

Could Edible Photonic Structures Be an Alternative to Traditional Food Coloring?

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Color is a fundamental characteristic of food, shaping the perception and influencing the expectations of flavor, freshness, and quality, and has been helpful throughout evolution to distinguish nutritious sources from potentially dangerous ones. Food producers have used these aspects to enhance visual appeal, ensure product consistency, and compensate for color loss during processing, but the use of food colorants has come under increasing scrutiny in recent years due to safety concerns. Therefore, there is a demand for new strategies toward food colorants. In this perspective, the focus is on the potential of structural color in food applications. Distinct advantages over available colorants are introduced, recent advances in edible photonic materials are highlighted, and key challenges and requirements along the entire process chain with the goal of fostering research and innovation in this emerging interdisciplinary field are critically discussed.

perceived flavor, and can impact consumers' emotional and cultural connections.^[4–8] In processed products, synthetic colorants are used to enhance sensory aspects and consumer experience, or to restore the original color of the ingredients. The food industry has suffered several challenges in recent years, with regulators and consumers increasingly demanding natural, environmentally friendly, and safer food colorants.^[9] This demand is driven by consumer interest in healthy and sustainable food products, where the clean label concept has invested considerable effort in research and development to find alternatives to traditional additives and ingredients.^[10,11] One of the main concerns regarding colorants is the associated consequences for human

1. The Role of Color in Food

“You eat with your eyes first” is a well-known saying among chefs that refers to the fact that we only eat foods that look appetizing.^[1,2] Color cues are everywhere around us, and like every other animal, we are strongly affected by them.^[3] In food, color is much more than mere aesthetics or appeal; it is intimately linked to our experience while eating. It has been shown that the food's color stimulates appetite, enhances the

health, where some food colorants have been linked to neurobehavioral effects in children.^[12,13] These concerns have led to increasingly stricter regulations. Notably, legislation differs between countries: several colorants are approved in some countries but banned in other regions,^[14] indicating that their safety and use in food products are not yet universally accepted. As recent examples, the European Union (EU) banned the classical white colorant titanium dioxide (TiO₂) in 2022,^[15] and the United States of America (USA) banned RED No 3 in 2025,^[16]

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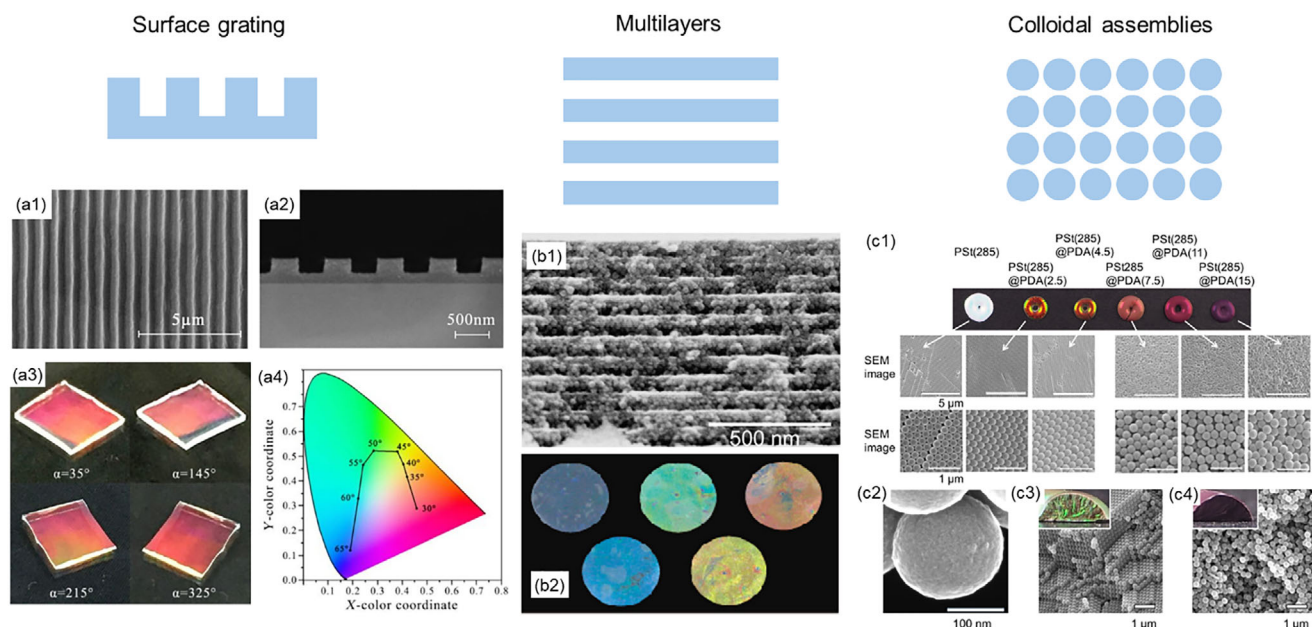


Figure 1. Structural color emerged from nanostructured materials. Surface grating: a1,a2) Scanning electron microscopy images of (a1) Top view, (a2) cross-sectional view of the fabricated photonic crystal film based on polydimethylsiloxane (PDMS) with a grating of 750 nm and a height of 170 nm formed by reverse nanoimprint lithography. a3) Photonic crystal structural color of PDMS grating for horizontal observation angles of 35°, 145°, 215°, and 325° under a vertical observation angle of 45°. a4) Relationship between horizontal observation angle and structural colors of the photonic crystal of PDMS grating by the reflected spectra in the CIE 1931 xy chromaticity diagram.^[23] Multilayers: b1) Field emission electron microscopy image of cross section of multilayer nanoparticles using SiO₂ and TiO₂ after infiltration with PDMS. b2) Photographs of flexible interference filters cut in circles using a 12-layer structure using SiO₂ and TiO₂ after infiltration with PDMS and with different lattice parameters.^[24] Colloidal assemblies: c1) Photographs and scanning electron microscopy images (5 and 1 micron scale bar) of structural color pellets prepared by monodisperse polystyrene (PSt) without and with a shell of polydopamine (PDA) which are designated by PSt(X)@PDA(Y) core-shell particles (X: diameter of PSt core particles, Y: thickness of PDA shell layer in nm). PSt(285)@PDA(Y) core-shell particles. c2) High resolution FE-SEM image of PSt(285)@PDA(15) particles. c3) Cross section view of PSt(285)@PDA(2.5) pellets. The inset shows a photograph of the samples. c4) Cross-section view of PSt(285)@PDA(15) pellets. The inset shows a photograph of the samples.^[25]

while several other colorants raised concern among regulators, such as vegetable carbon (E153) and iron oxides and hydroxides (E172).^[17]

The increasingly strict regulations, as well as the globally differing legislation, raised concerns among producers and consumers and have led to a global increase in the use of natural components as food colorants.^[18] Examples of such natural colorants approved in the European Union are anthocyanins (E163) and lycopene (E160d), producing purple and red colors, respectively. However, these natural dyes can be unstable during processing and storage (pH, temperature, and light) and affect the sensorial properties of the food by undesired reactions with micronutrients.^[19] In addition, it is essential to understand how their production, extraction and purification processes compare to other colorants regarding the life cycle assessment.^[20,21]

2. Traditional Colorants Versus Structural Colors and the Special Case of White

A common characteristic of the colorants mentioned above, whether natural or synthetic, is that the coloration is intrinsically linked to their chemical composition. Conventional pigments and dyes absorb light in a specific spectral region, while all other spectral regions are scattered or reflected and thus perceived as color. An interesting alternative to achieve coloration

is the use of interference of light waves with defined nano- and micro-structured materials. Such structural colors achieve their vivid appearance primarily through the precise arrangement of micro- and nanostructures, which governs light interference and scattering; however, the refractive index of the constituent materials, linked to their composition, also impacts the overall optical response. Such architectures can form photonic crystals, where the micro and nanostructures are periodically ordered in space, resulting in bright and iridescent colors; and photonic glasses, where the structures exhibit short-range order, and an angular independent coloration is achieved. **Figure 1** presents representative examples of nano- and micro-structured materials that have been developed to create structural coloration.

In contrast to periodic and correlated structures, which produce defined colors by interference, to obtain a white appearance, nonabsorptive disordered systems are necessary. Specifically, producing white requires the absence of absorption and an efficient scattering of light throughout the visible spectrum. Inorganic nanoparticles with a high refractive index and low absorption in the visible range satisfy this criterion and are thus used as typical white pigments. TiO₂ has been approved in the USA since 1966 for use in foods to achieve a white color, or to provide opacity, and remains the most widely used food additive for this purpose. Its high refractive index allows efficient scattering at low concentrations and is thus well-suited as an additive to produce white, or,

in combination with pigments, enhanced color saturation. However, European regulators have banned TiO₂ in food products,^[15] which has led to a new search for replacement materials. The challenge of creating white color from edible material is the inherent low refractive index of typical food materials. Yet, recent approaches have highlighted that control of shape and assembly of colloidal particles made from potentially edible materials, such as starch, calcium carbonate, or cellulose, can efficiently enhance their scattering properties and thus produce efficient white.^[26]

In the following sections, we present biological systems that create structural color and discuss existing approaches to creating structurally colored materials from edible components, potential exploitation strategies, and challenges that need to be overcome to translate structural color from laboratories into food products.

3. Food-Grade Structural Color

Structural color is widely found in nature and even exists as a natural means to provide color in certain foods. For example, the Damson fruit exhibits subtle iridescent effects due to its epicuticular wax layer,^[27] while the iridescent sheen on beef muscle tissue results from light interference within organized muscle fibers.^[28] Even the intense blue color of blueberries or plums results from controlled scattering effects from nanostructured epicuticular wax layers.^[29] These examples provide inspiration for edible photonic systems and demonstrate that structural coloration can be integrated into food matrices without compromising edibility, reinforcing the feasibility of translating similar principles into engineered, food-grade photonic materials.

To date, however, the only application of structural coloration in food products is on chocolate surfaces, where imprinting technology enabled the introduction of color impressions via diffraction gratings.^[30] Another simple approach, proposed but not implemented commercially, is to use thin film interference^[31] by creating a thin layer of an edible coating on top of a flat surface with a significantly different refractive index contrast. This method has been shown using alginate, a common polysaccharide widely used in the food industry (E401), obtained from marine brown seaweeds. Cathell and Schauer^[32] showed that spin-coated alginate films fixed by spraying of a CaCl₂ solution on flat Si-wafers as model substrates can produce structurally colored thin-film with hues ranging from magenta (266.5 nm), orange (226.2 nm), yellow (219.9 nm), aqua (122.4 nm), blue (102.8 nm), and purple (95.8 nm). In an industrial context, this strategy could be implemented on highly pigmented substrates that can be uniformly coated with a polymer layer.

More complex hues and optical appearances, as well as angle-independent colors, can be achieved with more complicated nanoarchitectures. In this case, the building blocks of such architectures are ideally approved food additives, such as polysaccharides, proteins, and lipids, which are natural food sources themselves. A potentially simpler alternative could be inorganic oxides, such as silica,^[33] which, in the form of amorphous SiO₂ nanoparticles, are considered edible and are often used as an anticaking agent in powdered food products and as a stabilizer in the production of beer.^[34]

Among polysaccharides, hydroxypropyl cellulose (HPC, E463), which is a common cellulose derivative used as a food additive as a thickener and as an emulsion stabiliser, has been shown

to produce structural colors. HPC is, in fact, capable of forming a cholesteric liquid crystalline phase^[35,36] which produces structural coloration both in water or gel (Figure 2a1–a3)^[37] but also as solid particles (Figure 2b1),^[38] opening possibilities for versatile integration within complex matrices of different food products.

To date, the number of studies using approved food ingredients and additives is limited. However, this might change in the future, as more bio-derived materials have the potential to receive approval for food use, as is the case with cellulose nanocrystals.^[40] When considering biomaterials as building blocks for structurally colored materials more broadly, the available materials spectrum can be significantly widened. In fact, materials such as cellulose, chitin, and lignin are already present in food products, but they have not yet been used or approved in a nanoscale or purified form for human consumption. Under current EU and USA regulations, any intentionally engineered nanomaterial is considered a novel food ingredient, requiring a comprehensive safety assessment that considers potential changes in bioavailability, toxicity, and interactions with biological systems compared to its bulk counterpart. The EU's Novel Food Regulation (EU 2015/2283) explicitly defines engineered nanomaterials and mandates nanospecific risk assessments, while the US FDA typically evaluates such materials under the Generally Recognized as Safe framework, demanding scientific evidence of safety. These requirements reflect the regulatory view that nanoscale forms may exhibit different hazard profiles, even when derived from substances already approved in bulk form. For materials that are considered soft and digestible in the human gut, this should not be an issue as the nanostructure itself will not persist in the body. However, for materials that are not digestible in the human gut, a thorough assessment is necessary.^[41]

In recent years, the field has seen a growing effort in using such bio-derived nanomaterials in the context of structural colors.^[42,43] Nanocellulose is probably the most studied type of colloidal system for the production of both color^[43] and white pigments,^[26] which are now also commercially available. Similarly, lignin, which is present in every fruit and vegetable along with cellulose and hemicellulose, is not digestible and is not used as a food ingredient in its pure form for human consumption. However, similar to the case of cellulose and chitin, it can be exploited to produce well-defined colloidal particles that can then be assembled into structurally colored materials,^[44] displaying different colors depending on the lignin particle size (Figure 2c1–c4).^[39] These recent efforts underscore how bio-derived colloidal particles of controlled size and low polydispersity can be applied to various surfaces to achieve structural color. This is an important step toward controlling edible structural color; in contrast to thin film-based materials, the availability of such particles allows tailoring the photonic properties by controlling the self-assembly process and thus opening avenues to create angle-independent coloration via glassy structural arrangements.

4. Challenges and Future Directions

The previous examples underline the potential of engineering food-grade building blocks into structurally colored materials. This would be advantageous compared to conventional dyes, as many colors and color effects could be produced with the same material. In contrast, dyes or pigments with different colors

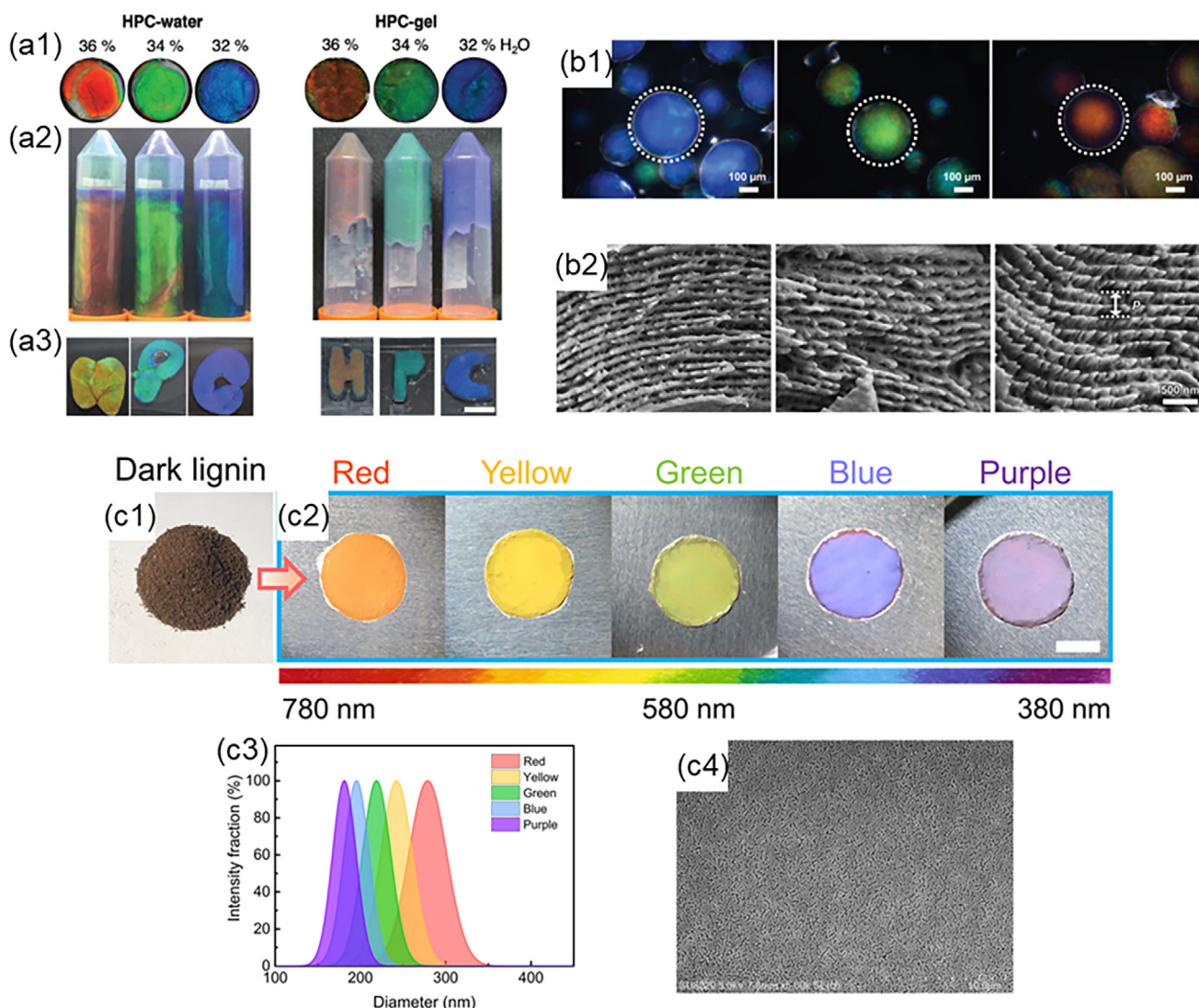


Figure 2. Examples of structural color developed using bio-based materials. a) Hydroxypropyl cellulose (HPC) in water (left) and HPC in gelatin (right), corresponding to 36, 34, and 32 wt% water, respectively. HPC formulations a1) in 6 mm thick rubber O-rings, sealed between glass slides with epoxy glue; a2) in Falcon tubes (50 mL) placed upside down for 48 h; and a3) placed between two glass slides and left at rest for at least 1 min (scale bar: 1 cm).^[37] b1) HPC microparticles produced by emulsification using a 45 wt% HPC solution. b2) Micrographs of individual HPC microparticles recorded in bright-field configuration. The microparticles were removed from the Petri dish prior to imaging. b3) Cross-sectional scanning electron microscopy (SEM) micrographs of blue, green, and red hydroxypropyl cellulose (HPC) microparticles prepared at 68.5, 71.0, and 77.5 °C, respectively. The white arrow indicates the pitch (p) of the helicoidal architecture, which determines the reflected color.^[38] c) Lignin-based structures. c1) Photos of original disordered lignin powder showing dark brownish color; c2) photonic lignin showing bright structural colors among the entire visible light range (from red to purple) (scale bar: 1 cm). c3) Average diameters of red, yellow, green, blue, and purple photonic lignin (being respectively 279, 242, 219, 195, and 181 nm). c4) SEM image of photonic lignin particles (Reprinted with permission from Wang et al. Copyright 2022. American Chemical Society).

require chemical alteration, necessitating new toxicological screenings. Moreover, if fabricated with inert compounds, structural colors remain chemically stable and maintain their color properties over time; in contrast, dyes and pigments require additives to enhance their photostability, risking additional toxicity. Structurally-colored materials also provide additional stability under varying pH, temperature, and light conditions, thereby preventing color fading and off-flavors, which are a challenge for natural colorants. However, for structural color to become a viable alternative to food coloring, many obstacles along the entire

process chain need to be addressed and resolved. In the following, we discuss these various challenges along key intermediate stages in the development.

Selection of the Material Used as Building Blocks: The Codex Alimentarius, which provides a list of approved materials for food use, can be utilized for this purpose. However, each country also has its own list of materials, which can vary from country to country. The list includes polysaccharides, proteins, surfactants, waxes, and inorganic materials, as well as specific information about the type of products and the allowed quanti-

ties of these materials in food. Some of those compounds, such as HPC and alginate, have already been explored for structural color, yet more options need to be developed. The key requirements to screen for suitable materials are their physicochemical characteristics (refractive index, solubility, thermal stability), but also their availability in controlled purity, molecular weight, etc., since they will affect the development of homogeneous building blocks.

Design and Production of Building Blocks from Edible Materials: Technologies already exist to produce micro- and nanostructures using identified food-grade materials. Examples include the production of nanoparticles, fibers, or patterned surfaces, which have mostly been used for compound encapsulation, surface modification, or gelation. However, structurally-colored materials have more stringent requirements and require well-defined and uniform particulate building blocks that remain stable during processing and can be produced at scale. Nanoprecipitation or emulsification technologies^[45,46] may be good candidates since they afford control over mean particle size and polydispersity.

Assembly and Integration of the Building Blocks Within Food Matrices: The complexity of food poses challenges for integrating structurally colored materials. Different approaches will be needed for different types of food, depending on whether a surface, a solid material, a liquid, or a gel-like matrix is targeted. Solid materials may be most easily colored via structural elements, as these may be deposited on the final surface. Gels provide means to integrate pre-formed structurally colored materials, for example in the form of supraparticles,^[47] which then provide the desired color effects. The integration of structural coloration in liquid foods presents unique challenges (unless the case of white, where scattering enhancers can be added).^[26] Structural color in liquids is difficult to achieve without altering the rheological properties of the liquid, as there will always be an addition of colloidal species in suspension.^[48] However, other color effects can be achieved by introducing low-content structural color pigment-like particles into a liquid, which would not significantly change the rheological response, but give a pixelating color effect, rather than a homogeneous coloration. In all cases, the final products need to be evaluated case-by-case, as is normally performed when a new ingredient/additive is used in food products. In addition, processing steps can involve high- or low-temperature shear forces and exposure to a wide range of components, which must not disintegrate the nano/microstructures of a structurally colored ingredient. A potential avenue to address these challenges is to encapsulate structurally colored materials, for example, in the form of supraparticles^[49,50] that fix the arrangement of the building blocks while providing dispersible, micron-scale materials to be added to the food matrix. Additionally, the use of Pickering emulsions and microgels, combined with electrostatic stabilization, can be employed to maintain uniformity and prevent coalescence in both emulsified and nonemulsified systems. Some of these approaches are well-established in food colloid science and can be adapted for structural color applications. To minimize impacts on mouthfeel, photonic structures should remain below 25 μm ^[51] and avoid using photonic structures that rely on components like HPC, where high concentrations are required.

Tackling Dispersities and Irregularities: Given the complex nature of both the starting materials and the matrix itself, photonic colorants derived from edible materials are likely to be less ho-

mogeneous, more distributed in size and shape, and less perfectly assembled. This can impact the saturation of developed structural color. In some cases, this challenge is overcome by the use of absorbing pigments^[47] that, despite being used in very small amounts, should be avoided in food applications. While these provide challenges to target desired colors accurately, they present opportunities for well-developed simulation and modelling tools already in use for structural color in other fields, such as the coatings industry, with the aim of seeing how optimized colors could be yielded from less-defined building blocks or under nonideal assembly conditions. Emerging AI tools used for modeling and prediction can also contribute to addressing this challenge.

Safety, Digestion, and Toxicity: Safety is a major concern to all stakeholders, and in this regard, the use of nanoengineered materials in foods needs to be evaluated under specific regulations. Guidelines for such assessments already exist in Europe and the United States. Solubility and digestibility may serve as a rule of thumb for applicability: If the produced building blocks are soluble or digestible, they may be less of a concern. However, nonsoluble or nondigestible building blocks, even from biological material such as cellulose or lignin, need to be evaluated to ensure safe usage or need to be firmly bound within larger structures to completely prevent their disintegration into nanoscale materials within the body.

Sustainability: Using food ingredients such as proteins and polysaccharides directly as colorants will contribute to more sustainable food systems. However, life cycle assessments must be performed to assess the carbon footprint of using photonic colorants to color foods. Besides the carbon footprint of the materials used, this analysis needs to consider the methodologies used to develop the photonic structures and technologies used for their incorporation into foods.

Scale-Up and Economic Considerations: The large-scale implementation of structural colorants in food products will ultimately depend on cost competitiveness relative to conventional pigments. While current fabrication methods for photonic structures can be resource-intensive, many strategies can leverage existing food processing technologies, such as emulsification, spray-drying, and spray coating, to reduce production costs. Furthermore, the use of abundant, low-cost biopolymers (e.g., cellulose, starch) and scalable self-assembly techniques offers a potential pathway toward economically viable solutions. Future research should prioritize process optimization and life cycle assessments to ensure that structural colorants not only meet safety and performance requirements but also align with the economic realities of the food industry.

Consumer Acceptance: Consumers are looking for similar or better sensory characteristics; therefore, colors need to be vivid and stable to replace existing ones. As for new technologies, most consumers are looking for natural, safer, and sustainable foods.^[52] In this regard, consumer acceptance of photonic colorants may be significantly influenced by the resemblance between naturally occurring photonic structures and their artificially produced counterparts, especially when these are derived from familiar, food-grade ingredients such as polysaccharides and proteins, which can impact perceptions of naturalness by consumers. As some photonic structures are based on particles that can be used to entrap different molecules, future research

could also explore the co-assembly of flavor molecules with photonic structures, enabling multisensory food experiences that combine visual appeal with enhanced taste perception, thereby improving consumer acceptance.

As this discussion shows, significant challenges arise at all key stages of the development of edible photonic materials. Many of these challenges are intertwined, bridge different scientific disciplines, and may, therefore, prevent individual trial-and-error solutions. Instead, with this perspective, we aim to provide an understanding and appreciation of the complexity of the challenges and how they transcend different scientific disciplines as we move along the process chain. Complex challenges translate into rich research opportunities. This emerging scientific field, therefore, needs to attract scientists from different scientific backgrounds to join forces, gain a mutual understanding, and appreciate different perspectives. If this succeeds, the ultimate goal can be a new class of safe, sustainable, and versatile food colorants based on nature's most inspiring color effects.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

dye, food ingredients, nanomaterial, photonic crystal, photonic glass, pigment

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- [1] C. Spence, K. Okajima, A. D. Cheok, O. Petit, C. Michel, *Brain Cogn.* **2016**, *110*, 53. <https://doi.org/10.1016/j.bandc.2015.08.006>.
- [2] J. F. Delwiche, *Physiol. Behav.* **2012**, *107*, 502. <https://doi.org/10.1016/j.physbeh.2012.07.007>.
- [3] I. C. Cuthill, W. L. Allen, K. Arbuckle, B. Caspers, G. Chaplin, M. E. Hauber, G. E. Hill, N. G. Jablonski, C. D. Jiggins, A. Kelber, J. Mappes, J. Marshall, R. Merrill, D. Osorio, R. Prum, N. W. Roberts, A. Roulin, H. M. Rowland, T. N. Sherratt, J. Skelhorn, M. P. Speed, M. Stevens, M. C. Stoddard, D. Stuart-Fox, L. Talas, E. Tibbetts, T. Caro, *Science* **2017**, *357*, aao2221. <https://doi.org/10.1126/science.aao2221>.
- [4] B. Piqueras-Fiszman, C. Spence, *Appetite* **2014**, *75*, 165. <https://doi.org/10.1016/j.appet.2014.01.004>.

- [5] K. Motoki, C. Spence, C. Velasco, *Food Qual. Prefer.* **2023**, *111*, 104996. <https://doi.org/10.1016/j.foodqual.2023.104996>.
- [6] C. Spence, X. Wan, A. Woods, C. Velasco, J. Deng, J. Youssef, O. Derooy, *Flavour* **2015**, *4*, 23. <https://doi.org/10.1186/s13411-015-0033-1>.
- [7] S. Jantathai, M. Sungsi-in, A. Mukprasirt, K. Duerrschmid, *Food Res. Int.* **2014**, *64*, 65. <https://doi.org/10.1016/j.foodres.2014.06.007>.
- [8] L. Zong, S. Wu, S. Duan, *Front. Psychol.* **2022**, *13*, 850086. <https://doi.org/10.3389/fpsyg.2022.850086>.
- [9] CBI. The European market potential for natural food colours **2022**, <https://www.cbi.eu/market-information/natural-food-additives/natural-food-colours/market-potential>, (accessed: July 2025).
- [10] A. C. Fernandes, C. Morais, B. Franchini, B. Pereira, O. Pinho, L. M. Cunha, *Appetite* **2024**, *197*, 107307.
- [11] T. Hüttenhofer, G. Ferro, The European Market Potential for Natural Food Colours **2022**, <https://www.cbi.eu/market-information/natural-food-additives/natural-food-colours/market-potential>, (accessed: July 2025).
- [12] M. Oplawska-Stachowiak, C. T. Elliott, *Crit. Rev. Food Sci. Nutr.* **2017**, *57*, 524.
- [13] M. D. Miller, C. Steinmaus, M. S. Golub, R. Castorina, R. Thilakartne, A. Bradman, M. A. Marty, *Environmental Health* **2022**, *21*, 45. <https://doi.org/10.1186/s12940-022-00849-9>
- [14] S. Lehto, M. Buchweitz, A. Klimm, R. Straßburger, C. Bechtold, F. Ulberth, *Food Addit Contam Part A Chem Anal Control Expo Risk Assess* **2017**, *34*, 335. <https://doi.org/10.1080/19440049.2016.1274431>
- [15] European Commission, Commission Regulation (EU) 2022/63 of 14 January 2022. Amending Annexes II and III to Regulation (EC) No 1333/2008 of the European Parliament and of the Council as Regards the Food Additive Titanium Dioxide (E 171), **2022**, <https://eur-lex.europa.eu/eli/reg/2022/63/oj/eng>.
- [16] FDA to Revoke Authorization for the Use of Red No. 3 in Food and Ingested Drugs **2025**, <https://www.fda.gov/food/hfp-constituent-updates/fda-revoke-authorization-use-red-no-3-food-and-ingested-drugs>, (accessed: July 2025).
- [17] EFSA. Food colours **2025**, <https://www.efsa.europa.eu/en/topics/topic/food-colours>, (accessed: November 2025).
- [18] E. G. de Mejia, Q. Zhang, K. Penta, A. Eroglu, M. A. Lila, *Annu. Rev. Food Sci. Technol.* **2020**, *11*, 145. <https://doi.org/10.1146/annurev-food-032519-051729>.
- [19] Y. Lin, C. Li, L. Shi, L. A. Wang, *Foods* **2023**, *12*, 71368. <https://doi.org/10.3390/foods12071368>.
- [20] M. Thakur, V. K. Modi, *Crit. Rev. Food Sci. Nutr.* **2024**, *64*, 4674. <https://doi.org/10.1080/10408398.2022.2144997>.
- [21] H. Monteiro, B. Moura, *Energy Reports* **2022**, *8*, 277. <https://doi.org/10.1016/j.egy.2022.01.034>.
- [22] K. Vynck, R. Pierrat, R. Carminati, L. S. Froufe-Pérez, F. Scheffold, R. Sapienza, S. Vignolini, J. J. Sáenz, *Rev. Mod. Phys.* **2023**, *95*, 45003. <https://doi.org/10.1103/RevModPhys.95.045003>.
- [23] X. Zheng, Q. Wang, J. Luan, Y. Li, N. Wang, R. Zhang, *Beilstein J. Nanotechnol.* **2019**, *10*, 1211. <https://doi.org/10.3762/bjnano.10.120>.
- [24] M. E. Calvo, H. F. Míguez, *Chem. Mater.* **2010**, *22*, 3909. <https://doi.org/10.1021/cm1001016>.
- [25] A. Kawamura, M. Kohri, G. Morimoto, Y. Nannichi, T. Taniguchi, K. Kishikawa, *Sci. Rep.* **2016**, *6*, 33984. <https://doi.org/10.1038/srep33984>.
- [26] H. Yang, G. Jacucci, L. Schertel, S. Vignolini, *ACS Nano* **2022**, *16*, 7373. <https://doi.org/10.1021/acsnano.1c09198>.
- [27] R. Middleton, M. Sinnott-Armstrong, *APL Photonics* **2024**, *9*, 81102. <https://doi.org/10.1063/5.0208528>.
- [28] C. Ruedt, M. Gibis, J. Weiss, *Compr. Rev. Food Sci. Food Saf.* **2023**, *22*, 3366. <https://doi.org/10.1111/1541-4337.13191>.
- [29] R. Middleton, S. A. Tunstad, A. Knapp, S. Winters, S. McCallum, H. Whitney, *Sci. Adv.* **2025**, *10*, adk4219. <https://doi.org/10.1126/sciadv.adk4219>.

- [30] M. A. Stark, Swiss Scientists Make Chocolate Shimmer in Different Colors **2020**. <https://www.lab-worldwide.com/swiss-scientists-make-chocolate-shimmer-in-different-colors-a-894738/>, (accessed: July 2025)
- [31] S. Kinoshita, S. Yoshioka, J. Miyazaki, *Reports Prog. Phys.* **2008**, 71, 076401. <https://doi.org/10.1088/0034-4885/71/7/076401>.
- [32] M. D. Cathell, C. L. Schauer, *Biomacromolecules* **2007**, 8, 33. <https://doi.org/10.1021/bm060433f>.
- [33] J. Chu, Y. Chen, S.-Y. Tan, Y.-Y. Liu, W. Liu, X. Liu, L. Shi, H. Wang, W. Li, J. Zi, *Adv. Opt. Mater.* **2022**, 10, 2102125. <https://doi.org/10.1002/adom.202102125>.
- [34] S. A. Khan, M. E. Johnson, M. S. Kalan, A. R. Montoro Bustos, S. A. Rabb, I. H. Streng, K. E. Murphy, T. R. Croley, *Food Addit. Contam. Part A* **2024**, 41, 9. <https://doi.org/10.1080/19440049.2023.2297420>.
- [35] S. Fortin, G. Charlet, *Macromolecules* **1989**, 22, 2286. <https://doi.org/10.1021/ma00195a050>.
- [36] M. H. Godinho, J. G. Fonseca, A. C. Ribeiro, L. V. Melo, P. Brogueira, *Macromolecules* **2002**, 35, 5932. <https://doi.org/10.1021/ma0118769>.
- [37] C. H. Barty-King, C. L. C. Chan, R. M. Parker, M. M. Bay, R. Vadrucchi, M. De Volder, S. Vignolini, *Adv. Mater.* **2021**, 33, 102112. <https://doi.org/10.1002/adma.202102112>.
- [38] S. Ming, X. Zhang, C. L. C. Chan, Z. Wang, M. M. Bay, R. M. Parker, S. Vignolini, *Adv. Sustain. Syst.* **2023**, 7, 00469. <https://doi.org/10.1002/adsu.202200469>.
- [39] J. Wang, W. Chen, D. Yang, Z. Fang, W. Liu, T. Xiang, X. Qiu, *ACS Nano* **2022**, 16, 20705. <https://doi.org/10.1021/acsnano.2c07756>.
- [40] O. Vincentini, A.-L. Blier, A. Bogno, M. Brun, S. Cecchetti, F. De Battisti, S. Denis, L. Etienne-Mesmin, F. Ferraris, F. S. Fumagalli, K. Hogeveen, F. Iacoponi, A. Raggi, L. Siciliani, D. Stanco, E. Verleysen, V. Fessard, J. Mast, S. Blanquet-Diot, S. Bremer-Hoffmann, F. Cubadda, *EFSA Support. Publ.* **2023**, 20, 8258E. <https://doi.org/10.2903/sp.efsa.2023.EN-8258>.
- [41] M. Xavier, I. A. Parente, P. M. Rodrigues, M. A. Cerqueira, L. Pastrana, C. Gonçalves, *Trends Food Sci. Technol.* **2021**, 109, 593. <https://doi.org/10.1016/j.tifs.2021.01.050>.
- [42] B. Frka-Petesic, T. G. Parton, C. Honorato-Rios, A. Narkevicius, K. Ballu, Q. Shen, Z. Lu, Y. Ogawa, J. S. Haataja, B. E. Droguet, R. M. Parker, S. Vignolini, *Chem. Rev.* **2023**, 123, 12595. <https://doi.org/10.1021/acs.chemrev.2c00836>.
- [43] B. E. Droguet, H.-L. Liang, B. Frka-Petesic, R. M. Parker, M. F. L. De Volder, J. J. Baumberg, S. Vignolini, *Nat. Mater.* **2022**, 21, 352. <https://doi.org/10.1038/s41563-021-01135-8>.
- [44] J. Li, D. Guan, S. Xia, Y. Fan, K. Zhao, Z. Zhao, A. Zheng, *Energy Convers. Manag.* **2024**, 322, 119123. <https://doi.org/10.1016/j.enconman.2024.119123>.
- [45] J. P. Rao, K. E. Geckeler, *Prog. Polym. Sci.* **2011**, 36, 887. <https://doi.org/10.1016/j.progpolymsci.2011.01.001>.
- [46] M. Kuddushi, C. Kanike, B. B. Xu, X. Zhang, *Soft Matter* **2025**, 21, 2759. <https://doi.org/10.1039/D5SM00006H>.
- [47] E. S. A. Goerlitz, R. N. Klupp Taylor, N. Vogel, *Adv. Mater.* **2018**, 30, 1706654. <https://doi.org/10.1002/adma.201706654>.
- [48] K. Sano, Y. S. Kim, Y. Ishida, Y. Ebina, T. Sasaki, T. Hikima, T. Aida, *Nat. Commun.* **2016**, 7, 12559. <https://doi.org/10.1038/ncomms12559>.
- [49] N. Vogel, S. Utech, G. T. England, T. Shirman, K. R. Phillips, N. Koay, I. B. Burgess, M. Kolle, D. A. Weitz, J. Aizenberg, *Proc. Natl. Acad. Sci* **2015**, 112, 10845. <https://doi.org/10.1073/pnas.1506272112>.
- [50] R. M. Parker, T. H. Zhao, B. Frka-Petesic, S. Vignolini, *Nat. Commun.* **2022**, 13, 3378. <https://doi.org/10.1038/s41467-022-31079-9>.
- [51] L. ENGELEN, A. VAN DER BILT, M. SCHIPPER, F. BOSMAN, *J. Texture Stud.* **2005**, 36, 373. <https://doi.org/10.1111/j.1745-4603.2005.00022.x>.
- [52] M. Siegrist, C. Hartmann, *Nat. Food* **2020**, 1, 343. <https://doi.org/10.1038/s43016-020-0094-x>.