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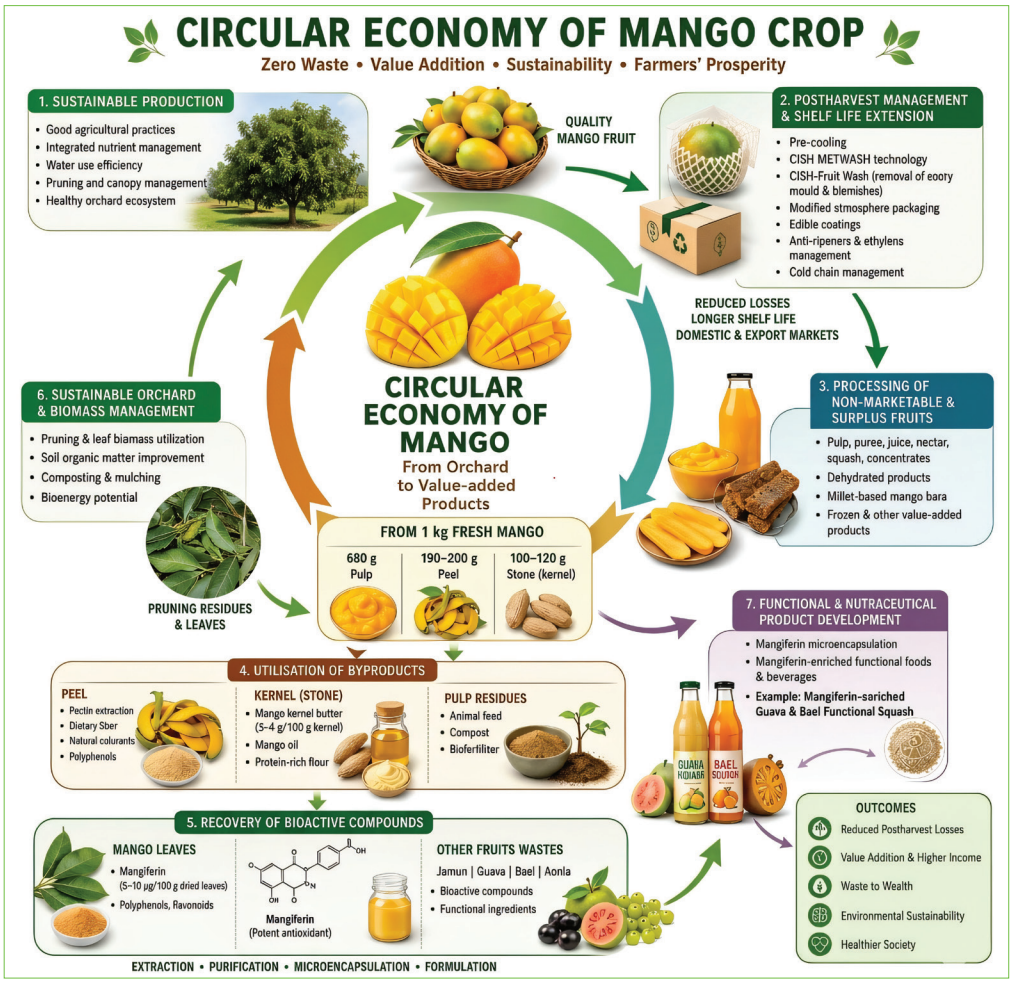
Circular Bio-economy Approach for Zero-Waste Processing and Value Addition in Mango

Mango, being a climacteric fruit, undergoes rapid physiological and biochemical changes after harvest, leading to accelerated deterioration and significant post-harvest losses. These losses contribute to substantial economic setbacks due to inadequate storage facilities, limited processing infrastructure and inefficiencies across the supply chain. A circular bio-economy approach provides a sustainable pathway for addressing these challenges through zero-waste processing and inclusive mango utilization. By integrating shelf-life extension strategies, value addition and valorization of mango peel, pulp and seed kernel into nutraceuticals and functional products, this approach minimizes waste, enhances resource-use efficiency, increases farmer income, promotes environmental sustainability and strengthens inclusive agri-food systems.

Keywords: Circular bio-economy; Mango; Mango kernel butter; Zero-waste processing

INDIA, the native home of mango, is the world's largest producer, contributing nearly 22.84 million tonnes annually. Despite this substantial production, considerable post-harvest losses occur across the value chain, from harvesting and transportation to storage, processing, and retail distribution. Mango post-harvest losses are estimated at approximately 3.19 million tonnes, representing nearly 14% of total production, with an associated economic loss of around ₹478.5 crore annually. In major mango-producing states such as Uttar Pradesh, which contributes nearly 4.8 million tonnes annually, post-harvest deterioration and inadequate processing infrastructure leads to estimated losses of approximately ₹101 crore. These significant quantitative and economic losses underscore the pressing need for sustainable post-harvest management strategies and resource-efficient utilization of mango produce. A circular



Circular bioeconomy for a sustainable, profitable & climate-resilient mango value chain

bio-economy approach offers a sustainable pathway for transforming mango production systems from a linear 'produce–consume–discard' model into an integrated, zero-waste framework. This approach emphasizes maximizing resource efficiency through shelf-life extension, innovative processing, value addition, and complete utilization of mango components, including pulp, peel, and seed kernel. By-products generated during processing, often considered waste, can be valorized into nutraceuticals, functional ingredients, bioactive compounds, dietary fibre, pectin, seed oil, and natural antioxidants, thereby converting waste into wealth. Such an integrated approach not only minimizes post-harvest and processing losses but also strengthens environmental sustainability, improves nutritional security, enhances industrial opportunities, and increases farmer income through diversified value chains. Ultimately, the adoption of circular bio-economy principles in mango processing can contribute significantly to inclusive growth, sustainable agri-food systems and zero-waste horticulture in India.

Innovative approaches for extended shelf life and export quality: Shelf-life extension technologies are critical for reducing postharvest losses and maintaining the market quality of fresh fruits during storage, transportation, and marketing. Mango, being a climacteric and highly perishable fruit, undergoes rapid ripening, moisture loss, physiological deterioration, and microbial infection after harvest, limiting its marketability, particularly for distant and export markets. Advanced postharvest interventions such as pre-cooling, edible coatings, modified atmosphere packaging (MAP), controlled atmosphere storage, cold chain management, and ethylene regulation have significantly improved fruit storability by slowing respiration, reducing transpiration, delaying ripening, and minimizing spoilage while preserving firmness, flavour, and nutritional quality. Technologies developed at ICAR-Central Institute for Subtropical Horticulture have demonstrated considerable success in extending the storage life of commercially important mango cultivars. Shelf life has been enhanced up to 22 days in *Dashehari*, 20 days in *Langra*, 30 days in *Chausa*, 32 days in *Kesar*, and 40 days in *Banganapalli*, enabling improved market access and long-distance transport. Among these innovations dipping fruits for 7-10 minutes in CISH METWASH, a secondary metabolite–based organic formulation, effectively controls postharvest diseases and regulates ethylene production during transit and storage. As a result, significant extension in mango shelf life can be achieved while maintaining fruit quality and market acceptability. Another significant innovation, CISH-Fruit Wash, addresses black spots and sooty mould problems common in *Chausa* and *Langra* mangoes, particularly in major production belts of Uttar Pradesh. The technology removes nearly 80–85% of surface blemishes and improves visual appeal and export acceptability. Collectively, these interventions reduce postharvest losses, strengthen export competitiveness and improve returns to farmers and supply-chain stakeholders. In addition to these, anti-ripening compounds and ethylene management systems are increasingly used in postharvest handling to regulate fruit ripening. CISH anti ripeners I and CISH anti ripeners II function by controlling ethylene biosynthesis and absorbing excess ethylene gas during storage and transportation. Ethylene absorbents and inhibitors delay senescence, maintain fruit firmness, preserve physicochemical quality and extend storage life. Such technologies are highly beneficial during domestic supply chains where fruits are exposed to extended transit durations and variable environmental conditions. Overall, shelf-life extension technologies are essential tools for reducing postharvest losses, improving fruit quality, enhancing export competitiveness and strengthening the economy.

Integrated mango processing for value realization: Mango processing plays a central role in the circular bio-economy framework by enabling efficient utilization of seasonal produce, reducing post-harvest losses, and creating diversified market opportunities. Given the highly perishable nature of mango and its seasonal glut during peak harvest, integrated processing approaches provide an effective pathway for converting fresh fruits into stable, marketable, and high-value products. Such approaches not only enhance product availability beyond the harvesting season but also facilitate value realization through diversified processed products. Integration of modern processing technologies has facilitated the development of shelf-stable, nutritious, and export-oriented products, while utilization of processing residues further supports waste minimization and resource valorization under a circular bio-economy approach.

Primary processing

Mango Pulp: Mango pulp processing is one of the most important value-addition strategies for efficient utilization of surplus and seasonal mango produce. Fully

Premium grade mango post-harvest packaging

Sweetened dashehari mango pulp designed for bakery applications

Freeze dried mango pulp powder and dehydrated cubes

mature and ripe fruits are selected, washed, graded, and peeled before estining and pulping. The extracted pulp is refined to remove fibres and impurities, followed by pasteurization to ensure microbial safety and extended shelf life. Processed pulp is packed aseptically for year-round use. Mango pulp serves as a key raw material for secondary products like juices, nectars, beverages, jams, fruit bars, dairy products, confectioneries and export-oriented processed foods, thereby enhancing value realization and reducing post-harvest losses.

Mango pulp powder and cubes: Mango pulp powder is a high-value product developed through low-temperature dehydration that preserves the fruit's natural colour, flavour, aroma, nutrients and bioactive compounds. In this process, mango pulp is frozen and moisture is removed through sublimation under vacuum, minimizing thermal degradation and maintaining product quality using freeze driers. The resulting powder possesses excellent solubility, extended shelf life and high retention of nutrients and flavour compounds. Freeze-dried mango powder can be used in beverages, bakery products, dairy formulations, confectionery, infant foods, nutraceuticals and instant mixes, offering significant opportunities for product diversification and export-oriented value addition.

Secondary processing

Value added products from pulp: Mango pulp serves as an important raw material for manufacturing a wide range of processed foods, including ready-to-serve (RTS) beverages, fruit bars, dehydrated products, and functional snacks. Mango RTS beverages are prepared by blending

Various value-added mango products

mango pulp with sugar syrup, citric acid, and water, followed by pasteurization and hygienic bottling to ensure product safety and stability. These beverages are widely accepted due to their refreshing taste, nutritional value, and storage stability of up to six months.

Mango-based nutri bars and fruit bars represent another promising avenue for value addition, offering convenient, ready-to-eat products rich in carbohydrates, dietary fibre, vitamins, and antioxidants. Blended formulations such as mango-jamun fruit bars further enhance nutritional quality through higher vitamin C and antioxidant content, making them attractive to children and health-conscious consumers. In addition, advanced dehydration technologies, including freeze drying, vacuum drying and osmotic dehydration, have enabled the production of premium products such as dried mango slices, mango chips, dehydrated cubes and freeze-dried snacks. Freeze drying, in particular, retains natural colour, flavour, aroma, and nutrients, thereby increasing product quality, shelf life, and suitability for premium and export markets.

High-value products from premature dropped mango fruits: Prematurely dropped fruits of Mango, which are usually unripe and considered waste, can be efficiently utilized to produce several high-value products due to their rich content of organic acids, starch, pectin and bioactive compounds. Instead of being discarded, these

Value-added products from dropped mango

immature mangoes can be processed into a variety of food, industrial and nutraceutical products. One of the most common uses is the preparation of pickles and chutneys, as unripe mangoes have a sour taste and firm texture that are ideal for traditional food products. They are also widely used for making amchur (dried mango powder), which serves as a natural souring agent in culinary applications. Unripe mangoes can also be processed into beverages such as panna, a refreshing drink known for its cooling properties and high vitamin content. Due to their high starch content, these fruits can be utilized for starch extraction, which has applications in food processing and textile industries. Furthermore, they contain significant amounts of phenolic compounds and antioxidants, which can be extracted for use in nutraceuticals and functional foods. In addition, premature mango fruits can be used for vinegar and fermentation products, where their natural sugars and acids support microbial fermentation. Thus, the utilization of prematurely dropped mango fruits not only helps in reducing agricultural waste but also creates

Mangiferin extracted from mango leaves

opportunities for value addition, income generation and sustainable resource management.

Leaf-derived mangiferin for nutraceutical enhancement: Mango orchards generate a substantial quantity of pruning residues and biomass during annual canopy management and orchard maintenance practices. However, mango leaves are rich sources of several bioactive compounds including mangiferin, polyphenols, flavonoids and other phytochemicals possessing strong antioxidant, antimicrobial, and anti-inflammatory properties. Mango leaf biomass can serve as an important raw material for the extraction of mangiferin, a naturally occurring xanthonoid compound well known for its antioxidant, antimicrobial, anti-inflammatory, antidiabetic and therapeutic properties. Sustainable utilization of mango pruning residues through mangiferin extraction offers an efficient approach for converting low-value orchard waste into high-value bioactive ingredients. Such utilization supports the principles of circular bioeconomy

Mangiferin-enriched bael and guava squash

by promoting resource efficiency, waste minimization, and value addition to agricultural biomass. To improve stability, bioavailability, and incorporation into food systems, mangiferin can be effectively microencapsulated using suitable encapsulating agents under controlled processing conditions. Microencapsulation protects the sensitive bioactive compound from degradation caused by environmental factors such as light, oxygen, temperature and moisture while enhancing its controlled release and functional efficiency in food applications.

Using this approach, mangiferin-enriched functional squash has been developed utilizing Guava and Bael fruit pulp as the base material. Microencapsulated mangiferin extracted from mango leaves was incorporated into the squash formulation to enhance its nutraceutical and antioxidant properties. The incorporation of mangiferin significantly improved the functional quality of the beverage by increasing its bioactive content and potential health-promoting benefits. Such circular economy approaches contribute towards sustainable horticulture, biomass valorization, waste reduction and development of eco-friendly agri-food systems.

Valorization of mango by-products

Mango processing generates large amounts of by-products such as peel, seed kernel, and stone, which can be converted into useful, high-value products instead of being wasted. Extraction of value-added products from mango by-products is an important aspect of food processing and waste utilization, particularly in a major mango-producing country like India. During the processing of Mango, a significant portion of the fruit, nearly 35–45% is discarded as waste in the form of peel and seed. These by-products, however, are rich in valuable compounds and can be converted into economically useful products. Mango peel, which constitutes about 15–20% of the fruit, is a rich source of pectin, dietary fiber, antioxidants, and natural pigments. Pectin extracted from mango peel is widely used as a gelling agent in the preparation of jams and jellies. The extraction process generally involves drying the peel, grinding it into powder, followed by acid extraction, filtration, and precipitation. Additionally, mango peel can be processed into dietary fiber powder, which is used in bakery products and health supplements due to its high nutritional value. The presence of bioactive compounds like carotenoids and polyphenols also makes it suitable for the extraction of natural colorants and antioxidants, which are useful in food and cosmetic industries. Various extraction techniques are employed to obtain these value-added products, including drying to reduce moisture content, solvent extraction for oils and bioactive compounds, steam distillation for essential oils, acid extraction for pectin, and mechanical pressing for oil recovery. The utilization of mango by-products not only helps in reducing environmental pollution caused by agro-waste but also provides additional income opportunities for farmers and entrepreneurs.

Table. Value addition of mango waste

Waste portion	Waste (%)	Nature of waste	Value added products
Mango peels	12-15	Peel and pulp	Pectin, Alcohol, Cattle feed, Compost
Mango pulper waste	5-10	Fibre	Wine, Vinegar, Juice
Mango Kernels	15-20	Hull & Kernel	Fat, Tannins, Starch

Extraction of butter from mango kernel: The mango seed, constituting approximately 20–25% of the fruit, contains a nutritionally and industrially valuable kernel. This kernel can be processed to extract mango kernel oil, commonly referred to as mango butter, which exhibits physicochemical properties comparable to cocoa

Mango butter

butter. Owing to its excellent emollient and stability characteristics, mango butter is extensively utilized in confectionery applications as well as in cosmetic formulations, including soaps, creams, and lotions. In addition to oil extraction, the kernel can be dried and milled into flour, serving as a gluten-free ingredient for various food products and as a supplementary component in animal feed. The kernel is also a potential source of starch, which can be isolated and employed as a thickening and binding agent in both food and textile industries. Furthermore, mango seed kernels contain appreciable amounts of tannins, which find applications in leather processing and certain pharmaceutical formulations.

Mango kernel butter can be efficiently extracted using the solvent extraction method with a Soxhlet apparatus. Standardized extraction conditions indicate that an optimum temperature of approximately 65°C yields high-quality butter. For a 20 g kernel sample, a minimum solvent volume of about 230 ml and extraction duration of 4 hours were found to be adequate. Under these conditions, the recovery of mango kernel butter was approximately 12%. The extracted butter also demonstrated significant bioactive potential, with total phenolic content measured at 135.6 mg/100 ml, indicating its antioxidant value and suitability for functional applications.

Compost, animal feed and bioenergy from mango processing waste: Following the extraction of bioactive compounds, nutrients and starch the residual mango by-products can be efficiently utilized for composting, animal feed and bioenergy production, ensuring complete resource recovery and minimizing waste. One of the most common methods is composting, in which mango peels, seeds, and pulp waste are biologically decomposed to produce nutrient-rich organic fertilizers that enhance soil fertility and reduce reliance on chemical fertilizers. Another important utilization is as animal feed, where mango by-products, especially pulp residues and seed kernels, provide a good source of fiber, carbohydrates, and bioactive compounds, making them a low-cost and nutritious feed option for livestock and poultry. Furthermore, mango processing waste can be used for bioenergy production through anaerobic digestion, where microorganisms break down organic matter to produce biogas that can be used for heat and electricity generation. The leftover digestate from this process can also serve as an organic fertilizer, making it a sustainable and efficient waste-to-energy solution.

SUMMARY

Zero waste approach enables complete utilization of mango resources through integrated strategies encompassing GAPs, shelf-life extension, value-added processing, bioactive extraction, and waste valorization. By transforming by-products into nutraceuticals, functional foods, compost and bioenergy, minimizes losses, enhances resource efficiency, and generates additional income. Ultimately, the adoption of circular bio-economy principles in mango processing can contribute significantly to inclusive growth and sustainable agri-food systems.

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