

NON-CONVENTIONAL FOOD PLANTS (PANCS) AS SOURCES OF BIOACTIVE COLORANTS: INTEGRATION WITH NANOTECHNOLOGY, ADVANCED ENCAPSULATION, SMART MATERIALS, AND CIRCULAR ECONOMY IN FOOD TECHNOLOGY

PLANTAS ALIMENTÍCIAS NÃO CONVENCIONAIS (PANCS) COMO FONTES DE CORANTES BIOATIVOS: INTEGRAÇÃO COM NANOTECNOLOGIA, ENCAPSULAÇÃO AVANÇADA, MATERIAIS INTELIGENTES E ECONOMIA CIRCULAR EM TECNOLOGIA DE ALIMENTOS

PLANTAS ALIMENTICIAS NO CONVENCIONALES (PANCS) COMO FUENTES DE COLORANTES BIOACTIVOS: INTEGRACIÓN CON NANOTECNOLOGÍA, ENCAPSULACIÓN AVANZADA, MATERIALES INTELIGENTES Y ECONOMÍA CIRCULAR EN TECNOLOGÍA DE ALIMENTOS

 <https://doi.org/10.56238/sevened2025.036-167>

Leonardo Angelo¹, Ana Paula Peron², Regiane da Silva Gonzalez³

ABSTRACT

Non-Conventional Food Plants (PANC's) have great potential for use as natural bioactive pigments for the food industry in response to the growing demand for clean label ingredients. Although rich in anthocyanins, betalains and carotenoids, which provide attractive coloration and relevant functional properties, such as antioxidant and anti-inflammatory activity, the inherent instability of these natural colorants under variations of pH, light and temperature, limits their application on an industrial scale. The present study proposes and discusses the integration of cutting-edge technologies to overcome this limitation. Nanotechnology and advanced encapsulation are presented as crucial tools to increase stability, protect and control the release of bioactive compounds. Additionally, the application of these natural pigments in smart materials allows the development of active films and packaging, capable of acting as freshness and quality indicators, reinforcing food safety. The approach is complemented by the perspective of the circular economy that aims at the integral use of PANC's biomass, reducing waste and promoting sustainability. It is concluded that there is synergy between PANC's and these technological innovations that represent a promising and sustainable path for the effective replacement of synthetic colorants in food technology promoting health, functionality and environmental responsibility.

Keywords: Nanotechnology. Bioactive Colorants. Encapsulation. Circular Economy.

RESUMO

As Plantas Alimentícias Não Convencionais (PANC's) possuem grande potencial de uso como pigmentos naturais bioativos para a indústria de alimentos em resposta à crescente

¹ Master's student. Universidade Tecnológica Federal do Paraná (UTFPR).

E-mail: nutri.leonardo.angelo@gmail.com Lattes: <https://lattes.cnpq.br/0463559963998367>

² Dr. in Genetics and Breeding. Universidade Tecnológica Federal do Paraná (UTFPR).

E-mail: anaperon@utfpr.edu.br Lattes: <http://lattes.cnpq.br/3605560420792065>

³ Dr. in Sciences. Universidade Tecnológica Federal do Paraná (UTFPR). E-mail: regiane@utfpr.edu.br Lattes: <https://lattes.cnpq.br/7581675568754949>

demanda por ingredientes clean label. Embora ricas em antocianinas, betalaínas e carotenoides, que conferem coloração atrativa e propriedades funcionais relevantes, como atividade antioxidante e anti-inflamatória, a instabilidade inerente desses corantes naturais frente a variações de pH, luz e temperatura, limita sua aplicação em escala industrial. O presente estudo propõe e discute a integração de tecnologias de ponta para superar essa limitação. A nanotecnologia e a encapsulação avançada são apresentadas como ferramentas cruciais para aumentar a estabilidade, proteger e controlar a liberação dos compostos bioativos. Adicionalmente, a aplicação desses pigmentos naturais em materiais inteligentes permite o desenvolvimento de filmes e embalagens ativas, capazes de atuar como indicadores de frescor e qualidade, reforçando a segurança alimentar. A abordagem é complementada pela perspectiva da economia circular que visa o aprimoramento integral da biomassa das PANC's, reduzindo resíduos e promovendo sustentabilidade. Conclui-se que existe sinergia entre as PANC's e essas inovações tecnológicas que representam um caminho promissor e sustentável para a substituição efetiva de corantes sintéticos na tecnologia de alimentos promovendo saúde, funcionalidade e responsabilidade ambiental.

Palavras-chave: Nanotecnologia. Corantes Bioativos. Encapsulação. Economia Circular.

RESUMEN

Las Plantas Alimenticias No Convencionales (PANC's) poseen gran potencial de uso como pigmentos naturales bioactivos para la industria de alimentos en respuesta a la creciente demanda por ingredientes clean label. Aunque ricas en antocianinas, betalaínas y carotenoides, que confieren coloración atractiva y propiedades funcionales relevantes, como actividad antioxidante y antiinflamatoria, la inestabilidad inherente de estos colorantes naturales frente a variaciones de pH, luz y temperatura, limita su aplicación a escala industrial. El presente estudio propone y discute la integración de tecnologías de punta para superar esta limitación. La nanotecnología y la encapsulación avanzada son presentadas como herramientas cruciales para aumentar la estabilidad, proteger y controlar la liberación de los compuestos bioactivos. Adicionalmente, la aplicación de estos pigmentos naturales en materiales inteligentes permite el desarrollo de películas y envases activos, capaces de actuar como indicadores de frescura y calidad, reforzando la seguridad alimentaria. El enfoque es complementado por la perspectiva de la economía circular que busca el aprovechamiento integral de la biomasa de las PANC's, reduciendo residuos y promoviendo sostenibilidad. Se concluye que existe sinergia entre las PANC's y estas innovaciones tecnológicas que representan un camino prometedor y sostenible para la sustitución efectiva de colorantes sintéticos en la tecnología de alimentos promoviendo salud, funcionalidad y responsabilidad ambiental.

Palabras clave: Nanotecnología. Colorantes Bioactivos. Encapsulación. Economía Circular.

1 INTRODUCTION

In this chapter, the use of Non-Conventional Food Plants (PANCs) as a strategic alternative to synthetic dyes in the food industry will be addressed. PANCs are plant species with high nutritional and gastronomic value, but still underused and little consumed on a large scale. Due to their diversity of bioactive natural pigments, such as anthocyanins, betalains, carotenoids, and chlorophylls, these plants have great potential for food diversification, the promotion of nutritional security, and the enhancement of local biodiversity. In addition to promoting attractive natural coloring, these compounds have relevant functional properties, including antioxidant, anti-inflammatory and health-protective potential, meeting the growing consumer demand for *safe and naturally derived* clean label ingredients.

Despite its high potential, the industrial application of colorants derived from PANCs faces technological challenges related to chemical and physical instability in the face of variations in pH, light, oxygen and temperature. In this context, integration with nanotechnology and advanced encapsulation techniques has proven to be fundamental to enable its replacement of synthetic dyes. Nano and micro-encapsulated systems, as well as natural biopolymeric matrices (gelatin, chitosan, alginate and vegetable proteins), promote stability, protection of bioactive compounds, controlled release and increased bioavailability, expanding the possibilities of application in functional foods and innovative ingredients.

Additionally, the development of smart materials based on natural dyes from PANCs allows the creation of films, coatings and active packaging capable of responding to environmental changes, such as pH variations and oxidative processes, acting as indicators of food freshness and quality. These solutions reinforce food safety and add technological value to products.

From the perspective of the circular economy, the full use of PANCs and their by-products as sources of bioactive dyes contributes to the reduction of waste, the valorization of local biodiversity and the strengthening of sustainable production chains. Thus, the convergence between PANCs, nanotechnology, advanced encapsulation, smart materials, and circular economy configures an innovative and sustainable approach to the replacement of synthetic dyes in food technology, promoting health, functionality, and environmental responsibility.



1.1 SYNTHETIC DYES

Color is a fundamental and indispensable sensory attribute, as it exerts a direct influence on the perception of quality, freshness and acceptance of a product by the consumer. Historically, mankind has used natural pigments from plants, insects, and minerals for the coloring of food, textiles, and cosmetics. These pigments played an essential role in past centuries, especially in a context where there were no artificial methods for the production of dyes. However, they had important technological limitations, such as low fixation in untreated fibers and reduced stability, which resulted in color fading when exposed to light or washed (PEREIRA; ROZENTALSKI, 2022).

With the development of the first synthetic dye in 1856, natural dyes were progressively replaced. This transition occurred mainly due to the advantages associated with synthetic dyes, such as lower production costs due to economies of scale, the possibility of industrial installation close to consumer centers, greater homogeneity in the composition and the guarantee of quality standardization. In the food sector, the use of dyes has become a widespread practice on a global scale, playing a fundamental role in standardizing the visual aspect and increasing the aesthetic appeal of products to the final consumer (ROSSI, 2008).

Among the available options, synthetic dyes stand out for offering significant technological advantages, including high physicochemical stability, uniformity of shade between different batches, versatility of application and relatively low cost (DEY; NAGABABU, 2022). However, although most of these additives are classified as safe by regulatory agencies, recent scientific studies have pointed to potential negative impacts on human health, such as medium and long-term toxicity, hypersensitivity reactions, and possible carcinogenic activity observed in *in vitro* systems and experimental animal models (AMBROZIEWICZ *et al.*, 2024).

Figure 1

Dyes and their applications



Source: Figure generated by the author using ChatGPT (OpenAI, 2025).

Against this backdrop, as public concern grows regarding the risks associated with synthetic dyes, there is a significant increase in interest in natural pigments. These compounds are perceived as safer alternatives, in addition to being in line with contemporary demands for food products with a more natural and sustainable profile (SIMON *et al.*, 2017). As a result, the food, cosmetics, paper and textile industries have intensified the use of natural dyes, which are already present in a wide variety of products, especially foods such as beverages, sauces, soups, mayonnaise, ice cream, seasonings and pasta.

The use of natural dyes has gained prominence for combining safety with potential bioactive properties, such as antioxidant, anti-inflammatory, neuroprotective, and cardioprotective activities. As a result, the natural pigments market has dominated the industry, driven by environmental concerns and the growing demand for "clean labels" and ingredients of natural origin (FORTUNE BUSINESS INSIGHTS, 2025).

Recent studies indicate that natural pigments present in unconventional food plants (PANCs) can play a dual role as coloring agents and nutraceutical ingredients (SILVA *et al.*, 2023). These natural pigments, in addition to providing attractive color, have relevant functional properties, contributing to the promotion of consumer health (DEL RIO *et al.*, 2013; CLIFFORD, 2017). Despite the high potential of natural dyes from PANCs, their industrial application is limited by low stability against light, oxygen, pH and temperature variations, in

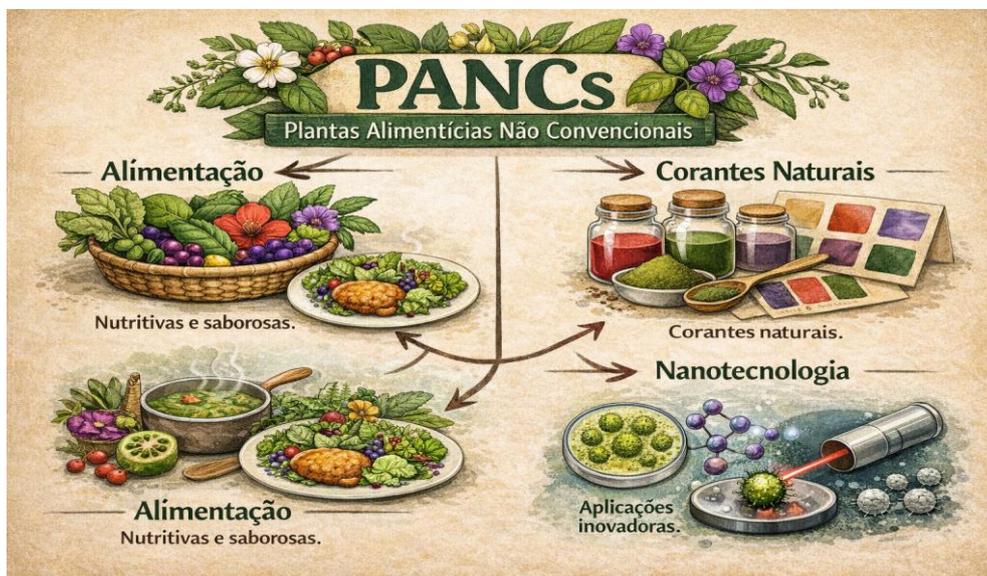
addition to the possible interaction with components of the food matrix (CAVALCANTI *et al.*, 2019). In this context, nanotechnology and advanced encapsulation techniques have been widely investigated as effective strategies to protect these bioactive compounds and enable their replacement of synthetic dyes (MCCLEMENTS, 2020; ALBUQUERQUE *et al.*, 2022).

2 PANCS, THEIR PROPERTIES AND USES

Non-Conventional Food Plants comprise plant species that remain underutilized in modern agri-food systems despite their wide biodiversity and high food and technological potential. These plants have extreme nutritional and functional relevance, being recognized in recent years as promising sources of bioactive compounds with technological and functional applications in food (ARAÚJO; CARVALHO; VILAS BOAS, 2023; TAVARES *et al.*, 2022).

Figure 2

Representative scheme of the use of PANCs



Source: Figure generated by the author using ChatGPT (OpenAI, 2025).

PANCS have a high nutritional density, including dietary fiber, essential minerals, vitamins, and secondary metabolites (TAVARES *et al.*, 2022). Among the secondary metabolites, flavonoids, anthocyanins, carotenoids, betalains, and total phenolic compounds stand out (ARAÚJO; CARVALHO; VILAS BOAS, 2023). These compounds are associated with antioxidant, anti-inflammatory activity, and metabolic modulation. (PUBMED, 2022). Recent studies indicate that regular consumption of foods rich in phenolic compounds can

contribute to reducing the risk of chronic non-communicable diseases (OLIVEIRA *et al.*, 2021).

The growing scientific interest in PANCs is associated with the need for food diversification, sustainability and innovation in food systems, food safety, and diversification of natural ingredients (ARAÚJO; CARVALHO; VILAS BOAS, 2023; FAO, 2021). In addition, the industry's interest in *clean label* ingredients drives the replacement of synthetic dyes with natural pigments extracted from edible plants (SANTOS *et al.*, 2024). International Science and Engineering events have highlighted the convergence between plant biotechnology, nanotechnology, and food science as a strategic axis of innovation (SANTOS *et al.*, 2024).

Considering that the bioactivity of these compounds is strongly influenced by the food matrix and processing conditions (CAVALCANTI *et al.*, 2021), the technological use of PANCs allows the integration between nutritional function, bioactivity, and sensory properties (NASCIMENTO *et al.*, 2024).

2.1 NATURAL PIGMENTS PRESENT IN PANCs

The natural pigments found in PANCs belong mainly to the classes of anthocyanins, carotenoids, betalains, and chlorophylls (PUBMED, 2022). Anthocyanins are water-soluble flavonoids responsible for red, purple, and blue colorations (CAVALCANTI *et al.*, 2021). Carotenoids are fat-soluble pigments associated with yellow, orange, and red colorations, in addition to having provitamin A activity (DLAMINI *et al.*, 2024). Betalains, present in some edible ornamental PANCs, have high stability at moderate pH (RODRÍGUEZ-MENA *et al.*, 2023). In addition to the coloring function, the aforementioned pigments have proven antioxidant bioactivity (PUBMED, 2022). These natural pigments are preferred by the food industry due to the increasing rejection of artificial colors by consumers (SANTOS *et al.*, 2024). Table 1 describes three examples of Technological Applications of PANCs.

Table 1

Bioactive compounds and technological use

PANC	Main compounds	Color	Application
<i>Clitoria ternatea</i>	Ternatins	Blue	Beverages, Jellies
<i>Tropaeolum majus</i>	Anthocyanins, carotenoids	Yellow/Red	Baking

Bougainvillea glabra Betalains

Pink

Functional drinks

Source: adapted from Nascimento *et al.* (2024).

Figure 3

Clitoria ternatea L.: The *Clitoria ternatea*, popularly known as butterfly pea, butterfly bean, and blue fairy, has flowers rich in acylated anthocyanins known as ternatins (NASCIMENTO *et al.*, 2024).



Source: Pixaby.

The use of encapsulation techniques as an alternative for stabilizing natural pigments has been promising due to its ability to improve stability against light, oxygen, and pH variations (OLIVEIRA *et al.*, 2025). In addition, natural materials such as polysaccharides (e.g. maltodextrin, pectin, and gum arabic) have been widely used as encapsulating agents (OLIVEIRA *et al.*, 2025). These strategies allow the industrial application of natural pigments obtained from PANCs (PUBMED, 2023).

Figure 4

Tropaeolum majus: Nasturtium has flowers and leaves rich in anthocyanins and carotenoids, with high bioactive potential (ARAÚJO; CARVALHO; VILAS BOAS, 2023). These compounds confer colorations ranging from yellow to intense red (NASCIMENTO *et al.*, 2024).



Source: Pixaby.

Studies indicate its application as a functional ingredient in baked goods and fermented beverages. (DLAMINI *et al.*, 2024). It was observed that nano emulsions containing extracts of this PANC showed greater color stability in bakery products (DLAMINI *et al.*, 2024).

Figure 5

Bougainvillea glabra: Species such as Bougainvillea glabra have a high concentration of betalains (RODRÍGUEZ-MENA *et al.*, 2023).



Source: Pixaby.

This PANC, popularly known as Primavera or Três-marias, has colored bracts (modified pink, white, yellow or purple leaves) edible, used as a natural coloring and in cooking, especially in drinks.

Anthocyanins confer an intense blue color and have high thermal stability when compared to other plant sources (SANTOS *et al.*, 2024). These pigments have high stability when nanoencapsulated in polymeric matrices (OLIVEIRA *et al.*, 2025). Nanoparticles containing *C. ternatea* extract have shown promising application in functional beverages and food gels, desserts, and dairy products. (SILVA *et al.*, 2023). In addition to coloration, ternatins have significant antioxidant activity. (PUBMED, 2022).

3 TECHNOLOGICAL TRENDS IN THE APPLICATION OF PANCS COLORANTS

Among the technological trends applied to the extraction of dyes (natural pigments), green extraction has been prioritized through safe solvents and methods with low environmental impact (MASYITA *et al.*, 2025). Other techniques such as ultrasound- and microwave-assisted extraction are important as they increase the extraction yield of bioactive compounds (SANTOS *et al.*, 2024).

Natural dyes can be easily extracted from plants using simplified extraction protocols. Fresh flowers of *Clitoria ternatea*, for example, when subjected to drying at 40 °C and

subsequent maceration in acidified hydroethanolic solution (50%) (SANTOS *et al.*, 2024) generate an extract rich in dyes. This extract, after filtration, when concentrated under reduced pressure (MASYITA *et al.*, 2025) results in a material of high colorimetric intensity and antioxidant activity (PUBMED, 2022).

However, despite the ease of extraction, the instability of natural pigments still limits the application of natural dyes in processed foods (PUBMED, 2023). Thus, stability and safety tests are required for regulatory approval (ANVISA, 2023). Despite this, consumer demand favors the expansion of these natural ingredients (SANTOS *et al.*, 2024).

Normative Instruction No. 211/2023 defines in detail the authorized food additives, including synthetic and natural dyes, as well as their conditions of use, ensuring the protection of consumer health (ANVISA, 2023). **Resolution RDC No. 778/2023** provides for the general principles for the use of food additives and technology adjuvants, aligning national legislation with the guidelines of the *Codex Alimentarius* (ANVISA, 2023).

3.1 INTEGRATION OF PANCS WITH NANOTECHNOLOGY IN FOOD

As previously highlighted, natural pigments extracted from PANCs have high instability when applied directly to food matrices (PUBMED, 2023). In this sense, nanotechnology applied to food science – by allowing the manipulation of ingredients on a nanometric scale – is capable of improving the functionality and stability of these dyes (OLIVEIRA *et al.*, 2025). Nanosystems, composed of inert or medium-resistant materials are viable alternatives to protect the bioactive compounds sensitive to light, oxygen, and pH variations contained within them (MASYITA *et al.*, 2025). Thus, nanoencapsulation emerges as an efficient strategy to preserve the active properties of these compounds such as antioxidant activity, as well as the color intensity of these pigments (OLIVEIRA *et al.*, 2025).

Regarding application, nanoencapsulated PANC pigments can be incorporated into different products, such as incorporation into functional isotonic drinks (JANNOCK, 2025). A great advantage in the use of this process is the fact that the products showed increased color stability during cold storage, as observed by Jannock (2025). In addition, it was observed that the bioaccessibility of phenolic compounds in a nanostructured system was significantly higher when compared to the free form (PUBMED, 2022).

Through the application of nanoencapsulated PANCs extract in enriched mixed juices, it was also observed that their use results in higher antioxidant content and color stability (JANNOCK, 2025). The use of PANC dyes, for example, in dairy products demonstrated good

sensory acceptance, with the resulting color derived from the presence of anthocyanins (SILVA *et al.*, 2023).

3.2 ADVANCED PIGMENT ENCAPSULATION OF PANCS

Advanced encapsulation involves the incorporation of bioactive compounds into micro or nanostructured polymeric systems (OLIVEIRA *et al.*, 2025). Natural polymers such as pectin, chitosan, alginate, proteins, and polysaccharides are widely used as encapsulating materials (SANTOS *et al.*, 2024). Polymeric nanoparticles allow for greater surface area and better control of pigment release (MASYITA *et al.*, 2025). Studies indicate that the encapsulation of anthocyanins significantly improves their thermal and oxidative stability (PUBMED, 2022).

3.3 SMART MATERIALS AND COLORFUL FUNCTIONAL FOODS

Smart materials are systems capable of responding to environmental stimuli such as pH, temperature, and humidity (SILVA *et al.*, 2023). Anthocyanins from PANCs have pH-dependent chromatic behavior (CAVALCANTI *et al.*, 2021). This property allows its application in smart packaging and freshness indicators (SANTOS *et al.*, 2024). Biodegradable films embedded with PANCS pigments can act simultaneously as active packaging and visual sensor (MASYITA *et al.*, 2025). Thus, the incorporation of bioactive dyes from PANCS in smart materials represents an innovative approach in food technology, allowing the development of films, coatings and active packaging with functions beyond coloring (YAM; TAKHISTOV; MILTZ, 2005; PRIYADARSHI; RHIM, 2020).

Natural pigments sensitive to pH variations and oxidative processes, such as anthocyanins and betalains, have been explored as visual indicators of freshness, spoilage, and microbiological quality of foods (KERRY; BUTLER, 2008; CHEN *et al.*, 2024). These applications contribute to increasing food safety, reducing waste and adding technological value to products, reinforcing the functional role of natural dyes in the context of smart food systems (REALINI; MARCOS, 2014; LI *et al.*, 2022).

3.4 RELEVANCE TO ENGINEERING AND APPLIED SCIENCE

The integration between PANCS, nanotechnology, and smart materials represents an emerging interdisciplinary field. (SANTOS *et al.*, 2024). This approach involves knowledge of materials engineering, chemical engineering, biotechnology, and food science (MASYITA

et al., 2025). The application of these systems in functional foods meets the global challenges of health, sustainability, and technological innovation (FAO, 2021).

4 GREEN NANOTECHNOLOGY AND CIRCULAR ECONOMY APPLIED TO PANCS

Green nanotechnology applied to PANCs is based on the use of renewable materials, low toxicity processes and reduced energy consumption (ANASTAS; WARNER, 2020). The circular economy applied to PANCs prioritizes the full use of plant biomass and the valorization of waste rich in bioactive compounds (GEISSDOERFER *et al.*, 2020). This technological convergence favors the development of sustainable functional foods in line with global demands for innovation (FAO, 2021).

Green nanotechnology applied to PANCs is based on the development of nanosystems using renewable raw materials, low toxicity processes and reduced energy consumption (SANTOS *et al.*, 2024). This concept is aligned with the principles of green chemistry and sustainable engineering, widely discussed at international Science and Engineering events (ANASTAS; WARNER, 2020). In the context of PANCs, green nanotechnology prioritizes the full use of plant biomass, including leaves, flowers, bark, and agro-industrial residues (FAO, 2021). The circular economy applied to PANCs proposes the reuse of plant by-products as sources of bioactive compounds and natural pigments (GEISSDOERFER *et al.*, 2020). Residues from the processing of PANCs have a high concentration of phenolic compounds and pigments with technological potential (ARAÚJO; CARVALHO; VILAS BOAS, 2023). Thus, the recovery of this waste reduces the environmental impact and adds economic value to the production chain (SANTOS *et al.*, 2024).

Green nanoencapsulation of pigments extracted from PANCs can be performed using natural biopolymers such as chitosan, alginate, starch, pectin, and plant proteins (OLIVEIRA *et al.*, 2025). These materials have biodegradability, biocompatibility, and low toxicity (SILVA *et al.*, 2023). The use of plant-based biopolymers strengthens the connection between nanotechnology and circular economy (MASYITA *et al.*, 2025).

Sustainable extraction methods, such as ultrasound-assisted extraction, microwaves, and pressurized fluids, are widely investigated for obtaining pigments from PANCs (SANTOS *et al.*, 2024). These technologies reduce the use of organic solvents and processing time (MASYITA *et al.*, 2025). The integration of these techniques with nanoformulations allows the production of functional ingredients with high added value (OLIVEIRA *et al.*, 2025).

Nanoparticles obtained from PANC waste have been studied as intelligent carriers of bioactive compounds (SILVA *et al.*, 2023). These nanosystems enable controlled release, increased bioaccessibility, and protection against oxidative degradation (PUBMED, 2022). The functionalization of these nanoparticles can generate responses to environmental stimuli, characterizing them as smart materials (SANTOS *et al.*, 2024).

Natural pigments from nanoencapsulated PANCs can act as visual sensors in active and smart packaging (CAVALCANTI *et al.*, 2021). Anthocyanins show color changes dependent on pH and the presence of volatile metabolites (SILVA *et al.*, 2023) and for this reason this property is explored in the development of indicators of food freshness and spoilage (SANTOS *et al.*, 2024).

From a materials engineering perspective, the incorporation of PANCs pigments into biodegradable films represents a strategic application of the circular economy (MASYITA *et al.*, 2025). These films can be produced from biopolymers obtained from plant waste (GEISSDOERFER *et al.*, 2020). The combination of biopolymers and natural pigments results in multifunctional systems with mechanical, antioxidant, and sensory properties (OLIVEIRA *et al.*, 2025).

The adoption of green nanotechnology applied to PANCs contributes to the reduction of dependence on synthetic additives (FAO, 2021). This approach meets regulatory requirements and the demand for *clean label products* (SANTOS *et al.*, 2024). In addition, it promotes innovation in line with the Sustainable Development Goals (UN, 2022).

In international Science and Engineering events, the convergence between green nanotechnology, circular economy, and functional foods is considered an emerging technological frontier (SANTOS *et al.*, 2024). In this context, PANCs are positioned as strategic raw materials for the development of sustainable and intelligent food solutions (TAVARES *et al.*, 2022).

5 FINAL CONSIDERATIONS

PANCs are strategic sources of bioactive natural pigments for functional foods (TAVARES *et al.*, 2022). Advances in extraction and stabilization are essential to expand its industrial application (OLIVEIRA *et al.*, 2025). In addition, nanotechnology and advanced encapsulation increase the technological feasibility of these compounds (OLIVEIRA *et al.*, 2025).



The integration between color, functionality, and sustainability positions these ingredients as an emerging trend in food technology (NASCIMENTO *et al.*, 2024). Smart materials based on PANCs pigments represent a promising frontier for innovation in food and packaging (SANTOS *et al.*, 2024). These advances position PANCs as key elements in research presented at international Science and Engineering events (SANTOS *et al.*, 2024).

ACKNOWLEDGEMENTS

CAPES, PROEX-PG, AUXPE 1152/2024, UTFPR

REFERENCES

- Agência Nacional de Vigilância Sanitária. (2023a). Resolução da Diretoria Colegiada - RDC nº 778, de 1º de março de 2023. Dispõe sobre os princípios gerais para o uso de aditivos alimentares e coadjuvantes de tecnologia em alimentos. Diário Oficial da União. <https://www.in.gov.br/web/dou/-/resolucao-rdc-n-778-de-1-de-marco-de-2023-468499613>
- Agência Nacional de Vigilância Sanitária. (2023b). Instrução Normativa nº 211, de 1º de março de 2023. Dispõe sobre as funções tecnológicas, os limites máximos e as condições de uso dos aditivos alimentares e dos coadjuvantes de tecnologia autorizados para uso em alimentos. Diário Oficial da União. <https://www.in.gov.br/en/web/dou/-/instrucao-normativa-in-n-211-de-1-de-marco-de-2023-468509746>
- Albuquerque, P. M., Azevedo, S. G., de Andrade, C. P., D'Ambros, N. C. d. S., Pérez, M. T. M., & Manzato, L. (2022). Biotechnological applications of nanoencapsulated essential oils: A review. *Polymers*, 14(24), Article 5495.
- Ambroziewicz, Z. M., Siemiątkowski, R., Łata, M., Dowgiert, S., Sikorska, M., & Kamiński, M. (2024). Long-term health effects of artificially colored foods in adults and children: A review of scientific literature on attention deficits, carcinogenicity, and allergy risks. *Journal of Education, Health and Sport*. <https://apcz.umk.pl/JEHS/article/view/56522>
- Anastas, P. T., & Warner, J. C. (2020). *Green chemistry: Theory and practice* (2nd ed.). Oxford University Press.
- Araújo, P. R., Carvalho, E. E. N., & Vilas Boas, E. V. B. (2023). Plantas alimentícias não convencionais: Composição bioativa e aplicações. *Scientia Naturalis*.
- Cavalcanti, R. N., et al. (2021). Anthocyanins: Stability and food applications. *Food Research International*.
- Chen, D., Lv, J., Wang, A., Yong, H., & Liu, J. (2024). Intelligent food packaging: Quaternary ammonium chitosan/gelatin blended films enriched with blueberry anthocyanin-derived cyanidin for shrimp and milk freshness monitoring. *Foods*, 13(14), Article 2237. <https://doi.org/10.3390/foods13142237>



- Clifford, M. N. (2017). Anthocyanins – Nature, occurrence and dietary burden. *Journal of the Science of Food and Agriculture*, 80, 1063–1072.
- Del Rio, D., et al. (2013). Dietary polyphenolics in human health: Structures, bioavailability, and evidence of protective effects. *Antioxidants & Redox Signaling*, 18, 1818–1892.
- Dey, S., & Nagababu, B. H. (2022). Applications of food color and bio-preservatives in the food and its effect on the human health. *Food Chemistry Advances*, 1, Article 100019. <https://doi.org/10.1016/j.focha.2022.100019>
- Dlamini, B. C., et al. (2024). Recent developments in the application of natural pigments as pH-sensitive food freshness indicators in biopolymer-based smart packaging: Challenges and opportunities. *International Journal of Food Science & Technology*, 59(4), 2148–2161.
- Food and Agriculture Organization of the United Nations. (2021). *The state of food and agriculture*. FAO.
- Fortune Business Insights. (2025). Organic pigments market size, share & industry analysis, by source, by type, by application, and regional forecast 2025-2032. <https://www.fortunebusinessinsights.com/pt/organic-pigments-market-112729>
- Geissdoerfer, M., Savaget, P., Böhm, S., & Tetzlaff, B. (2020). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757–768. <https://doi.org/10.1016/j.jclepro.2016.12.048>
- Geissdoerfer, M., et al. (2020). The circular economy – A new sustainability paradigm. *Journal of Cleaner Production*.
- Jannock, N. (2025). Anthocyanins through time: A bibliometric analysis of research (1975–2024). *Journal of Food Science and Technology*. <https://doi.org/10.1080/87559129.2025.2528099>
- Kerry, J., & Butler, P. (Eds.). (2008). *Smart packaging technologies for fast moving consumer goods*. John Wiley & Sons.
- Li, Y., Yu, Y., Wang, K., Zhou, C., Li, X., & Wang, F. (2022). Preparation and characterization of pH-sensitive indicator films based on natural pigments and biopolymers for intelligent food packaging. *Food Hydrocolloids*, 133, Article 107885.
- Masyita, A., et al. (2025). Natural pigments: Innovative extraction technologies and their potential application in health and food industries. *Frontiers in Pharmacology*, 15, Article 1507108. <https://doi.org/10.3389/fphar.2024.1507108>
- McClements, D. J. (2020). Advances in nanoparticle and microparticle delivery systems for increasing the dispersibility, stability, and bioactivity of phytochemicals. *Biotechnology Advances*, 38, Article 107287.
- Nascimento, E. S., et al. (2024). PANCs com potencial bioativo na elaboração de bebidas. *Revista Semiárido de Visu*.
- Natural pigments of plant origin: Classification, extraction and application in foods. (2022). *Food Chemistry*, 388, Article 133908. <https://doi.org/10.1016/j.foodchem.2022.133908>
- Oliveira, L. S. de, et al. (2025). Edible polysaccharides as stabilizers and carriers for the delivery of phenolic compounds and pigments in food formulations. *Biomolecules*.



- Oliveira, L. S., et al. (2025). Encapsulation of natural pigments for food systems. *Food Hydrocolloids*.
- Oliveira, M. E. P., Silva, W. M. B., Alves, D. R., et al. (2021). Dyes and pigments used in foods: An integrative literature review. *Research, Society and Development*, 10(10), Article e316101018925. <https://rsdjournal.org/rsd/article/view/18925>
- Organização das Nações Unidas. (2022). *Transforming our world: The 2030 Agenda for Sustainable Development*. United Nations.
- Pereira, A. de S., & Rozentalski, E. F. (2022). A produção de corantes sintéticos no século XIX e suas implicações sociais. Universidade Federal de Itajubá.
- Priyadarshi, R., & Rhim, J.-W. (2020). Chitosan-based biodegradable functional films for food packaging applications. *Innovative Food Science & Emerging Technologies*, 62, Article 102346.
- PubMed. (2022–2024). Natural food colorants and functional properties.
- Realini, C. E., & Marcos, B. (2014). Intelligent packaging systems and indicators for monitoring food quality and safety. In *Smart packaging technologies for food applications*. Elsevier.
- Rodríguez-Mena, A., et al. (2023). Natural pigments of plant origin: Classification, extraction and application in foods. *Food Chemistry*, 398, Article 133908. <https://doi.org/10.1016/j.foodchem.2022.133908>
- Rossi, T. (2008, July 15). Corantes naturais: Fontes, aplicações e potencial para uso da madeira. Instituto de Pesquisas e Estudos Florestais. https://www.ipef.br/publicacoes/acervohistorico/informacoestecnicas/corantes_naturais_fontes_aplicacoes_e_potencial_para_uso_da_madeira.aspx
- Santos, J. S., et al. (2024). Smart materials and natural pigments in functional foods. *Trends in Food Science & Technology*.
- Silva, R. M., et al. (2023). Nanoencapsulation of bioactive compounds for food applications. *Journal of Food Engineering*.
- Simon, J. E., Decker, E. A., Ferruzzi, M. G., Giusti, M. M., Mejia, C. D., Goldschmidt, M. R., & Talcott, S. T. (2017). Establishing standards on colors from natural sources. *Journal of Food Science*, 82(11), 2533–2773. <https://doi.org/10.1111/1750-3841.13927>
- Tavares, A. V. N. M., et al. (2022). Plantas alimentícias não convencionais na dieta humana. *Saúde-UNG-Ser*.
- Yam, K. L., Takhistov, P. T., & Miltz, J. (2005). Intelligent packaging: Concepts and applications. *Journal of Food Science*, 70(1), R1–R10. <https://doi.org/10.1111/j.1365-2621.2005.tb09052.x>