acid bacteria in biopolymeric matrices. Molecules. (2020) 25:1700. doi: 10.3390/molecules25071700

49. Oancea A-M, Hasan M, Vasile AM, Barbu V, Enachi E, Bahrim G, et al. Valorizations of sweet cherries skins phytochemicals by extraction, microencapsulation and development of value-added food products. Foods. (2021) 10:310. doi: 10.3390/foods10020310

50. Gentile L. Protein–polysaccharide interactions and aggregates in materials. A review. Advances in Colloid and Interface Science. (2019) 25:1700. doi: 10.1016/j.cis.2021.102398

51. Tie S, Tan M. Current advances in multifunctional nanocarriers based on polysaccharides for colon delivery of food polyphenols. Curr Opin Colloid Interface Sci. (2017) 31:77–89. doi: 10.1016/j.cocis.2017.01.078

52. Wei Z, Huang Q. Assembly of protein–polysaccharide complexes for delivery of bioactive ingredients: a perspective paper. J Agric Food Chem. (2019) 67:1344–52. doi: 10.1021/acs.jafc.8b06603

53. Cortés-Morales EA, Mendez-Montealvo G, Velazquez G. Interactions of the molecular assembly of polysaccharide-protein systems as encapsulation materials for encapsulation of blueberry anthocyanins: optimization by artificial neural network and genetic algorithm and a comprehensive analysis of anthocyanin powder properties. Powder Technol. (2017) 311:77–87. doi: 10.1016/j.powtec.2017.01.078

54. Califius F, Fernandes PA, Wessel DF, Cardoso SM, Rocha SM, Coimbra MA. Interaction of wine mannoproteins and arabinogalactans with anthocyanins. Food Chem. (2018) 243:1–10. doi: 10.1016/j.foodchem.2017.09.097

55. Yang L, Zhang J, Shen L, Feng L, Zhou Q. Inhibition mechanism of diacetylated anthocyanins from purple sweet potato (Ipomoea batatas L) against α-amylase and α-glucosidase. Food Chem. (2021) 359:129934. doi: 10.1016/j.foodchem.2021.129934

56. Yang W, Deng C, Xu L, Jin W, Zeng J, Li B, et al. Protein-neutral polysaccharide nano-and micro-biopolymer complexes fabricated by lactoferrin and oat β-glucan: structural characteristics and molecular interaction mechanisms. Int Food Res J. (2020) 132:109111. doi: 10.1016/j.ifrj.2020.109111

57. Dragan ES, Dinu MV. Polysaccharides constructed hydrogels as vehicles for proteins and peptides. A review. Carbohydr Polym. (2019) 225:115210. doi: 10.1016/j.carbpol.2019.115210

58. Albano KM, Cavallieri ÀLF, Nicoletti VR. Electrostatic interaction between proteins and polysaccharides: physicochemical aspects and applications in emulsion stabilization. Int Food Res J. (2019) 35:54–89. doi: 10.1080/07559129.2018.1467442

59. Gentile L. Protein–polysaccharide interactions and aggregates in food formulations. Curr Opin Colloid Interface Sci. (2020) 48:18–27. doi: 10.1016/j.cocis.2020.04.002

60. Tie S, Tan M. Current advances in multifunctional nanocarriers based on marine polysaccharides for colon delivery of food polyphenols. J Agric Food Chem. (2021) 70:903–15. doi: 10.1021/acs.jafc.1c050102

61. Tao Y, Wang P, Wang J, Wu Y, Han Y, Zhou J. Combining various wall materials for encapsulation of blueberry anthocyanin extracts: optimization by artificial neural network and genetic algorithm and a comprehensive analysis of anthocyanin powder properties. Powder Technol. (2017) 311:77–87. doi: 10.1016/j.powtec.2017.01.078

62. Yang W, Zhou W. Microencapsulation of anthocyanins through two-step emulsification and release characteristics during in vitro digestion. Food Chem. (2019) 278:357–63. doi: 10.1016/j.foodchem.2018.11.073

63. Rosales TXO, da Silva MP, Lourenço FR, Hassisimo NMA, Fabi JP. Nanocapsulation of anthocyanins from blackberry (Rubus sp) through pectin and lysozyme self-assembling. Food Hydrocoll. (2021) 114:106563. doi: 10.1016/j.foodhyd.2020.106563
77. Zhang Q, Zhou Y, Yue W, Qin W, Dong H, Vasanthan T. Nanostructures of protein-polsaccharide complexes or conjugates for encapsulation of bioactive compounds. Trends Food Sci Technol. (2021) 109:169–96. doi: 10.1016/j.tifs.2021.01.026

78. Li H, Wang T, Hu Y, Wu J, Van der Meer P. Designing delivery systems for functional ingredients by protein/polsaccharide interactions. Trends Food Sci Technol. (2021) 119:272–87. doi: 10.1016/j.tifs.2021.12.007

79. Mansour M, Salah M, Xu X. Effect of microencapsulation using soy protein isolate and gum Arabic as wall material on red raspberry anthocyanin stability, characterization, and simulated gastrointestinal conditions. Ultrason Sonochem. (2020) 63:104927. doi: 10.1016/j.ultsonch.2019.104927

80. Victoria-Campos CL, de Jesús Ornelas-Paz J, Rocha-Guzmán NE, Gallegos-Infante JA, Failla ML, Pérez-Martínez JD, et al. Gastrointestinal metabolism and bioaccessibility of selected anthocyanins isolated from commonly consumed fruits. Food Chem. (2022) 132451. doi: 10.1016/j.foodchem.2022.132451

81. Zhang Q, Cheng Z, Chen R, Wang Y, Miao S, Li Z, et al. Covalent and non-covalent interactions of cyanidin-3-O-glucoside with milk proteins revealed modifications in protein conformational structures, digestibility, and allergic characteristics. Food Funct. (2021) 12:10107–20. doi: 10.1039/D1FO01946E

82. Wang Y, Zhang J, and Zhang L. Study on the mechanism of non-covalent interaction between rose anthocyanin extracts and whey protein isolate under different pH conditions. Food Chem. (2022) 132492. doi: 10.1016/j.foodchem.2022.132492

83. Sui X, Sun H, Qi B, Zhang M, Li Y, Jiang L. Functional and conformational changes to soy proteins accompanying anthocyanins: focus on covalent and non-covalent interactions. Food Chem. (2018) 245:871–8. doi: 10.1016/j.foodchem.2017.11.090

84. Arruda HS, Silva EK, Peixoto Araujo NM, Pereira GA, Pastore GM, Marostica Junior M. Anthocyanins recovered from agri-food by-products using innovative processes: trends, challenges, and perspectives for their application in food systems. Molecules. (2021) 26:2632. doi: 10.3390/molecules26092632

85. Dominguez-Avila JA, Wall-Medrano A, Velderrain-Rodríguez GR, Chen C-YO, Salazar-López NJ, Robles-Sánchez M, et al. Gastrointestinal interactions, absorption, splanchnic metabolism and pharmacokinetics of orally ingested phenolic compounds. Food Funct. (2017) 8:15–38. doi: 10.1039/C6FO01747E

86. Kamiloglu S, Tomas M, Ozdal T, Capanoglu E. Effect of food matrix on the content and bioavailability of flavonoids. Trends Food Sci Technol. (2021) 117:15–33. doi: 10.1016/j.tifs.2020.10.030

87. Guo Y, Qiao D, Zhao S, Zhang B, Xie F. Starch-based materials encapsulating food ingredients: recent advances in fabrication methods and applications. Carbohydr Polym. (2021) 270:118358. doi: 10.1016/j.carbpol.2021.118358

88. Guldiken B, Gibis M, Boyacioglu D, Capanoglu E, Weiss J. Ascorbic acid-induced degradation of liposome-encapsulated acylated and non-acylated anthocyanins of black carrot extract. J Sci Food Agric. (2021) 101:5707–14. doi: 10.1002/jsfa.11225

89. Wang Y, Ye A, Hou Y, Jin Y, Xu X, Han J, et al. Microcapsule delivery systems of functional ingredients in infant formulae: research progress, technology, and feasible application of liposomes. Trends Food Sci Technol. (2022) 119:36–44. doi: 10.1016/j.tifs.2021.11.016

90. Zhang R, Zhou L, Li J, Oliveira H, Yang N, Jin W, et al. Microencapsulation of anthocyanins extracted from grape skin by emulsification/internal gelation followed by spray/freeze-drying techniques: characterization, stability and bioaccessibility. LWT. (2020) 123:109097. doi: 10.1016/j.lwt.2020.109097

91. Ramos SDP, Giaconia MA, Assis M, Jimenez PC, Mazzo TM, Longo E, et al. Uniaxial and coaxial electrospinning for tailoring jussara pulp nanofibrers. Molecules. (2021) 26:1206. doi: 10.3390/molecules26051206

92. Kanha N, Surawang S, Pitchakarn P, Laoskulitik T. Microencapsulation of copigmented anthocyanins using double emulsion followed by complex coacervation: Preparation, characterization and stability. LWT. (2020) 133:110154. doi: 10.1016/j.lwt.2020.110154

93. Ren Z, Cui Y, Wang Y, Shi L, Yang S, Hao G, Weng W. Effect of ionic strength on the structural properties and emulsion characteristics of myofibrillar proteins from hairtail (Trichiurus haumela). Int Food Res J. (2022) 157:111248. doi: 10.1016/j.foodres.2022.111248

94. Sarkar R, Dutta A, Patra A, Saha S. Bio-inspired biopolymeric coacervation for entrapment and targeted release of anthocyanin. Cellulose. (2021) 28:377–88. doi: 10.1007/s10570-020-03523-w

95. Patel AR. Functional and engineered colloids from edible materials for emerging applications in designing the food of the future. Adv Funct Mater. (2020) 30:1806809. doi: 10.1002/adfm.201806809

96. Dumitracu L, Stănciu N, Borda D, Neagu C, Enachi E, Barbú V, et al. Microencapsulation of bioactive compounds from cornelian cherry fruits using different biopolymers with soy proteins. Food Biosci. (2021) 41:101032. doi: 10.1016/j.fbio.2021.101032

97. Ghosh S, Sarkar T, Das A, Chakraborty R. Natural colorants from plant pigments and their encapsulation: an emerging window for the food industry. LWT. (2022) 153:112527. doi: 10.1016/j.lwt.2021.112527

98. Ren Z, Li Z, Chen Z, Zhang Y, Lin X. Weng W. Li B. Characteristics and application of fish oil-in-water pickering emulsions structured with tea water-insoluble proteins/k-carrageenan complexes. Food Hydrocoll. (2022) 114:106562. doi: 10.1016/j.foodhyd.2020.106562

99. Neuenfeldt NH, Farias CAA, de Oliveira Mello R, Robalo SS, Barin JS, da Silva LP, et al. Effects of blueberry extract co-microencapsulation on the survival of Lactobacillus rhamnosus. LWT. (2022) 155:112886. doi: 10.1016/j.lwt.2021.112886

100. Ghimian R, Nistor M, Foc¸ san M, Pintea A, A¸ stilean S, Rugin a D. Fluorescent food sensors for their application in food systems. Trends Food Sci Technol. (2021) 101:782. doi: 10.3390/nano11030782

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Copyright © 2022 Song, Yu, Chen, Ren, Chen, Fu, Ma and Li. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.