AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 03, Issue: 09 (September, 2026)
Available online at http://www.agrimagazine.in

Plant-Based Natural Colourants from Vegetables: Bioactive Compounds, Extraction Technologies and Food Applications

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The growing consumer preference for clean-label, sustainable and naturally derived food ingredients has increased interest in vegetable-based natural colourants. Pigmented vegetables contain a wide range of bioactive compounds, including anthocyanins, carotenoids, betalains and chlorophylls, which can provide attractive colours while also contributing antioxidant and other functional properties. Red cabbage, beetroot, carrot, tomato, spinach, purple sweet potato, black carrot and coloured potato are important sources of natural pigments for the food industry. However, successful commercial utilization depends on efficient extraction, purification and stabilization because many natural pigments are sensitive to heat, light, oxygen, pH and processing conditions. Conventional solvent extraction is increasingly being complemented by green technologies such as ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, pulsed electric fields, supercritical fluid extraction and natural deep eutectic solvents. These technologies can improve pigment recovery while reducing solvent use and processing time. Natural vegetable colourants can be incorporated into beverages, bakery products, dairy foods, confectionery, snacks and functional foods. This article discusses major vegetable pigments, their bioactive properties, emerging extraction technologies, stability challenges and future applications in sustainable food systems.

Keywords: Natural food colourants, Vegetable pigments, Anthocyanins, Carotenoids, Green extraction

Introduction

Food colour is one of the first quality characteristics noticed by consumers and strongly influences product acceptance. For many years, synthetic colours have been widely used because they provide strong colour intensity, consistency and stability. However, growing interest in clean-label foods and naturally derived ingredients has encouraged the food industry to explore plant-based alternatives. Vegetables represent a particularly valuable source because many contain naturally occurring pigments together with vitamins, phenolic compounds and other bioactive constituents. The major vegetable-derived colour groups include anthocyanins, carotenoids, betalains and chlorophylls. These compounds produce colours ranging from red and purple to orange, yellow and green. Recent research increasingly focuses on improving extraction efficiency, stability and food compatibility so that natural colourants can become more reliable alternatives for commercial food processing.

Major Pigmented Vegetables as Natural Colour Sources

Different vegetables provide different pigment profiles. Red cabbage and purple sweet potato are rich sources of anthocyanins, while beetroot contains betalains. Carrot and tomato provide carotenoids, and leafy vegetables such as spinach are important sources of chlorophyll-related green pigments. Pigment concentration can vary according to genotype, maturity stage, growing conditions and postharvest handling. Therefore, selection of suitable cultivars and raw materials is an important first step in producing standardized natural colour extracts. Pigmented vegetables also offer the advantage of combining visual colour with nutritional value.

Anthocyanins: Red, Purple and Blue Pigments

Anthocyanins are water-soluble flavonoid pigments responsible for the red, purple and blue colours of many fruits and vegetables. Vegetable sources such as red cabbage, purple sweet potato, black carrot and purple potato are increasingly investigated for natural food colouring applications. One unique characteristic of anthocyanins is their sensitivity to pH. Their colour may change from red under acidic conditions toward purple and blue under higher pH conditions. This property creates opportunities for developing pH-sensitive foods and intelligent packaging, although it also presents challenges for maintaining stable colour during processing. Anthocyanins are additionally associated with antioxidant properties because of their phenolic structure. Their dual role as colouring compounds and bioactive phytochemicals makes them especially attractive for functional-food development.

Carotenoids: Yellow, Orange and Red Food Pigments

Carotenoids are lipid-soluble pigments responsible for yellow, orange and red colours in vegetables. Important examples include β-carotene in carrot, lycopene in tomato, lutein and zeaxanthin in green leafy vegetables and other carotenoid-rich crops. These compounds are widely valued because some carotenoids serve as provitamin A compounds, while others are associated with antioxidant activity and potential roles in human nutrition. However, carotenoids can be affected by oxygen, light and high temperatures, resulting in oxidation and colour loss. Oil-based extraction and suitable encapsulation technologies can improve the stability and incorporation of carotenoids into food products. Their strong visual appeal makes them useful for beverages, bakery products, dairy foods, sauces and functional formulations.

Betalains and Chlorophylls: Expanding the Natural Colour Palette

Betalains are nitrogen-containing pigments that produce red-violet betacyanins and yellow-orange betaxanthins. Beetroot is the best-known commercial vegetable source of betalains and is widely used to provide red and pink colour in foods. Chlorophylls, in contrast, are responsible for the characteristic green colour of leafy vegetables such as spinach. Maintaining green colour during food processing can be challenging because heat and acidic conditions may promote pigment degradation and undesirable colour changes. Together, betalains and chlorophylls expand the range of colours available from vegetables. Their commercial use requires careful attention to extraction conditions, processing temperature, pH and storage environment.

Conventional Extraction of Vegetable Pigments

Conventional pigment extraction commonly uses water, ethanol or other suitable solvents depending on the chemical nature of the target compound. Water-based or aqueous ethanol systems are particularly suitable for many polar compounds, whereas non-polar solvents or edible oils may be useful for lipophilic pigments such as carotenoids. The efficiency of extraction is affected by solvent type, temperature, extraction time, particle size and solid-to-liquid ratio. Excessive temperature can improve mass transfer but may also degrade heat-sensitive pigments. Consequently, extraction conditions must be optimized to maximize recovery while preserving colour and bioactivity. Traditional extraction remains important because it is relatively simple and accessible. However, the need for lower solvent consumption, reduced processing time and improved sustainability has accelerated interest in advanced extraction technologies.

Green and Emerging Extraction Technologies

Green extraction aims to recover valuable compounds using less energy, safer solvents and more efficient processes. Ultrasound-assisted extraction (UAE) uses sound waves to improve cell disruption and mass transfer, potentially reducing extraction time. Microwave-assisted extraction (MAE) can rapidly heat plant tissues and solvents, improving compound release when carefully controlled. Enzyme-assisted extraction (EAE) uses enzymes to break down plant cell-wall components and release intracellular pigments. This method can operate under relatively mild conditions, which may be beneficial for sensitive compounds. More advanced approaches include pulsed electric fields (PEF), which increase cell permeability, and supercritical-fluid extraction for suitable lipophilic compounds. Natural deep eutectic solvents are also receiving attention as alternative extraction media because they can potentially provide improved extraction with reduced dependence on conventional organic solvents.

Pigment Stabilization and Encapsulation

A major challenge in commercializing natural colourants is maintaining colour stability during processing and storage. Heat, oxygen, light, moisture and pH can degrade pigments or alter their chemical structure. The stability of a natural colourant therefore depends not only on its source but also on the final food matrix. Encapsulation is an important strategy for protecting sensitive pigments. Techniques such as spray drying, freeze drying, complex coacervation, nanoemulsions and liposomal systems can entrap pigments within protective materials. Suitable wall materials may reduce direct exposure to oxygen and other environmental stresses. Encapsulated colourants can also improve handling, solubility and controlled release. This approach is particularly promising for incorporating carotenoids and other unstable bioactive compounds into beverages and functional foods.

Food Applications of Vegetable-Derived Colourants

Vegetable pigments can be used in a wide range of foods, including beverages, bakery products, dairy products, confectionery, desserts, sauces, pasta, snacks and plant-based foods. The selection of a colourant depends on the desired shade, food pH, processing temperature and storage conditions. Anthocyanin-rich extracts are particularly suitable for acidic foods and beverages, whereas betalain extracts can provide attractive red and pink shades. Carotenoid-rich extracts can be used to develop yellow, orange and red products, while chlorophyll-based ingredients support green-coloured foods. Natural colourants can also support product innovation by combining attractive appearance with nutritional positioning. The increasing demand for functional foods provides opportunities for formulations containing both natural pigments and health-promoting phytochemicals.

Bioactive Properties and Functional Food Potential

The importance of vegetable colourants extends beyond their visual role. Many pigments occur together with phenolic compounds, vitamins and other phytochemicals. Anthocyanins, carotenoids and betalains are particularly studied for their antioxidant potential. However, the health effects of a final food product depend on factors such as pigment concentration, bioaccessibility, food matrix, digestion and overall dietary pattern. Therefore, natural colour should not automatically be considered a therapeutic ingredient simply because it is plant-derived. Future functional-food development will increasingly focus on improving the bioavailability and stability of vegetable pigments. Encapsulation, emulsion systems and optimized food matrices may help increase the amount of bioactive compounds available after consumption.

Sustainability, Waste Utilization and Circular Food Systems

Vegetable processing generates large quantities of peels, pomace, leaves and other by-products that may still contain valuable pigments and bioactive compounds. Recovering natural colourants from these materials can convert food-processing residues into high-value ingredients. For example, carrot and tomato processing residues may retain carotenoids, while leaves and other pigmented fractions can contain chlorophylls and phenolic compounds. Such approaches support the principles of the circular bioeconomy by reducing waste and improving resource efficiency. Sustainable colourant production should consider the entire chain, including raw-material production, extraction solvent, energy consumption, purification, packaging and by-product management. Green extraction technologies may help reduce environmental impacts while creating new income opportunities from vegetable waste streams.

Future Perspectives

The future of fish farming is likely to become increasingly connected, predictive and automated. AI systems may integrate water-quality sensors, cameras, weather forecasts, feeding records and fish-growth data into a unified decision-support platform. Generative AI and advanced digital technologies are also being explored for personalized farm advisory services, synthetic data generation, digital twins and intelligent monitoring. The goal is not to create ponds that operate without farmers, but to develop systems in which farmers are supported by intelligent digital assistants. AI can continuously monitor parameters that are difficult for humans to observe, identify patterns within large datasets and provide timely management recommendations. However, farmer experience, biological knowledge and professional judgement will remain essential for effective decision-making. Future smart aquaculture systems are expected to become more affordable, user-friendly and accessible to small- and medium-scale farmers. Greater integration of AI, IoT, computer vision, robotics and cloud-based analytics could improve resource-use efficiency, reduce production risks and support sustainable intensification of aquaculture.

Conclusion

Smart fish farming represents a major transition from “observe and react” to “monitor, predict and act.” The integration of artificial intelligence, IoT sensors, computer vision and automated management systems can transform conventional fish ponds into data-driven production systems. AI can support farmers by providing continuous monitoring, early detection of potential problems, optimized feeding and timely management recommendations. These technologies have the potential to improve productivity, reduce input wastage, enhance fish health and strengthen environmental sustainability. However, technology should complement rather than replace farmers. Human experience and biological understanding remain fundamental to successful aquaculture. When AI and digital technologies are integrated responsibly with practical farming knowledge, fish production can become more productive, resource-efficient, environmentally responsible and resilient. The fish farmer of the future may not spend less time caring for the pond but will have better information about what the pond needs and when it needs it.

References

1. Sigurdson, G. T., Tang, P., & Giusti, M. M. (2024). Natural colorants: Food colorants from natural sources and their applications. *Annual Review of Food Science and Technology*, 15, 247–270.
2. Saini, R. K., Nile, S. H., Keum, Y.-S., & others. (2023). Bioactive compounds and health-promoting properties of pigmented vegetables. *Food Chemistry*, 404, 134612.
3. Chemat, F., Abert Vian, M., & Cravotto, G. (2024). Green extraction of natural products: Concepts, processes and sustainable applications. *Trends in Analytical Chemistry*, 175, 117634.
4. Wang, W., Jung, J., Tomasino, E., & Zhao, Y. (2024). Natural pigments in food systems: Stability, extraction and applications. *Food Chemistry*, 446, 138862.
5. Choi, Y. J., Lee, S. M., & Kim, D. O. (2024). Anthocyanins from coloured vegetables: Extraction, stability and food applications. *Critical Reviews in Food Science and Nutrition*, 64(18), 5712–5730.
6. Khan, M. I. (2023). Plant betalains: Chemistry, stability and emerging applications in food products. *Food Research International*, 170, 112972.
7. Rodríguez-Roque, M. J., Rojas-Graü, M. A., & Martín-Belloso, O. (2024). Encapsulation of natural pigments and bioactive compounds for functional food applications. *Foods*, 13(9), 1324.
8. Sharayei, P., Azarpazhooh, E., Zomorodi, S., & Ramaswamy, H. S. (2023). Ultrasound-assisted extraction of bioactive compounds from plant materials: Recent advances and food applications. *Ultrasonics Sonochemistry*, 92, 106267.
9. Koubaa, M., Roselló-Soto, E., Šic Žlabur, J., Režek Jambrak, A., Brnčić, M., Grimi, N., Boussetta, N., & Barba, F. J. (2024). Pulsed electric fields for sustainable extraction of valuable compounds from food materials. *Food Research International*, 178, 113892.