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Probiotic Fermentation of Fruits and Vegetables: A Novel Approach for Nutritional Enhancement and Horticultural Value Addition

India faces a critical 'triple burden' of malnutrition: undernutrition, hidden hunger, and rising overnutrition. Alarmingly, 35% of children under five are stunted, and fewer than 10% of rural Indians eat enough vegetables. The root issue is a lack of nutrient-dense food, worsened by high spoilage rates and thermal preservation methods that destroy vital vitamins. The breakthrough solution? Advanced probiotic bioprocessing. By moving away from heat treatments and embracing targeted microbial fermentation, scientists are turning highly perishable produce into shelf-stable, therapeutic functional foods. This modern twist on a traditional technique promises to bridge India's steep nutritional gap.

Keywords: Fruits and Vegetables; Functional food; Probiotic fermentation; SDG; Sustainable food systems

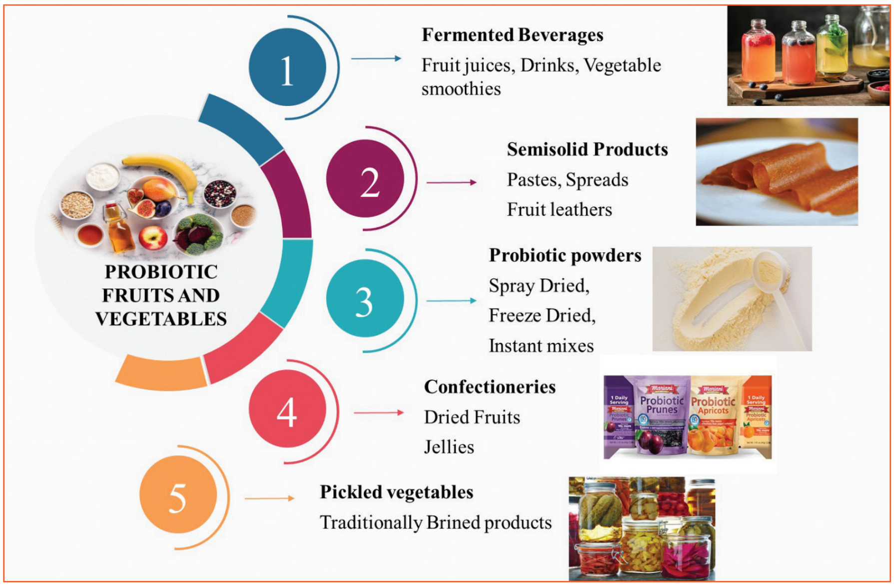
CURRENTLY, India is witnessing triple burden of malnutrition in the era of globalization, characterised through the concurrent occurrence of undernutrition, hidden hunger, and overnutrition. This condition arises from interconnected determinants like poverty, dietary transition towards ultra-processed foods, limited access to nutrient-dense foods, and a lack of knowledge about nourishing foods and a healthy diet. However, a unifying cause of the triple burden of malnutrition among these distal factors is the low nutrient density of foods and diets.

Findings from the Comprehensive National Nutrition Survey conducted in 2016-2018, provide explicit evidence of the triple burden of malnutrition in India, with 35% of children under 5 years being stunted, 17% wasted, and 33% underweight. Concurrently, a high prevalence of hidden hunger persists, as 46-53% of preschoolers being anaemic, along with considerable deficiencies of vitamin A (18%), vitamin D (14%), Zinc (19%), and other micronutrients (14-31%) reported in this age group. Further, recent evidence from the latest NIN survey indicates inadequate consumption of fruits and vegetables, with merely 8.8% of rural population consuming recommended vegetable intake and 15.9% meets fruit intake levels, while in urban population the corresponding values are 17% and 28.6% respectively, against the recommended consumption of more than 350g per day vegetables and 150g per day fruits.

The inadequate intake is not merely a matter of the availability of this produce, but also relates to the perishability, seasonal supply, and consumer acceptability in the fresh form. Although numerous processing methods and value-added fruit and vegetable products exist, most of them rely on thermal preservation techniques that may compromise the nutritional quality to some extent. Therefore, increasing attention is being directed towards bioprocessing technologies that improve the nutritional profile while achieving desirable shelf life. Fermentation represents one such traditional method offering improved nutritional characteristics and shelf stability. Further, advancements in knowledge about health-promoting microbes, 'probiotics' have expanded the horizons of conventional fermentation into a targeted value-addition approach producing functional fruit and vegetable-based products with defined therapeutic potential.

Fruits and vegetables as ideal carriers for functional food

Probiotics are beneficial viable microorganisms when ingested in adequate quantities, can colonize in the gut, and confer health benefits to the host. Generally, dairy products are served as substrates for probiotic delivery; however, increasing allergenicity towards them and veganism led to the necessity for research into non-dairy substrates for this purpose. Fruits and vegetables are ideal substrates for probiotic delivery, as they contain readily available macronutrients like sugars, vitamins, and minerals, which support the growth and proliferation of probiotic microorganisms. Further, the presence of phenolic compounds and dietary fiber not only enhances the growth of beneficial probiotics, but also aids in the synthesis of novel bioactive metabolites with specific therapeutic potential, thereby enhancing the functional value and utilization of this horticultural produce. Numerous probiotic products have been developed using fruits and vegetables as substrates, including probiotic fruit and vegetable-based beverages, semi-solid or pulp-based products, dried powders, confectioneries, as well as traditional pickled products.



Types of probiotic fruit and vegetable products

From fresh produce to functional foods: Probiotic processing as a horticultural value addition strategy

Fruit / vegetable-based probiotic beverages: Probiotic fruit or vegetable beverages are prepared either by the addition of probiotic strains into the final beverage or by a fermentation technique. The latter was found to enhance the nutritional quality and shelf stability, since fermented food matrix will harbour potent metabolites like short-chain fatty acids, organic acids, and bacteriocins, which facilitate the keeping quality of the produce. The key probiotic strains used in juice fermentation are from the genera *Lactobacillus*, *Bifidobacterium*, *Enterococcus*, *Lactococcus*, *Streptococcus,* and heat-resistant spore formers, including *Bacillus spp*.

A variety of fruits like apple, pineapple, grapes, pear, strawberry, jackfruit, chokeberry have been successfully used as substrates for probiotic fermentation. Fermentation of pineapple juice using *L. plantarum* exhibited high probiotic viability and enhanced antioxidant properties. Likewise, probiotic fermentation in apple juice resulted in reduction of patulin, a common contaminant found in apple juice, therefore enhancing the product safety. Further, certain probiotics like *Bacillus coagulans* enriched fruit beverages improve immunoglobulins and lymphocytes.

Fermentation of fruits and vegetables with probiotics has also been explored for the production of functional compounds like γ-aminobutyric acid (GABA), an inhibitory neurotransmitter that promotes relaxation and mental calmness. Grape-must fermented with *L plantarum* yielded significant levels of GABA along with a viable probiotic population in the final food matrix.

Fermentation of fruit juices using probiotics not only improves the nutritional quality but also alters the flavour profile of the final product by producing various volatile and non-volatile compounds. Probiotic passion fruit juice with *L. plantarum* resulted in the production of volatile compounds like 2,6-octadien-1-ol, 3,7-dimethyl-, (z), 1-dodecanol, and methyl salicylate, providing sensory perceptions pertaining to floral, fatty odour and taste of wintergreen, respectively.

Probiotic fruit and vegetable beverages qualify as the most feasible technology among probiotic horticultural products due to high consumer acceptance and good probiotic survival in liquid matrix, while cold storage, sedimentation and phase separation in the product may be of practical concern.

Semi-solid/pulp-based products: Microencapsulated probiotic strains enriched vegetable pastes have gained increased attention recently and have facilitated product diversification in premium fruit and vegetable product lines. Olive paste has been reported to be an effective carrier of microencapsulated *L. plantarum* strains without altering the sensory attributes of the product while maintaining the probiotic viability.

Probiotic fruit leathers have been developed and optimized via the incorporation of probiotic cultures into fruit puree dispersions. However, the conventional process of fruit leather production was challenging due to high-temperature processing, which can be mitigated by the use of spore formers like *Bacillus coagulans.*

Semi-solid and pulp-based probiotic products are promising carriers for the microencapsulation and targeted delivery of probiotic strains; however, process parameters like texture standardization and drying temperature must be optimized to prevent loss of probiotic viability.

Probiotic fruit and vegetable powders: Juice powders enriched with probiotics constitute another form of plant-based probiotic products. Several fruit and vegetable food matrices have been optimized as suitable substrates for the development of probiotic powders. Underutilized fruits have also been explored for this purpose; for instance, sohiong (*Prunus nepalensis*), an underutilized fruit from the Northeastern region of India, has been identified as an ideal substrate for the delivery of *L. plantarum.* Maoberry, a tropical fruit from Southeast Asia rich in anthocyanins, phenolics, and flavonoids, has been successfully enriched with *L. casei* for optimization of probiotic powder.

Spray-dried probiotic orange juice powder was developed as a novel functional non-dairy product, using *Lactobacillus plantarum* and *Pediococcus acidilactici,* demonstrating promising probiotic potential. Probiotic banana powders are proposed for complementary feeding, as fermentation facilitates the breakdown of complex nutrients and enhances nutrient bioavailability. Furthermore, controlled fermentation with probiotic strains enhances the mineral and antioxidant composition of such flours.

Probiotic powders represent the most shelf-stable format and are suitable for large-scale distribution; however, maintaining cell viability during drying remains a key technological challenge.

Confectioneries: Fruit or vegetable-based jellies often exhibit limited consumer acceptance due to increasing avoidance of high-sugar products and the use of animal-derived bovine gelling agents. Consequently, the demand for searching for vegan probiotic alternatives has accelerated the search for new delivery matrices. Tomato and peach juice fermented with probiotic *L. rhamnosus* exhibited higher antioxidant capacity, as probiotic metabolism induced enzymatic activity led to increased release of phenolic compounds in jellies, providing additional functional benefits to the consumers.

Dried fruits snacks have been traditionally consumed since drying enhances the total energy, nutrient density, and fiber content in fruits. Additionally, they serve as a promising substrate for probiotic delivery via techniques such as vacuum impregnation. Impregnation of apple slices with probiotic *L paracasei* enhanced their total phenolic content, bioactive properties, and sensory characteristics. Thus, the incorporation probiotics into fruits and vegetables can lead to the development of high-value premium products.

Snack-type probiotic products enhance consumer acceptance and market value, but standardization and regulatory positioning needs careful consideration.

Key advancements in the nutritional profile of fruits and vegetable based probiotic products

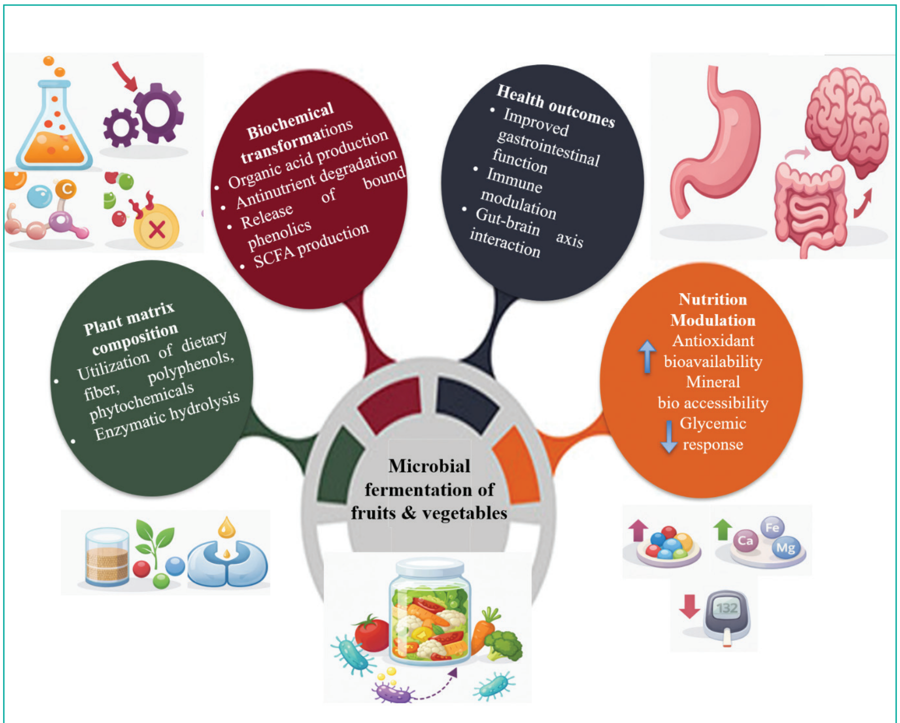
Fibres and prebiotics in fruits and vegetables not only sustain probiotic growth but also act as precursors for the production of beneficial metabolites. Beyond promoting microbial growth, these fibres are further utilized by probiotics to produce functional metabolites such as short-chain fatty acids, including acetate, propionate, and butyrate. Inulin, fructo-oligosaccharides, and galacto-oligosaccharides are examples of prebiotics in these plant matrices, which will be utilized by probiotic enzymes for the production of SCFAs. SCFAs further enhance gut integrity, strengthen immune responses, and also stimulate protective immune cells. Fermentation also facilitates the breakdown of complex and bound compounds, anti-nutrients, resulting in the release of bound minerals and phytochemicals into the final food matrix. This process enhances the antioxidant potential and reduces oxidative stress of the fermented food when compared to their unfermented counterparts.

Fermentation further improves digestibility by partially hydrolysing complex carbohydrates and plant proteins, thereby lowering glycaemic response and making the products suitable for children and elderly individuals. Additionally, certain probiotic strains are capable of producing vitamins, particularly B-complex vitamins such as folate, leading to natural micronutrient enrichment of the final product. Thus, probiotic fermentation transforms horticultural produce from merely perishable commodities into nutritionally enhanced, bioactive, and health-promoting functional foods.

Contribution to sustainable food systems & SDGs

Probiotics have transformed traditional fermentation into a scientifically validated process, enhancing the nutritional and therapeutic value of the products. Converting fresh horticultural produce into fermented probiotic foods offers a sustainable preservation strategy by reducing post-harvest losses and extending shelf life without heavy reliance on energy-intensive preservation techniques or synthetic preservatives. Probiotic-based preservation enhances the shelf life by suppressing pathogens and reducing contamination. Integrating probiotics into food supply chains, therefore, has the potential to minimize post-harvest wastage and support global sustainability objectives.

Probiotic fruit and vegetable products can also improve dietary diversity and nutrition security. Fermentation encourages regular intake of protective foods, helps address micronutrient deficiencies, and enhances taste, stability, and convenience. Fermented powders and beverages are shelf-stable formats that can be integrated into school meals and community nutrition programmes, supporting preventive health care.



Fermentation-induced biochemical and nutritional changes in fruits and vegetables

Seasonal surpluses or visually imperfect produce can be transformed into high-value functional foods through fermentation, which otherwise go to waste, thereby benefiting rural livelihoods by opening new avenues of fruit and vegetable valorisation. This approach will strengthen local food systems by creating opportunities for farmer-producer organisations, women self-help groups and small entrepreneurs, further reducing transport-related losses.

Such interventions support several Sustainable Development Goals (SDGs), including Zero Hunger (SDG-2) by improving access to nutritious foods; Good Health and Well-being (SDG-3) through preventive nutrition; Responsible Consumption and Production (SDG-12) by minimizing waste; and Climate Action (SDG-13) through low-energy processing. Thus, probiotic fermentation bridges the gaps in horticulture, nutrition, and sustainability in a practical and impactful way.

Indian opportunities and future scope

Despite sufficient production of fruits and vegetables, India still witnesses a substantial portion of this produce remaining underutilized or wasted, due to seasonal gluts, inadequate cold-chain infrastructure, and market price fluctuations. Optimization of probiotic foods from locally available horticultural crops presents a promising opportunity to enhance both utilization and nutritional impact. Region-specific crops such as mango, banana, jackfruit, amla, pineapple, carrot, and beetroot can be developed into fermented beverages, powders, and semi-solid products suited to local dietary preferences. Such products have potential applications in national nutrition programmes, including mid-day meal scheme, Integrated Child Development Services (ICDS), and community health initiatives, where shelf-stable and nutrient-rich foods are required.

India's growing functional food market and increasing consumer awareness about gut health further support the commercial potential of probiotic horticultural products. Future research should focus on selecting region-specific probiotic strains adapted to tropical conditions, improving ambient shelf stability, and developing synbiotic formulations combining native fruits, vegetables and probiotics. Standardisation, regulatory clarity, and clinical validation of health benefits will strengthen consumer trust and market adoption.

SUMMARY

Bioprocessing of fruits and vegetables via controlled and precision fermentation using probiotic microorganisms offers a promising avenue in fruit and vegetable value addition. On the other hand, perishable produce can be converted to high-value therapeutic foods for specific health uses, thereby enhancing product diversity and marketability. Beyond commercial prospects, such products can contribute to improving dietary quality, addressing micronutrient deficiencies, and supporting preventive healthcare through regular intake of bioactive foods. Fermentation also aids in reducing post-harvest losses and enables better utilization of seasonal surpluses, creating livelihood opportunities for farmer-producer organizations and small-scale enterprises.

Further, more research is required in this arena for identifying potent probiotic strains and analysing suitable fruit and vegetable matrices for fermentation. Fruit and vegetable-based beverages, fermented fruit and vegetable powders, and snacks are some of the existing scalable products in this area. With coordinated efforts among horticulturists, food technologists, and public health agencies, probiotic fermentation of fruits and vegetables can evolve from a niche concept into a scalable strategy that supports nutrition security, farmer income, and preventive healthcare in India.

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