Ningthoujam Samarendra Singh,
Akath Singh, Bharati Khilladi and
Dheerendra Rastogi

Micro-encapsulation of fruit extracts for food applications: An innovative approach

Fruit extracts are rich in bioactive compounds such as polyphenols, carotenoids, flavonoids, and vitamins, which offer significant health benefits. However, their direct incorporation into food systems is limited by low stability, poor solubility, and susceptibility to degradation during processing and storage. Microencapsulation and bigel technologies have emerged as effective strategies to overcome these challenges by enhancing compound stability, bioavailability, and controlled release. Microencapsulation and bigel systems using fruit extracts, particularly mangiferin from mango and anthocyanins from *jamun*, have been standardized at ICAR-CISH Lucknow. Extraction, stabilization protocols, and wall material interactions were optimized to preserve color, phytochemical content, and sensory properties. These innovations enable the development of value-added, fruit-based functional foods with improved stability, enhanced health benefits, and greater consumer appeal, contributing to healthier and market-ready food products.

Keywords: Anthocyanins, Bioactive compounds, Functional foods, Mangiferin, Microencapsulation

FRUITS are widely recognized as a rich source of bioactive compounds such as polyphenols, flavonoids, carotenoids, vitamins, and organic acids that contribute to human health by providing antioxidant, anti-inflammatory, antimicrobial, and anticancer benefits. Incorporating these compounds into functional foods has gained significant interest from both the food industry and consumers, particularly as the demand for natural, health-promoting ingredients continues to rise. However, the direct use of fruit extracts in food formulations remains challenging due to their inherent instability. Many of these bioactives are highly sensitive to environmental factors such as light, heat, oxygen, pH fluctuations, and enzymatic activity, which can result in rapid degradation, loss of functionality, and undesirable changes in colour, taste, or aroma. Additionally, low solubility and poor bioavailability often limit the effective utilization of fruit-derived compounds in functional food systems. Among numerous fruits, mango (*Mangifera indica*) and *jamun* (*Syzygium cumini*) stand out for their traditional, nutritional, and functional significance.

Despite their remarkable therapeutic potential, extracts from these fruits are difficult to stabilize in food systems without protective technologies. To address these challenges, microencapsulation has emerged as an effective delivery strategy. This approach entraps sensitive bioactive compounds within a protective matrix, improving their stability, masking undesirable flavors, enhancing solubility, and enabling controlled or sustained release during processing, storage, and digestion. Advances in encapsulating materials such as proteins, polysaccharides, lipids, bigels, and novel biopolymers have further broadened opportunities for developing targeted and sustainable delivery systems. Notably, bigel-based carriers have shown considerable promise in stabilizing anthocyanins, offering improved protection against degradation and facilitating their controlled release, thereby highlighting the versatility of bigel matrices for encapsulating diverse phytochemicals.

To address the above issue, ICAR-CISH Lucknow evaluated the extractable bioactive compounds in fruits, particularly mango and jamun, and standardized protocols for extraction, stabilization, and techniques of encapsulation, including the development of a bigel system for anthocyanins, commonly used wall materials, and their functional applications in various value-added products. The impact on food quality, stability, and bioavailability is also discussed alongside technological challenges and limitations.

Extraction and microencapsulation of mangiferin

Mango is a rich source of mangiferin, lupeol, β-carotene, quercetin, and several phenolic acids that work synergistically to exert antioxidant, anti-inflammatory, hepatoprotective, neuroprotective, and anti-diabetic effects. Among these, mangiferin is recognized globally as a multifunctional natural molecule capable of modulating oxidative stress pathways, enhancing glucose uptake, regulating lipid metabolism, and supporting immune responses. Mangiferin is a naturally occurring C-glucosyl xanthone that is widely recognized as one of the signature bioactive compounds of the mango tree. It is abundantly present in the leaves, bark, flowers, and kernels, with comparatively lower but still functionally important levels in the peel and occasionally the pulp. Its chemical structure features a xanthone backbone attached to a glucose unit via a stable C-glycosidic bond–a configuration that is considerably more resistant to enzymatic degradation, acidic hydrolysis, and thermal breakdown than the more common O-glycosidic linkage found in many plant metabolites. This structural robustness enhances its bioavailability and persistence, contributing to its broad biological functionality. It acts as a potent antioxidant, efficiently quenching reactive oxygen species and protecting cellular components from oxidative damage. Its anti-inflammatory properties have been linked to the downregulation of pro-inflammatory mediators and stabilization of cellular membranes. Furthermore, mangiferin demonstrates antidiabetic activity by modulating glucose metabolism, enhancing insulin sensitivity, and inhibiting α-glucosidase enzymes. Studies also report antimicrobial and antiviral effects, with activity against a range of pathogens, along with strong hepatoprotective and neuroprotective actions that support liver function and guard neuronal cells from degeneration. Increasing evidence also highlights its anticancer potential, attributed to its ability to influence cell-cycle regulation, inhibit tumor proliferation, and modulate apoptotic pathways. The compound's role in human health, combined with its relevance as a metabolic marker, has made it central to research in nutraceutical development, pharmacology, metabolomics, and functional food innovation.

Extraction of mangiferin from mango leaves

Mangiferin is widely distributed throughout the mango plant, with considerable variability among different tissues. The highest concentrations are found in leaves, followed by bark and stem tissues. Among fruit, the peel and seed kernel contain appreciable levels and are increasingly recognized as valuable by-products for recovery, whereas the pulp typically exhibits very low mangiferin content. Within the leaves, substantial variation occurs according to developmental stage. Young and semi-mature leaves usually accumulate higher amounts due to active metabolic processes and higher phenolic biosynthesis, although levels vary with cultivar, environmental conditions, and season.

Extraction of mangiferin from mango leaves was carried out using solvent-based techniques, with aqueous ethanol (around 70%) preferred for food and nutraceutical applications due to efficiency and safety. General extraction involves drying and grinding the leaves, followed by maceration, reflux, extraction, filtration, and concentration. To enhance purity, activated charcoal was subsequently added to the extract to adsorb pigments and additional interfering substances. The mixture was filtered again to remove charcoal and residual particulates, and the filtrate was rinsed with methanol to maximize recovery of soluble metabolites. The purified extract was then dried to obtain concentrated mangiferin. The dried material was carefully triturated using a mortar and pestle to produce a fine, homogeneous powder suitable for storage, quantitative estimation, and downstream analytical procedures.

Mangiferin concentration in young and mature leaves across major Indian mango cultivars

Cultivar	Young (ppm)	Old (ppm)
Dasahri	115.78	104.26
Chausa	129.63	99.30
Alphonso	168.36	55.59
Langra	131.09	99.33
Vanraj	101.51	63.79

Development of mangiferin micro encapsulation system

The mangiferin dispersion was prepared using a solvent dispersion method. Briefly, 5 mg of MG was dissolved in 120 mL of dimethyl sulfoxide (DMSO). Subsequently, 1 g of ethyl cellulose and 1 g of hydroxypropyl methylcellulose were added to the solution, which was then heated on a magnetic hot plate with stirring until the polymers were completely dissolved. Separately, a glycerin solution (50 mL) was prepared by mixing 30 mL of glycerol with 20 mL of distilled water. The mangiferin-polymer solution was added dropwise to the glycerin solution under constant stirring using a syringe. The resulting dispersion was finally filtered and dried in a hot air oven.

Microencapsulated mangiferin from mango leaves

Anthocyanin extraction for food application

Jamun is a rich source of bioactive compounds. Its most prominent feature is its high concentration of anthocyanins–notably delphinidin, petunidin, malvidin, peonidin, and cyanidin glycosides. These water-soluble pigments are responsible for the fruit's vibrant colour and are recognized for their potent antioxidant capacity. The anthocyanins confer strong anti-hyperglycemic, cardioprotective, anti-obesity, anti-inflammatory, and antioxidant activities, making them a subject of significant interest in nutraceutical and therapeutic research.

Extraction protocol for anthocyanins from *jamun*

Anthocyanins were extracted from the pulp of *jamun* fruit using five solvent systems to evaluate the influence of solvent composition on pigment recovery. In Treatment 1, which employed a mixed system of ethanol and methanol, the extracted anthocyanin concentration reached 8.36 mg/g. Meanwhile, Treatment 2, consisting solely of methanol, yielded the highest recovery, producing 10.19 mg/g of anthocyanins, indicating superior extraction efficiency of pure methanol for *jamun* pigments. Moreover, Treatment 3, combining ethanol with DMSO, resulted in a comparatively lower yield of 6.90 mg/g. In Treatment 4, where DMSO, ethanol, and methanol were used together, the anthocyanin content increased to 8.60 mg/g, suggesting a synergistic effect of mixed polar solvents. Lastly, Treatment 5, containing methanol and DMSO, produced 8.23 mg/g of anthocyanins.

Extraction of anthocyanin using different solvent systems

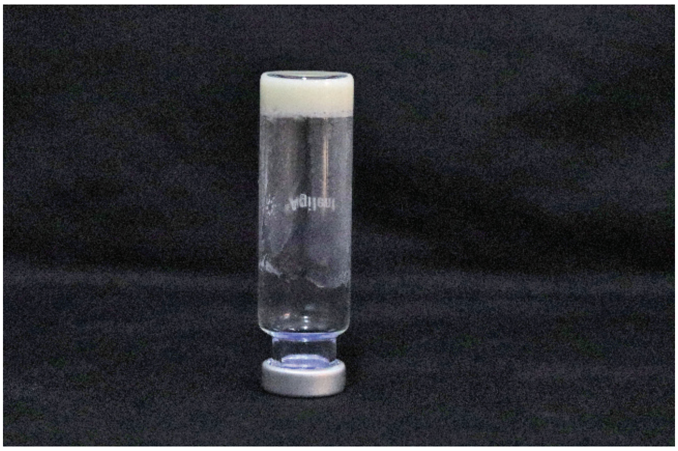
Phytochemical properties of anthocyanin

Anthocyanins are a class of water-soluble flavonoid pigments responsible for the red, purple, and blue hues in many fruits, vegetables, and flowers. Their phytochemical profile is defined by a diverse set of structural, functional, and stability-related attributes that influence their biological activity and extractability. These compounds are glycosylated derivatives of anthocyanidins, typically linked to sugars such as glucose, galactose, rhamnose, or arabinose. This glycosylation enhances their solubility in polar solvents and stabilizes the flavylium cation–the core structure that imparts vibrant coloration under acidic conditions. Structural variations arise through differences in hydroxylation, methoxylation, and acylation patterns, which together determine their color expression, antioxidant potential, and resistance to degradation. Anthocyanins exhibit strong antioxidant activity due to their ability to donate hydrogen atoms and delocalize electrons across their conjugated aromatic rings. Their redox behavior also supports metal-chelating properties, contributing to protective effects against oxidative stress.

Additionally, anthocyanins display notable sensitivity to pH, temperature, light exposure, and enzymatic oxidation. Under acidic conditions, they exist predominantly as stable red flavylium ions, whereas neutral or alkaline environments shift them toward colorless or bluish forms through structural transformations. Acylation with organic or phenolic acids further enhances their stability against heat, light, and pH fluctuations, making acylated anthocyanins particularly desirable for food and nutraceutical applications. Their strong affinity for forming copigmentation complexes with other phenolics and organic molecules also contributes to improved color intensity and shelf stability.

Development of anthocyanin-loaded bigels

Bigels were fabricated by first preparing separate hydrogel and oleogel phases. The primary hydrogel was formulated by dissolving compound 1 and maltose in 10 mL of deionized water under gentle heating, followed by the incorporation of 100 µL of plant-based oil and 100 µL of anthocyanin extract. Concurrently, the oleogel was synthesized by melting 400 mg of natural product into 7 mL of plant-based oil at 70–75 °C, with 1 mL of Tween 80 then added as an emulsifier under high-shear mixing. The final bigel was produced by homogenizing a mixture of 1.5 mL of the primary hydrogel with 0.5 mL of the oleogel and an additional 0.5 mL of Tween 80 to form a uniform, stable matrix.



Bigel developed as carrier for anthocyanin

CONCLUSIONS

Microencapsulation has emerged as a powerful strategy to preserve, stabilize, and deliver fruit-derived bioactives, which are otherwise highly sensitive to thermal, oxidative, and storage-induced degradation. By entrapping these compounds within protective wall materials, encapsulation not only safeguards their functional integrity but also extends shelf life, improves sensory attributes, and enhances consumer acceptance of fruit-based functional foods. Furthermore, encapsulation enables controlled release and improved bioavailability, ensuring that bioactives can exert their intended health-promoting effects more effectively in the human body. It offers opportunities to develop innovative, stable, and consumer-friendly functional foods that contribute to both human health and sustainable resource utilization.

For further information, please write to:
ICAR-Central Institute for Subtropical Horticulture, Lucknow, Uttar Pradesh; Corresponding email: tairenki@gmail.com