

Citrus-Based Functional Foods and Beverages

Recent innovations in citrus-based functional beverages, fortified confectionery, fibre-enriched snacks, and peel-derived nutraceutical ingredients demonstrate how horticultural science can directly contribute to preventive healthcare. Not-from-concentrate citrus drinks enhance hydration and antioxidant intake, while vitamin C-fortified gummies and jelly bites provide child-friendly immune nutrition. Pomace-based cubes and cookies improve fibre intake and metabolic moderation, and peel-derived pectin and essential oils extend applications into functional food formulation and natural preservation. These products demonstrate how citrus bio-resources can address nutritional gaps while promoting sustainability, circular bioeconomy principles, and reduction of post-harvest losses. Citrus value-addition thus represents a powerful convergence of horticulture, nutrition science, preventive healthcare, and green enterprise development.

Keywords: Bioactives; Bioeconomy; Citrus; Functional foods and beverages; Health benefits; Human nutrition

Nutrition today extends beyond the provision of calories; it encompasses immune resilience, metabolic stability, gut health, and long-term disease prevention. In this context, citrus fruits occupy a strategic position because of their dense concentration of essential nutrients and bioactive compounds. India, being world's third largest producer of citrus fruits such as mandarin, sweet orange, acid lime, lemon, pomelo, and many underutilized citrus species grown across diverse agro-climatic zones possesses enormous potential not only for fresh consumption but also for functional food development.

Citrus fruits are uniquely positioned at the interface of horticulture and health. Their characteristic composition of vitamin C, flavonoids, limonoids, carotenoids, dietary fibre, organic acids, pectin, and essential oils offer multiple physiological benefits. With increasing consumer awareness regarding immunity, oxidative stress, and lifestyle disorders, citrus-based functional foods and beverages provide a practical and culturally acceptable route to integrate preventive nutrition into daily diets. Recent developments demonstrate how scientific value-addition can convert perishable citrus fruits and their by-products into nutritionally enriched, shelf-stable, and health-oriented products.

Citrus as a functional food matrix

The health potential of citrus lies in its complex phytochemical architecture. The health benefits of important phytochemicals are outlined below.

Citrus Flavonoids: Flavonoids are a major class of polyphenolic compounds in citrus, responsible for flavour attributes and a wide range of bioactivities. Flavonoid

profiles vary by cultivar, maturity stage, agro-climatic conditions, and post-harvest handling. The primary flavonoids in citrus are flavanones, which exist mainly as glycosides (bound to a sugar molecule). Hesperidin and narirutin are the most abundant flavanones in oranges and mandarins, including Indian varieties like mandarins (Nagpur, Khasi and Kinnow) and sweet oranges. Hesperidin is particularly concentrated in the albedo and peel. Naringin, a flavanone, is responsible for the characteristic bitter taste. It is a key bioactive in Indian pomelo varieties. Eriocitrin, predominantly found in lemons and limes, is a key flavonoid in Indian acid lime and lemon. Polymethoxyflavones (PMFs) are unique class of flavonoids, including nobiletin and tangeretin, is almost exclusively found in citrus. They are highly concentrated in the peel of mandarins and sweet oranges. PMFs are highly bioavailable and possess potent anti-inflammatory properties. Besides, many other flavonoids like hesperetin (aglycone of hesperidin), naringenin (aglycone of naringin), diosmin and rutin, etc. are also found in different types of citrus fruits.

The health benefits of citrus flavonoids are supported by evidence from different levels of scientific research. Flavonoids are powerful antioxidants and contribute to redox homeostasis through scavenging reactive oxygen species and upregulate body's endogenous antioxidant and enzymes (SOD, catalase, glutathione peroxidase), thereby protecting cells from oxidative damage. They also exhibit significant anti-inflammatory effects by modulating transcription factors such as NF- κ B and reducing the production of pro-inflammatory cytokines (e.g., TNF- α , IL-6). In the context of cardiometabolic health, these

mechanisms translate into tangible benefits. Human observational studies have shown that regular consumption of orange juice can help reduce systolic and diastolic blood pressure and improve endothelial function. Clinical trials have demonstrated that flavonoid-enriched supplements or juices can improve lipid profiles (lowering LDL-cholesterol). Citrus flavonoids also known for reducing inflammation markers, and enhance glycaemic control in individuals with obesity or prediabetes. Flavonoids modulate carbohydrate metabolism by influencing glucose transporters, improving insulin sensitivity and reducing postprandial glucose spikes.

Beyond their well-recognized free radical scavenging, anti-inflammatory, anti-hyperglycaemic and cardiometabolic effects, citrus flavonoids exhibit several distinct and clinically relevant bioactivities. Hesperidin, hesperetin and eriocitrin, for instance, have demonstrated promising neuroprotective potential by attenuating oxidative stress in neural tissues and modulating redox-sensitive pathways implicated in neurodegeneration. Diosmin is widely employed in the management of chronic venous insufficiency, varicose veins, and hemorrhoids; it enhances lymphatic drainage, improves capillary resistance, and confers protective effects on the vascular endothelium. Naringenin, narirutin and eriocitrin have shown hepatoprotective properties, particularly through regulation of lipid metabolism and mitigation of hepatic steatosis. Rutin, likewise, contributes to vascular health by strengthening capillaries and reducing vascular fragility.

Vitamin C: Citrus fruits are well-known for their rich vitamin C content. Vitamin C acts as a potent water-soluble antioxidant, cofactor in collagen synthesis and immune-supportive micronutrient. Importantly, synergistic interactions between vitamin C and flavonoids may enhance overall antioxidant capacity.

Limonoids: Limonoids such as limonin and nomilin are highly oxygenated triterpenoids found in seeds and peel. Limonoids showed promising anti-inflammatory activity, chemopreventive potential and detoxification enzymes modulation activity.

Carotenoids: Citrus carotenoids (e.g. β -cryptoxanthin and β -carotene) are precursors to vitamin A, act as antioxidants and support immune function. Mandarins and sweet oranges are important dietary sources.

Phenolic acids: Compounds like ferulic acid and caffeic acid are also present in citrus, contributing to the overall antioxidant capacity of the fruit. Mandarin peel has been identified as a good source of ferulic acid.

Organic acids: Citrus fruits are rich in organic acids, primarily citric acid, along with malic acid. Citric acid acts as a natural antioxidant and chelating agent, helping in detoxification and improving mineral absorption. Malic acid supports energy production in the body through its role in the Krebs cycle.

Citrus pectin: Citrus peel is an exceptionally rich source of pectin, a complex structural polysaccharide that functions as a soluble dietary fibre. Pectin can constitute 20-30% of the peel's dry weight. It consists of homogalacturonan and rhamnogalacturonan regions, and its gelling properties and functional behaviour depend on the degree of esterification (DE). Pectins are classified as

high-methoxyl (DE > 50%) or low-methoxyl (DE < 50%), suiting them for different applications.

Citrus pectin is not digested in the upper gastrointestinal tract. Upon reaching the colon, it undergoes fermentation by colonic microbiota, producing short-chain fatty acids (SCFAs), including butyrate, propionate and acetate. These SCFAs are vital for colon cell health and contribute to maintenance of colonic epithelial integrity, modulation of systemic inflammation and metabolic regulation. Thus, pectin acts as a prebiotic, promoting the growth of beneficial gut bacteria. This modulation of the gut microbiome is a cornerstone of pectin's health benefits.

Furthermore, its ability to form a gel-like matrix in the gut helps in cholesterol control by binding to bile acids and promoting their excretion, and in glycaemic control by slowing down glucose absorption. Given that India imports a substantial amount of pectin, developing a domestic industry based on valorizing citrus peel waste aligns perfectly with national goals of 'Make in India' and promoting a zero-waste circular economy.

Essential oils: Extracted from the flavedo, citrus essential oils are complex mixtures of volatile compounds, with limonene often being the major component. The composition can vary significantly between species. Citrus essential oils are widely used in the food, cosmetic, and pharmaceutical industries for their aromatic and antimicrobial properties.

However, it is crucial to note that these bioactives support health as part of a balanced diet and are not treatments for disease. When these bioactive components are preserved and strategically incorporated into food formulations, citrus transcends its role as a simple fruit and becomes a functional food platform capable of delivering multiple health benefits simultaneously.

A glimpse of citrus-based functional foods and beverages

Delivering essential nutrients and bioactives through commonly consumed foods and beverages increases compliance and long-term dietary integration compared to standalone supplements. Hence, citrus-based functional foods and beverages represent a food-first nutritional strategy that integrates immunity, hydration, gut health, and sustainability.

Functional citrus beverages: The development of not-from-concentrate (NFC) citrus beverages represents a significant advancement in retaining natural nutrients and sensory authenticity. Acid lime-based functional energy drinks formulated with real juice provide not only rapid carbohydrate-derived energy but also natural vitamin C and flavonoids that help mitigate oxidative stress. Unlike conventional synthetic energy beverages, these formulations reduce reliance on artificial flavoring systems and emphasize clean-label nutrition. The inclusion of balanced functional ingredients and amino acids further supports sustained energy release, making such beverages relevant for physically active and health-conscious individuals.

Similarly, NFC acid lime sports drinks enriched with electrolytes support hydration and neuromuscular balance. During intense physical activity, the body loses sodium,

potassium, and fluids, and the isotonic nature of citrus-based hydration beverages facilitates rapid replenishment. The antioxidants help counter exercise-induced oxidative damage, while organic acids enhance palatability and fluid absorption. In tropical climates, where dehydration risk is high, such natural hydration solutions are particularly valuable.

Ready-to-serve (RTS) citrus beverages and fizzy citrus drinks offer healthier alternatives to conventional soft drinks. By incorporating authentic fruit juice and moderate sugar levels, these beverages deliver refreshment along with micronutrient contribution. Vitamin C content enhances daily intake, while the absence of artificial colors aligns with consumer demand for transparency and ingredient simplicity.

Functional confectioneries: One of the most innovative applications of citrus bioactives lies in functional confectionery. Vitamin C-fortified acid lime gummies and polyphenol-rich mandarin jelly bites transform immune-support nutrients into child-friendly formats. These products provide enhanced vitamin C levels (180-200 mg/100g) along with flavonoids (76-80 mg/100g), supporting immune resilience, antioxidant defense, and tissue repair. Since children often resist conventional supplementation, fortified citrus confectionery serves as an acceptable and enjoyable nutrient delivery vehicle.

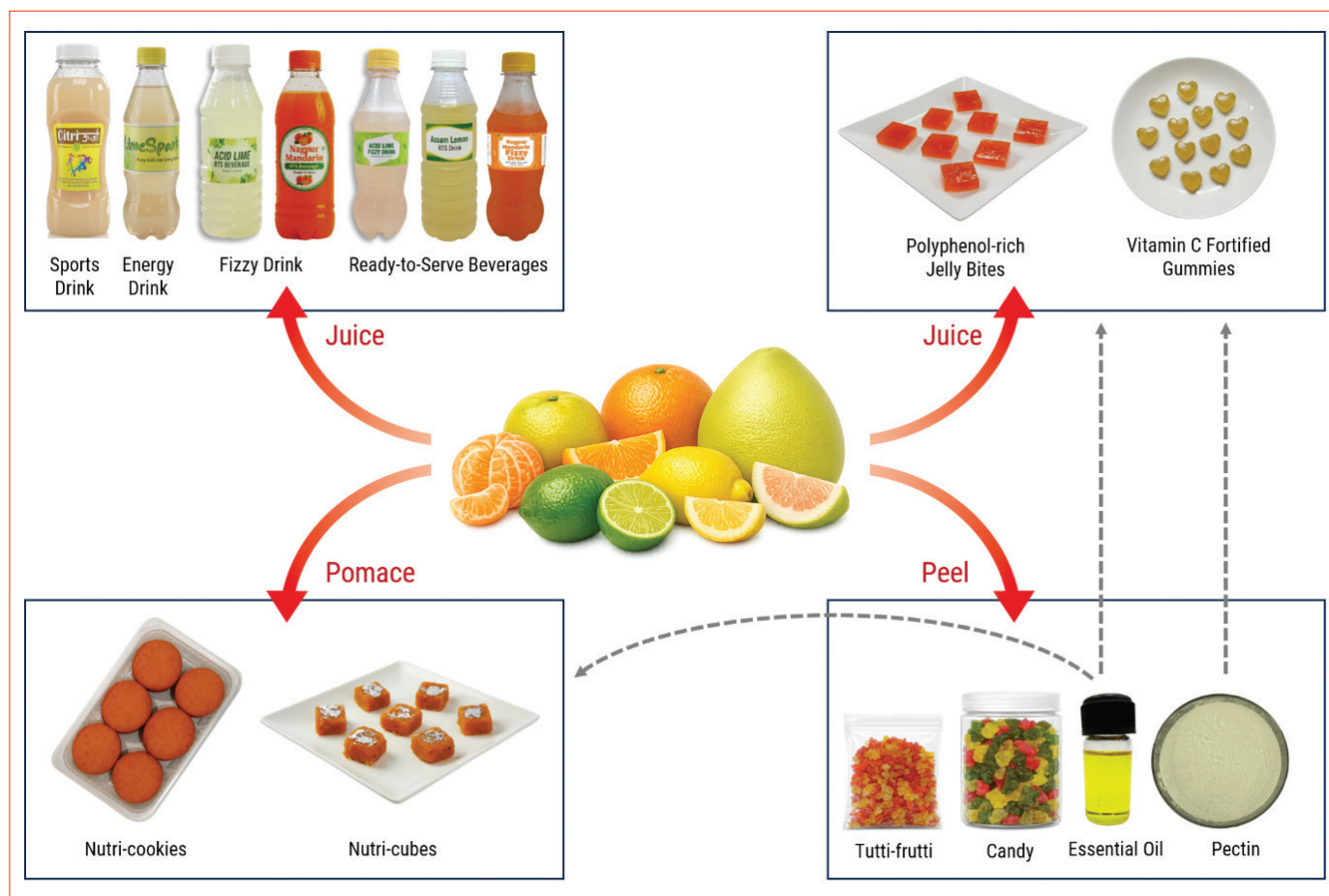
The use of peel-derived pectin as a natural gelling agent further enhances the nutritional value by contributing soluble fibre. Clean-label formulations devoid of synthetic colors, flavors, and preservatives reinforce consumer

confidence and promote healthier snacking habits. Such products demonstrate that indulgence and preventive nutrition can coexist within thoughtfully designed food systems.

Pomace-based functional foods: Citrus pomace, the nutrient-rich residue left after juice extraction, contains valuable fibre, residual vitamin C, flavonoids, and other phytochemicals. Transforming pomace into nutri-rich mandarin cubes represents an exemplary model of nutritional upcycling. These cubes exhibit enhanced protein, fibre, and antioxidant content compared to conventional sweets. The dietary fibres are known to support digestive regularity, improves satiety, and moderates post-prandial glucose response. Sugar-free variants further extend their applicability to calorie-conscious and diabetic populations.

Mandarin pomace nutri-cookies, blended with millets or oats, provide a functional bakery alternative with improved fibre density and lower glycemic potential. While a large population is facing the dual burden of micronutrient deficiency and rising lifestyle disorders, fibre-enriched snacks represent a strategic intervention for promoting balanced dietary patterns. The subtle citrus notes from peel components enhance sensory appeal while delivering additional phytochemicals.

Peel-based innovations: Citrus peel, particularly pomelo albedo, is often discarded despite its high fibre and bioactive content. Converting pomelo peel albedo into candy and tutti-frutti-like products demonstrates how waste streams can be transformed into nutritionally superior



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confectionery. These products retain dietary fibre and flavonoids, contributing to digestive health and antioxidant intake while reducing environmental waste and promoting a zero-waste citrus industry. Prepared with natural colors, these products are entirely free from synthetic additives, including preservatives. Nutritionally, these products offer superior nutritional value and enhanced sensory and textural appeal compared to conventional variants, making it a versatile ingredient for a wide range of applications from standalone healthy snacking to incorporation in different bakery formulations. Aligned with zero-waste principles and the circular economy, these products represent a sustainable, clean-label confectionery solution that appeals to modern consumers seeking both taste and health in their dietary choices.

Citrus-based functional processed products developed by ICAR-CCRI

A defining strength of citrus-based processed products lies in its zero-waste orientation. Juice is converted into functional beverages, pomace into fibre-rich snacks, peel into confectionery. This circular bioeconomy model maximizes nutrient recovery from each fruit, reduces post-harvest losses, and enhances economic sustainability. Nutrition security and environmental responsibility thus converge within citrus value chains. By increasing nutritional output per unit of harvested fruit, citrus processing innovations contribute to both health outcomes and citricultural resilience. This integrated approach supports farmers, processors, entrepreneurs,

and consumers simultaneously.

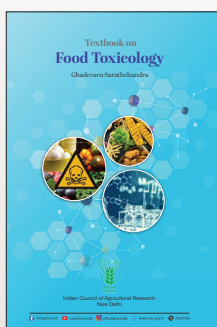
SUMMARY

Citrus-based functional foods and beverages represent a powerful convergence of horticultural innovation, nutritional science, and sustainability. Rich in vitamin C, flavonoids, dietary fibre, and bioactive essential oils, citrus products support immunity, metabolic balance, cardiovascular wellness, and digestive health. Innovations such as NFC functional beverages, fortified gummies, pomace-based fibre snacks, peel-derived confectioneries demonstrate how science-backed value addition can transform perishable fruits into health-promoting, shelf-stable products and preventive nutrition solutions. Equally important, the upcycling of citrus by-products aligns health promotion with circular bioeconomy principles. In an era marked by lifestyle disorders and micronutrient gaps, citrus-based functional products offer an accessible, consumer-friendly, and sustainable pathway to improve public health and nutrition while strengthening India's horticultural sector. By integrating these innovations into mainstream food market, India can simultaneously enhance public health, reduce post-harvest losses, and strengthen its citrus value chain.

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