

Research Article

Mango Dehydration by Immersion–Impregnation: A Review of Technological Advances, Critical Parameters, and Industrial Applications

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Abstract

Immersion–impregnation dehydration is an emerging pre-treatment technique used in fruit processing to partially remove water, improve structural stability, and enhance final drying efficiency. Mango (*Mangifera indica* L.), a climacteric tropical fruit valued for its sensory and nutritional qualities, remains challenging to process due to its high moisture content, thermal sensitivity, and pronounced seasonality. Immersion–impregnation relies on osmotic mass transfer, during which water diffuses outward while solutes migrate into plant tissues under controlled thermodynamic gradients. Recent studies have shown that this approach can increase water loss, shorten drying time, reinforce tissue microstructure, and preserve bioactive compounds prior to conventional or advanced drying operations. This review summarizes current scientific and technological advances related to immersion–impregnation dehydration applied to mango. It examines key process parameters—such as solute concentration, immersion time, temperature, osmotic solution composition, hydrodynamic effects, and fruit microstructure—and evaluates their influence on mass transfer behaviour, activation energy, solute gain, and final product quality. Comparative findings between continuous and intermittent immersion methods are presented, together with recent technological developments that support industrial scalability. The review also identifies major scientific and operational challenges, including process modelling, energy–quality optimization, and standardization for use in emerging economies. Finally, future perspectives highlight the potential of hybrid dehydration strategies, sustainable osmotic solutions, and automation-based process control to support large-scale industrial implementation.

Keywords

Mango, Immersion-impregnation Dehydration, Drying Kinetics, Process Optimization

1. Introduction

Mango (*Mangifera indica* L.) is one of the most widely consumed tropical fruits globally and holds significant socio-economic relevance in regions such as West Africa, South Asia, and Latin America [1]. The fruit is valued for its distinctive flavour, colour, and nutritional attributes, including

carotenoids, polyphenols, vitamins, and dietary fibre [2]. However, its high moisture content (typically 78–83% w.b.) combined with rapid post-harvest metabolic activity makes mango highly perishable, leading to substantial seasonal losses in countries with limited cold-chain infrastructure [3].

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Processing into shelf-stable products is therefore essential to reducing food waste, stabilizing supply, and expanding market opportunities in both domestic and export contexts [4].

Dehydration is among the most common preservation methods used for mango valorization, enabling production of dried fruit snacks, semi-finished ingredients, powders, and functional food components [5]. Nevertheless, mango dehydration presents difficulties related to structural collapse, case hardening, browning reactions, prolonged drying times, and the deterioration of sensory and nutritional quality when exposed to elevated thermal conditions [6]. These challenges are particularly evident when traditional convective drying is applied alone [7]. As a result, interest has grown in the development of pre-treatments and hybrid drying strategies capable of improving water removal efficiency while preserving the functional and sensory characteristics of the fruit.

Immersion-impregnation dehydration, often referred to within the wider framework of osmotic dehydration, has emerged as a promising technique to improve drying performance [8]. The process involves immersing fruit pieces in a hypertonic solution, generating a mass transfer gradient that promotes partial water removal while facilitating solute uptake [9]. The result is a product that undergoes reduced cellular collapse during subsequent drying, demonstrating enhanced texture, stability, and reduced energy demand [9, 10]. Advances in solution formulation, process time-temperature profiles, hydrodynamic conditions, and equipment design have further expanded the applicability of immersion-impregnation to mango processing at laboratory, pilot, and industrial scale [11].

Recent scientific literature also demonstrates growing interest in comparing different modes of immersion-impregnation, including continuous immersion treatments (D2I) and intermittent immersion cycles (D3I), each offering distinct advantages depending on mass transfer kinetics, equipment configuration, and intended product quality attributes [12]. Optimisation studies highlight the relevance of modelling approaches based on Fickian diffusion, activation energy estimation, and empirical modelling using response surface methodologies to define optimal process windows [13].

Despite significant advances, several knowledge gaps remain regarding industrial scalability, solute sustainability, process standardization, environmental impacts, and techno-economic feasibility, especially in emerging agri-food economies where mango is abundant but processing capacity remains limited [14].

The objective of this review is therefore to synthesize current knowledge on immersion-impregnation dehydration applied to mango, evaluate the influence of key processing parameters, compare recent technological variations, and assess industrial potential. The article also identifies future research directions required to standardize and scale immersion-impregnation systems for commercial mango dehydration.

2. Principles of Immersion-Impregnation and Osmotic Mass Transfer in Mango

Immersion-impregnation dehydration belongs to the family of osmotic dehydration techniques and operates according to a simple but effective principle: when mango slices are submerged in a hypertonic solution, typically composed of sugars or salts, a concentration gradient is created between the intracellular fluid and the surrounding medium [15]. This gradient drives two simultaneous mass transfer phenomena: the outward movement of water from the mango tissues and the inward diffusion of solutes from the immersion solution. The result is a partial dehydration process that reduces moisture content while modifying the internal structure, improving stability during subsequent drying steps [16].

The efficiency of mass transfer during immersion-impregnation depends on several interacting physical, compositional, and structural factors [11-13]. Fruit maturity, cell wall integrity, porosity, soluble solid content, and initial moisture all influence the rate and uniformity of water loss [17]. Mango, being a soft and climacteric fruit, exhibits tissue breakdown during ripening, which facilitates mass transfer compared with firmer fruits. However, this also increases the risk of textural degradation if processing parameters are not carefully controlled.

The thermal profile of the process plays a key role. Moderate heating of the immersion solution accelerates molecular mobility and softens cell walls, leading to faster water and solute transfer. However, excessive temperatures may cause denaturation of cellular structures, pigment degradation, or excessive solute uptake that alters the natural flavour of mango. For this reason, most studies recommend operating within low to moderate processing temperatures, ensuring balance between kinetics and product stability.

Solution composition also strongly affects performance. Sugar-based media such as sucrose, glucose, fructose, or invert syrups are the most common because they maintain colour, enhance perceived sweetness, and contribute to desirable texture. In some cases, the use of calcium salts or structuring agents improves firmness by reinforcing pectin crosslinking, particularly in ripe mango varieties. More recently, natural osmotic solutions derived from fruit extracts or concentrated juices have been explored as alternatives to refined sugars.

The immersion process is influenced not only by time and concentration, but also by hydrodynamic conditions. Gentle agitation, vacuum pulsing, or intermittent exposure cycles can enhance diffusion and improve uniformity throughout the tissue. These methods help eliminate trapped air, increase contact efficiency, and limit the formation of concentration boundary layers around the fruit surface.

One of the major practical benefits of immersion-impregnation dehydration is its ability to reduce subsequent drying time. By removing water before thermal treatment, the drying kinetics in convective or hybrid systems are

shortened, leading to lower processing energy consumption and better retention of heat-sensitive nutrients and volatile compounds. Moreover, the solute infiltration step stabilizes the mango microstructure, reducing shrinkage and case hardening during drying.

Overall, immersion-impregnation acts as a preparatory dehydration step that improves processing efficiency, enhances product quality, and reduces operational energy demand. Its effectiveness depends on proper selection of processing parameters, including solution composition, temperature, immersion time, hydrodynamics, and fruit characteristics. When optimized, the method can significantly improve the technological and sensory qualities of dried mango.

3. Technological Advances and Processing Optimization in Mango Immersion-Impregnation

Technological developments in immersion-impregnation dehydration of mango have evolved considerably during the last decade, driven by the need to improve mass transfer efficiency, reduce processing time, and obtain products with enhanced sensory, nutritional, and functional properties [16]. While the fundamental principle relies on osmotic pressure differences between the fruit matrix and the surrounding solution, recent advances have focused on optimizing operational parameters, introducing hybrid processing techniques, and integrating automation and process control for industrial scalability [12-26].

One major area of innovation concerns the optimization of solution composition [18]. Traditional osmotic solutions rely primarily on sucrose, which provides favourable sensory attributes but may lead to excessive sweetness and high solute gain [19-24]. Research has explored alternative solutes such as glucose, fructose, maltodextrins, honey, and concentrated fruit juices, with the aim of modifying osmotic pressure profiles and reducing caloric content [20, 21]. The emergence of low-calorie or functional osmotic systems, incorporating natural sweeteners (stevia, erythritol) or bioactive-rich extracts, reflects growing consumer demand for healthier processed fruit products [22]. In addition, mineral salts such as calcium chloride and calcium lactate have been incorporated into osmotic formulations to reinforce cell wall structure, reduce tissue softening, and enhance firmness through pectin crosslinking [23]. These modifications are particularly relevant for ripe mango varieties with fragile cellular matrices.

Process optimization research has also focused on refining time-temperature-concentration relationships to ensure maximum efficiency. Studies have shown that mass transfer is not linearly proportional to immersion duration; instead, rapid water loss occurs initially, followed by a progressively slower diffusion phase [24]. This behaviour has motivated the use of intermittent or pulsed immersion (D3I) rather than continuous exposure (D2I), with studies reporting improved solute uni-

formity, better texture preservation, and comparable or enhanced overall dehydration efficiency [12]. Comparisons between continuous and intermittent immersion show that while both achieve similar levels of water removal, intermittent cycles may prevent oversaturation and excessive solute uptake, leading to products with improved sensory balance [12].

Hydrodynamic and physical enhancement techniques represent another significant development [18]. Mechanical agitation, controlled flow circulation, ultrasound-assisted impregnation, and vacuum pulsing have been employed to accelerate mass transfer kinetics by reducing boundary layer resistance and improving contact between the solution and fruit tissues [8]. Ultrasound application, in particular, introduces microscopic cavitation events that increase porosity and permeability of plant cell membranes, allowing faster water removal and reduced processing time [27]. Vacuum impregnation, meanwhile, operates by removing entrapped air within the intercellular spaces, followed by solute infiltration during pressure restoration, resulting in improved uniformity and deeper penetration across the mango matrix [28]. These methods may require specialized equipment, but they offer clear pathways for industrial intensification.

Temperature remains one of the most influential operational variables. While elevated temperatures accelerate diffusion and reduce viscosity of the osmotic medium, they must be carefully controlled to avoid structural weakening, loss of thermolabile nutrients, and enzymatic browning [29]. Controlled temperature systems with automated thermal feedback loops have therefore become increasingly common in pilot-scale and industrial trials. In addition, integrating immersion-impregnation with pretreatments such as blanching, anti-browning dips, or enzyme inactivation has been shown to enhance quality and stability throughout processing and storage [30].

Another technological development relates to the monitoring and modelling of immersion-impregnation dynamics. While earlier research relied predominantly on empirical observations, recent approaches incorporate response surface methodology, artificial neural networks, and predictive modelling to simulate mass transfer behaviour and optimize processing at reduced experimental cost [31]. These tools allow prediction of water loss, solute gain, textural outcomes, and energy requirements under different processing conditions, supporting decision-making for industrial scale-up [20].

Finally, integration with subsequent drying steps has received considerable attention. Immersion-impregnation pre-treatment is increasingly positioned as part of a hybrid dehydration system, combined with convective drying, heat pump drying, solar-assisted systems, or freeze-drying [23]. The pre-dehydration effect reduces drying time, improves microstructural stability, and allows production of higher-quality dried mango with improved colour retention, texture, antioxidant capacity, and flavour [32]. Technological advances in equipment design, including modular immersion

tanks, automated solution regeneration systems, continuous/batch configurations, and stainless-steel sanitary designs, support feasibility for industrial adoption, especially in emerging economies where mango is abundant but processing infrastructure remains limited [33].

In summary, technological advances in immersion-impregnation dehydration of mango reflect multidisciplinary progress spanning material science, process engineering, food chemistry, and automation. These developments enable improved product quality, reduced energy consumption, and enhanced process control, marking immersion-impregnation as a relevant technology for modern mango processing industries.

Optimizing mango dehydration requires the combination of mild pre-treatments and controlled drying conditions. Immersion-impregnation (D2I/D3I) helps stabilize the cellular structure by partially removing water and reinforcing tissue integrity, which reduces collapse during subsequent thermal drying. Using moderate temperatures, osmotic solutions with protective solutes, and optimized immersion time lowers enzymatic browning and limits thermal degradation. This approach also decreases the effective drying time, improving colour, texture, and nutrient retention compared with conventional high-temperature drying.

4. Applications of Immersion-Impregnation in Mango Processing and Product Development

Immersion-impregnation dehydration has found diverse applications in mango processing as both a stand-alone partial dehydration technique and a preparatory step for downstream preservation, formulation, or structural stabilization. Its versatility arises from its ability to modify physical, chemical, and sensory characteristics of mango tissue in ways that support different product categories ranging from dried snacks to functional ingredients and composite formulations [34].

One of the primary applications is the production of semi-dried mango snacks. In this format, immersion-impregnation is used to partially remove moisture while infusing controlled amounts of sugars or stabilizing compounds. The resulting product maintains a soft, elastic texture, vivid colour, and enhanced flavour profile compared with conventional dehydrated mango [35]. This category has gained traction in Asian and Latin American markets, where semi-moist fruit snacks are valued for their chewiness and sensory appeal [36]. The method is also suitable for flavour diversification through the incorporation of natural extracts, spices, or bioactives during the impregnation phase. Examples include ginger-infused mango, chili-lime mango, or functional variants enriched with vitamin C, polyphenols, or prebiotics [37].

Immersion-impregnation also plays a role in the production

of fully dried mango products. When used as a pretreatment prior to convective or hybrid drying, the process improves mass transfer efficiency, reduces final drying time, and enhances microstructural integrity [38]. This can lead to lower energy expenditure, reduced case hardening, and softer rehydration profiles. For industrial processors, these improvements translate to increased throughput and more consistent product quality. Moreover, the incorporation of osmotic solutes, particularly invert sugar or low molecular weight carbohydrates, can protect colour and reduce enzymatic browning during subsequent thermal exposure [19].

Another emerging application is the stabilization of mango for freeze-drying or vacuum drying. In such cases, immersion-impregnation reduces water content and reinforces the structure, leading to lighter, porous freeze-dried products with better texture retention and reduced collapse during storage. Because freeze-drying is energy-intensive, the reduction in initial moisture creates opportunities for cost savings [39]. Products derived through this pathway include freeze-dried mango crisps, instant rehydratable mango inclusions, and high-value specialty ingredients for cereals, dairy mixes, bakery items, or nutraceuticals.

In liquid or semi-liquid product development, immersion-impregnation facilitates the creation of intermediate ingredients used in yogurts, ice cream, toppings, syrups, or fruit preparations. The partial dehydration and solute uptake ensure controlled viscosity, reduced water activity, and enhanced microbial stability; characteristics essential for food systems requiring refrigerated storage [40]. These intermediate products can also act as inclusions for cheese formulations, pastry fillings, or ready-to-eat desserts, where structural integrity during mixing or thermal processing is desirable.

Beyond direct food applications, immersion-impregnation also contributes to ingredient engineering. Mango pieces treated with functional solutes may act as carriers for micro-nutrients, probiotics, or antioxidants [3]. This function intersects with the growing functional food market, where fruits are increasingly used as delivery systems for health-promoting compounds. Research has explored the incorporation of calcium to improve firmness, iron as a fortificant for nutritional interventions, and polyphenols for enhanced antioxidant potential [41].

A promising industrial application concerns shelf-life extension through reduced water activity and structural reinforcement. Processed mango treated via immersion-impregnation shows improved resistance to microbial spoilage and enzymatic degradation [16]. This characteristic supports logistical and supply chain resilience, especially in tropical regions where refrigeration infrastructure may be limited. For export industries, the technique allows mango to be transformed into more stable, high-value products with extended market windows beyond the short harvesting season [42].

Finally, immersion-impregnation lends itself to product innovation linked to regional consumer preferences. In West

Africa, for instance, pairing mango with traditional flavours such as tamarind, hibiscus... offers opportunities for culturally relevant product design and market differentiation. The capacity to customize flavour and texture through controlled solute diffusion positions immersion-impregnation as a key enabling technology for food innovation in mango-producing regions.

In summary, immersion-impregnation supports a broad spectrum of mango-derived product categories, ranging from minimally processed intermediate ingredients to high-value consumer-ready snacks. Its role in enhancing sensory attributes, improving stability, and enabling formulation flexibility underscores its relevance as a transformative process in mango industrialization [43].

5. Industrial Integration, Equipment Options, and Scale-Up Feasibility

The industrial deployment of immersion-impregnation dehydration for mango requires consideration of equipment selection, process flow integration, operational capacity, energy efficiency, and economic viability. While the technology has been extensively validated in laboratory and pilot-scale studies, successful industrial implementation depends on adapting the process to the realities of mango supply chains, variable raw material quality, seasonal production patterns, and cost constraints typical of processing industries in developing regions.

From an engineering perspective, immersion-impregnation systems can range from simple batch tanks to highly automated continuous or semi-continuous reactors [44]. Batch systems are the most widely used configuration due to their operational flexibility, relatively low capital cost, and capacity to process varied product formats. These systems typically consist of stainless-steel insulated tanks equipped with temperature control units, agitation mechanisms, filtration or recirculation systems, and drain valves [45]. Such configurations allow processors to adjust parameters including solute concentration, immersion duration, and temperature depending on fruit maturity, variety, and final product specifications.

Semi-continuous and continuous systems represent the next level of technological integration. These systems use conveyor immersion tunnels, fluidized tanks, or rotary reactors to maintain consistent contact between mango slices and the osmotic solution while optimizing throughput. Automation features, including programmable logic control (PLC), inline temperature regulation, solute concentration monitoring, and automated dosing, enhance product uniformity and reduce labour requirements [46]. Continuous recirculation and filtration systems maintain solution consistency and reduce waste by enabling longer reuse cycles. For industrial processors operating at large scale, these features contribute to cost optimization and consistency in quality outcomes.

One of the key technical considerations during scale-up is

solution management. Since immersion-impregnation relies on osmotic solution stability, changes in solute concentration, microbial load, and viscosity over multiple production cycles must be carefully controlled. Industrial systems increasingly incorporate automated refractometers, pasteurizing loops, and dosing systems to maintain constant osmotic gradients. Heat-assisted regeneration or membrane filtration technologies (ultrafiltration or nanofiltration) may also be implemented to extend solution life and reduce operational costs [47].

Integration of immersion-impregnation into existing processing lines requires alignment with upstream and downstream operations. For example, pre-treatments including washing, peeling, slicing, and anti-browning dips must be designed to ensure uniformity of mass transfer during immersion. Downstream operations, particularly drying, packaging, and storage, must be compatible with modified moisture profiles and solute compositions resulting from impregnation. Convective drying systems, heat pump dryers, solar-hybrid systems, and freeze-drying units may all be used following immersion-impregnation, depending on the targeted product category. In many cases, immersion-impregnation reduces drying time and energy consumption, generating cost efficiencies and improving quality performance [48].

Economic feasibility plays a decisive role in industrial adoption. Initial investment varies depending on equipment capacity, automation level, and materials of construction [49]. Batch systems represent the lowest entry cost, making them suitable for small and medium-sized processors or enterprises in emerging agro-processing sectors [12]. While continuous systems offer higher throughput and labour efficiency, their installation may require greater capital and technical expertise. Operational costs depend primarily on energy consumption, labour, solute replenishment, and solution treatment needs. When combined with reductions in drying time and waste losses, immersion-impregnation can be financially advantageous, especially in regions with high seasonal surplus of fresh mango [12].

Industrial feasibility is also influenced by supply chain dynamics. In countries where mango seasonality is pronounced, the ability to stabilize and store processed mango provides significant value by extending production beyond the peak harvest window. This ability contributes to business continuity, reduces post-harvest losses, and supports export-oriented processing strategies. The technology also offers potential alignment with local manufacturing ecosystems, particularly where stainless steel fabrication, automation support, and industrial maintenance services are available.

Finally, regulatory and quality compliance impacts scale-up readiness. Depending on the intended market, immersion-impregnation operations may need to align with Good Manufacturing Practices (GMP), Hazard Analysis Critical Control Point (HACCP) systems, ISO 22000 food

safety management frameworks, or organic and fair-trade certification standards. Ensuring traceability of solute inputs, sanitation of equipment, and process monitoring throughout production is essential to meet safety and labelling regulations, particularly for international distribution.

In summary, immersion-impregnation dehydration is technically feasible at industrial scale and compatible with a range of production capacities and product formats. While economic considerations, equipment access, and operational expertise may influence deployment pace, technological versatility, energy efficiency, and potential for high-quality output position the method as a promising processing solution for mango-producing regions seeking to expand value-added production.

6. Limitations, Technical Challenges, and Knowledge Gaps

Despite significant progress in understanding and applying immersion-impregnation dehydration for mango processing, several limitations and knowledge gaps remain. These relate to variability in raw materials, process standardization, solute management, equipment availability, and long-term product stability. Addressing these challenges is essential to improving reproducibility, scalability, and industrial adoption.

One major limitation concerns variability in fruit properties. Mango cultivars differ widely in texture, sugar content, fibre structure, moisture levels, and ripening behaviour [50]. These differences influence diffusion kinetics, solute uptake, and final sensory attributes. Even within a single cultivar, ripeness stage has a strong effect on tissue permeability and behaviour during immersion, making it difficult to define universally applicable processing conditions. Standardizing raw material handling and establishing cultivar-specific process conditions remain areas requiring further research [51].

Another challenge involves optimizing solute uptake. While solute diffusion contributes to structural stability and sensory enhancement, excessive uptake may produce undesirably sweet products or alter the characteristic flavour of mango. Balancing water loss and solute gain is therefore critical. Although several studies have explored concentration-time relationships and alternative osmotic media, more work is needed to identify formulations that combine functional value, health considerations, and desirable sensory profiles.

Process control and sanitation also present operational challenges. Since immersion-impregnation requires a liquid food contact medium, maintaining microbial stability is essential, particularly during long production runs. Osmotic solutions can accumulate organic residues, microorganisms, or enzymatic activity over repeated use, affecting safety and product quality. The development of solution regeneration protocols, inline monitoring tools, and closed-loop management systems would help improve industrial reliability.

From an equipment standpoint, access to automated or semi-continuous systems remains limited in many mango-producing regions, especially among small and medium enterprises. Most processors rely on manually operated batch tanks with limited process control capabilities. While these systems are functional, they may lead to batch-to-batch variability, longer processing times, and reduced repeatability. Engineering developments focused on affordable, modular equipment adapted to local manufacturing capacity may help bridge this gap.

Another area requiring further investigation concerns the long-term stability of impregnated mango products. While immersion-impregnation reduces water activity and improves texture stability, few studies have explored extended storage under real commercial conditions. Variables such as solute crystallization, moisture migration, oxidation, and colour degradation require further evaluation to determine optimal packaging solutions and shelf-life performance [52].

Finally, environmental considerations remain insufficiently explored. Some osmotic solutions, especially those containing refined sugars or inorganic salts, may generate waste streams requiring treatment before disposal. The environmental footprint of large-scale immersion-impregnation processes has not yet been fully assessed, and strategies for solution recycling, ingredient valorisation, or use of natural solute sources could contribute to more sustainable processing models.

Overall, immersion-impregnation remains a promising technology for mango dehydration but requires continued research to address variability, process control, solute formulation, equipment access, and long-term product performance. Improvements in these areas will support its broader adoption across industrial contexts.

7. Future Perspectives and Industry Opportunities

Looking forward, immersion-impregnation dehydration presents significant opportunities for industrial growth in mango-processing markets, particularly in emerging economies where the fruit is abundant but post-harvest losses remain high. Several trends indicate the potential for broader commercial adoption and diversification of product lines using this technology.

One key opportunity lies in responding to the growing demand for value-added tropical fruit products in export markets. Semi-dried fruit snacks, functional ingredients, and flavoured fruit inclusions are expanding product categories in Europe, Asia, and North America, driven by interest in natural, minimally processed ingredients. Immersion-impregnation aligns well with this demand because it improves texture, maintains colour, and preserves nutritional qualities while allowing controlled sugar or functional ingredient delivery. Manufacturers can leverage the process to create differentiated products with added sensorial or nutritional value, in-

cluding premium snack lines or ready-to-mix ingredient solutions.

Another promising area is integration with hybrid drying systems to optimize energy and cost efficiency. As immersion-impregnation reduces initial moisture content, it shortens subsequent thermal drying times, improving overall process throughput. This can make technologies such as heat-pump drying, solar-hybrid systems, or dehumidified air dryers more economically viable, particularly in regions with high electricity costs or limited access to continuous power. For small and mid-scale processors, this can significantly reduce operational expenses and improve production continuity.

Industry developments also point toward opportunities in customized and flavoured fruit markets. By selectively modifying solutes during impregnation, companies can offer mango products with regionally relevant taste profiles, such as ginger, tamarind, chili, or hibiscus, creating niche or culturally aligned product lines. This capability supports diversification strategies for processors seeking competitive positioning in both domestic and international markets.

There is also potential for immersion-impregnation to support the functional food and nutraceutical sector. The process can be used to incorporate vitamins, minerals, prebiotics, probiotics, or plant bioactives into mango pieces, transforming them into delivery systems for health-focused formulations. As demand grows for foods with added nutritional or physiological benefits, impregnated mango could serve as a basis for fortified children's snacks, sports nutrition products, or therapeutic food applications.

Investment in technological platforms adapted to resource-limited environments represents another industry opportunity. Developing modular immersion systems with automated controls, solution regeneration capabilities, and adjustable capacity could accelerate adoption among small to medium-sized enterprises. Local fabrication of equipment, using stainless-steel expertise available in industrial workshops, would further reduce procurement costs and improve maintenance access.

Supply chain resilience offers an additional advantage. With mango production concentrated within a short harvesting window, processors require methods to maintain production beyond the fresh season. Immersion-impregnation supports this by stabilizing partially processed mango for intermediate storage, enabling year-round manufacturing. This approach increases capacity utilization, improves cost recovery, and supports predictable market supply, particularly for exporters.

Finally, the sector may benefit from the development of processing standards and certification pathways. Clear technical specifications, including optimal solute systems, processing conditions, sanitation standards, and packaging recommendations, would improve consistency and market confidence. Partnerships between research institutions, food safety agencies, and industry associations could accelerate this standardization and support market access, especially for

international distribution channels.

In summary, immersion-impregnation dehydration holds strong potential to support industrial innovation, economic value creation, and market expansion in mango processing. By enabling product diversification, technological efficiency, and alignment with emerging consumer preferences, it represents a strategic pathway for transforming fresh mango into competitive, shelf-stable, and high-value products across multiple commercial segments.

8. Conclusion

Immersion-impregnation dehydration has emerged as a promising enabling technology for improving mango processing efficiency and product quality. Its capacity to simultaneously remove water and introduce functional solutes offers a strategic advantage over traditional dehydration techniques, particularly when the objective is to preserve sensory integrity, reduce thermal degradation, and maintain nutritional value in processed mango products. Compared with conventional drying alone, immersion-impregnation allows partial dehydration prior to heat exposure, resulting in reduced drying times, lower energy consumption, and improved textural and structural outcomes. These process advantages are especially relevant for mango, a climacteric fruit characterized by high moisture content and sensitivity to thermal stress.

High-temperature drying is still widely used because it is inexpensive, easy to operate, and requires minimal technical infrastructure factors that are crucial in many mango producing regions. Despite quality losses, these methods allow processors to dry large quantities quickly without investing in advanced technologies. The adoption of optimized or hybrid methods remains limited by cost, lack of equipment, and limited technical knowledge. Therefore, traditional high-heat drying persists mainly due to accessibility rather than quality advantages.

Scientific progress over the past decade demonstrates significant advancements in understanding mass transfer behavior, optimizing formulation variables, and developing equipment systems tailored to the physical properties of mango tissue. Research has contributed to identifying optimal solute systems, refining process temperature and duration parameters, and demonstrating the benefits of enhanced diffusion approaches such as vacuum pulsing and ultrasound assistance. Comparative findings between continuous and intermittent immersion approaches highlight the importance of balancing water loss with controlled solute gain, ensuring desirable quality outcomes while avoiding excessive sweetness or structural collapse. These developments provide a foundation for wider industrial adoption.

Despite these advancements, several challenges remain before immersion-impregnation becomes a standard step in mango industrialization. Variability in fruit maturity, cultivar-dependent responses, solution stability, sanitation control,

and long-term product behavior are areas requiring further investigation. Moreover, the scalability of immersion-impregnation systems depends on equipment availability, affordability, and accessibility, particularly in emerging economies where mango is abundant but food processing infrastructure is still developing. Addressing these gaps through integrated applied research, design of modular equipment, and establishment of technical processing standards will be key to enabling broader industry uptake.

Looking forward, immersion-impregnation dehydration presents strong potential to support product innovation, expand value-added mango supply chains, and reduce post-harvest losses in mango-producing regions. Its alignment with global consumer trends, including functional foods, natural ingredient systems, and minimally processed fruit snacks, positions the technology as a relevant tool for modern food industry development. As research continues to refine scientific understanding and engineering practice, immersion-impregnation may play a central role in transforming fresh mango into high-value, shelf-stable products capable of competing in domestic and export markets, ultimately contributing to economic development and improved food system resilience.

Abbreviations

D2I	Immersion-Impregnation Dehydration
D3I	Intermittent Immersion-impregnation Dehydration
PLC	Programmable Logic Control
GMP	Good Manufacturing Practices
HACCP	Hazard Analysis Critical Control Point
ISO	International Organization for Standard

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Conflicts of Interest

The author declares no conflicts of interest.

References

- [1] E. A. Tesema, M. A. Delele, S. W. Fanta, F. B. Masrie, M. A. Workie, and E. A. Tsegaye, "Design, development, and performance evaluation of baffled solar mango slice dryer," *Case Stud. Therm. Eng.*, vol. 74, p. 106786, Oct. 2025, <https://doi.org/10.1016/j.csite.2025.106786>
- [2] M. A. Ullah, A. M. Kiloos, A. A. Aziz, and D. C. Joyce, "Impact of factors contributing to internal disorders of mango (*Mangifera indica* L.) fruit—A systematic literature review," *Sci. Hortic.*, vol. 331, p. 113150, May 2024, <https://doi.org/10.1016/j.scienta.2024.113150>
- [3] C. P. Lamilla, S. R. Vaudagna, S. M. Alzamora, M. Mozgovo, and A. Rodriguez, "Effect of the high-pressure assisted-infusion processing on nutritional and antioxidant properties of mango cubes," *Innov. Food Sci. Emerg. Technol.*, vol. 71, p. 102725, July 2021, <https://doi.org/10.1016/j.ifset.2021.102725>
- [4] M. Bekele, N. Satheesh, and S. J. a, "Screening of Ethiopian mango cultivars for suitability for preparing jam and determination of pectin, sugar, and acid effects on physico-chemical and sensory properties of mango jam," *Sci. Afr.*, vol. 7, p. e00277, Mar. 2020, <https://doi.org/10.1016/j.sciaf.2020.e00277>
- [5] D. Li *et al.*, "Role of maturity status on the quality and volatile properties of mango fruits dried by infrared radiation," *Food Biosci.*, vol. 52, p. 102497, Apr. 2023, <https://doi.org/10.1016/j.fbio.2023.102497>
- [6] S. Fongin, K. Kawai, N. Harnkarnsujarit, and Y. Hagura, "Effects of water and maltodextrin on the glass transition temperature of freeze-dried mango pulp and an empirical model to predict plasticizing effect of water on dried fruits," *J. Food Eng.*, vol. 210, pp. 91–97, Oct. 2017, <https://doi.org/10.1016/j.jfoodeng.2017.04.025>
- [7] L. Yao, L. Fan, and Z. Duan, "Effect of different pretreatments followed by hot-air and far-infrared drying on the bioactive compounds, physicochemical property and microstructure of mango slices," *Food Chem.*, vol. 305, p. 125477, Feb. 2020, <https://doi.org/10.1016/j.foodchem.2019.125477>
- [8] K. Zou, J. Teng, L. Huang, X. Dai, and B. Wei, "Effect of osmotic pretreatment on quality of mango chips by explosion puffing drying," *LWT - Food Sci. Technol.*, vol. 51, no. 1, pp. 253–259, Apr. 2013, <https://doi.org/10.1016/j.lwt.2012.11.005>
- [9] J. Jimenez-Hernandez *et al.*, "Osmotic dehydration of mango with impregnation of inulin and piquin-pepper oleoresin," *LWT - Food Sci. Technol.*, vol. 79, pp. 609–615, June 2017, <https://doi.org/10.1016/j.lwt.2016.11.016>
- [10] P. Labaky *et al.*, "Improving dried mango physicochemical properties using conventional hot-air drying coupled with a novel technology 'intensification of vaporization by decompression to the vacuum,'" *Innov. Food Sci. Emerg. Technol.*, vol. 95, p. 103739, July 2024, <https://doi.org/10.1016/j.ifset.2024.103739>

- [11] H. A. Makroo, P. K. Prabhakar, N. K. Rastogi, and B. Srivastava, "Characterization of mango puree based on total soluble solids and acid content: Effect on physico-chemical, rheological, thermal and ohmic heating behavior," *LWT*, vol. 103, pp. 316–324, Apr. 2019, <https://doi.org/10.1016/j.lwt.2019.01.003>
- [12] C. Tsopwo Zena and Y. Jiokap Nono, "Investigating intermittent immersion during osmotic dehydration of mango (*Mangifera indica* L. Moench). Part A: Determination of optimal conditions for mango (*Mangifera indica* L. Moench) dehydration impregnation by immersion (D2I) and intermittent immersion (D3I)," *Heliyon*, vol. 10, no. 16, p. e35808, Aug. 2024, <https://doi.org/10.1016/j.heliyon.2024.e35808>
- [13] A. Putranto and X. D. Chen, "An assessment on modeling drying processes: Equilibrium multiphase model and the spatial reaction engineering approach (S-REA)," *Chem. Eng. Res. Des.*, vol. 94, pp. 660–672, Feb. 2015, <https://doi.org/10.1016/j.cherd.2014.10.007>
- [14] A. C. Ribeiro, E. F. D. Januario, T. B. Vidovix, A. M. S. Vieira, E. da C. N. F. de A. Duarte, and R. Bergamasco, "Synthesis of a novel functionalized biosorbent from mango stone and its application in the pharmaceutical's removal from water and a synthetic mixture," *Chemosphere*, vol. 346, p. 140520, Jan. 2024, <https://doi.org/10.1016/j.chemosphere.2023.140520>
- [15] M. Maldonado and J. Gonzalez Pacheco, "Mathematical modelling of mass transfer phenomena for sucrose and lactitol molecules during osmotic dehydration of cherries," *Heliyon*, vol. 8, no. 1, p. e08788, Jan. 2022, <https://doi.org/10.1016/j.heliyon.2022.e08788>
- [16] N. Indrati, N. Phonsatta, P. Pounsombat, S. Khoomrung, P. Sumpavapol, and A. Panya, "Metabolic profiles alteration of Southern Thailand traditional sweet pickled mango during the production process," *Front. Nutr.*, vol. 9, Sept. 2022, <https://doi.org/10.3389/fnut.2022.934842>
- [17] J. P. dos Santos Neto, M. W. D. de Assis, I. P. Casagrande, L. C. Cunha Junior, and G. H. de Almeida Teixeira, "Determination of 'Palmer' mango maturity indices using portable near infrared (VIS-NIR) spectrometer," *Postharvest Biol. Technol.*, vol. 130, pp. 75–80, Aug. 2017, <https://doi.org/10.1016/j.postharvbio.2017.03.009>
- [18] I. Sulistyawati, R. Verkerk, V. Fogliano, and M. Dekker, "Modelling the kinetics of osmotic dehydration of mango: Optimizing process conditions and pre-treatment for health aspects," *J. Food Eng.*, vol. 280, p. 109985, Sept. 2020, <https://doi.org/10.1016/j.jfoodeng.2020.109985>
- [19] I. Ahmed, I. M. Qazi, and S. Jamal, "Developments in osmotic dehydration technique for the preservation of fruits and vegetables," *Innov. Food Sci. Emerg. Technol.*, vol. 34, pp. 29–43, Apr. 2016, <https://doi.org/10.1016/j.ifset.2016.01.003>
- [20] "Use of response surface methodology to optimise vacuum impregnation of β -carotene from *Daucus carota* in *Pachyrhizus erosus*," *Sustain. Food Technol.*, vol. 1, no. 3, pp. 404–414, June 2023, <https://doi.org/10.1039/d2fb00036a>
- [21] J. E. Gonzalez-Perez, O. Jimenez-Gonzalez, N. Ramírez-Corona, J. A. Guerrero-Beltrán, and A. López-Malo, "Vacuum impregnation on apples with grape juice concentrate: Effects of pressure, processing time, and juice concentration," *Innov. Food Sci. Emerg. Technol.*, vol. 77, p. 102981, May 2022, <https://doi.org/10.1016/j.ifset.2022.102981>
- [22] R. A. B. de Medeiros, E. V. da Silva Júnior, Z. M. P. Barros, J. H. F. da Silva, S. C. R. Brandão, and P. M. Azoubel, "Convective drying of mango enriched with phenolic compounds from grape residue flour under different impregnation methods," *Food Res. Int.*, vol. 158, p. 111539, Aug. 2022, <https://doi.org/10.1016/j.foodres.2022.111539>
- [23] I. Guiamba, L. Ahrne, M. A. M. Khan, and U. Svanberg, "Retention of β -carotene and vitamin C in dried mango osmotically pretreated with osmotic solutions containing calcium or ascorbic acid," *Food Bioprod. Process.*, vol. 98, pp. 320–326, Apr. 2016, <https://doi.org/10.1016/j.fbp.2016.02.010>
- [24] J.-H. Zhao et al., "Osmotic dehydration pretreatment for improving the quality attributes of frozen mango: effects of different osmotic solutes and concentrations on the samples," *Int. J. Food Sci. Technol.*, vol. 49, no. 4, pp. 960–968, Apr. 2014, <https://doi.org/10.1111/ijfs.12388>
- [25] M. Akbarian, N. Ghasemkhani, and F. Moayedi, "Osmotic dehydration of fruits in food industrial: A review," *Int. J. Biosci. IJB*, vol. 3, Dec. 2013, <https://doi.org/10.12692/ijb/4.1.42-57>
- [26] A. K. Yadav and S. V. Singh, "Osmotic dehydration of fruits and vegetables: a review," *J. Food Sci. Technol.*, vol. 51, no. 9, pp. 1654–1673, Sept. 2014, <https://doi.org/10.1007/s13197-012-0659-2>
- [27] A. V. S. Bernardino et al., "Effect of ultrasound on cell viability and storage of dehydrated jackfruit (*Artocarpus heterophyllus* Lam.) impregnated with *Lactobacillus casei*," *LWT*, vol. 139, p. 110790, Mar. 2021, <https://doi.org/10.1016/j.lwt.2020.110790>
- [28] S. Wangsomboonsiri et al., "Effects of vacuum impregnation and calcium compounds on preservation of the microstructure and quality of frozen Aloe vera (*Aloe barbadensis* Miller)," *J. Agric. Food Res.*, vol. 21, p. 101785, June 2025, <https://doi.org/10.1016/j.jafr.2025.101785>
- [29] S. Maldonado, E. Arnau, and M. A. Bertuzzi, "Effect of temperature and pretreatment on water diffusion during rehydration of dehydrated mangoes," *J. Food Eng.*, vol. 96, no. 3, pp. 333–341, Feb. 2010, <https://doi.org/10.1016/j.jfoodeng.2009.08.017>
- [30] S. Zhang, W. Jiao, C. Ni, G. Hao, M. Huang, and X. Bi, "Effect of pectin on the inactivation of mango polyphenol oxidase treated by high-intensity ultrasound," *LWT*, vol. 222, p. 117620, Apr. 2025, <https://doi.org/10.1016/j.lwt.2025.117620>
- [31] D. Castañeda-Valbuena, T. Ayora-Talavera, C. Lujan-Hidalgo, P. Alvarez-Gutierrez, N. Martínez-Galero, and R. Meza-Gordillo, "Ultrasound extraction conditions effect on antioxidant capacity of mango by-product extracts," *Food Bioprod. Process.*, vol. 127, pp. 212–224, May 2021, <https://doi.org/10.1016/j.fbp.2021.03.002>

- [32] F. R. Assis, L. G. G. Rodrigues, G. Tribuzi, P. G. de Souza, B. A. M. Carciofi, and J. B. Laurindo, "Fortified apple (*Malus spp.*, var. Fuji) snacks by vacuum impregnation of calcium lactate and convective drying," *LWT*, vol. 113, p. 108298, Oct. 2019, <https://doi.org/10.1016/j.lwt.2019.108298>
- [33] L. Yu *et al.*, "Effect of spatial distribution of water on rock mechanical properties and characterization of water diffusion," *Constr. Build. Mater.*, vol. 470, p. 140551, Apr. 2025, <https://doi.org/10.1016/j.conbuildmat.2025.140551>
- [34] R. Oliver-Simancas, L. Labrador-Fernandez, M. C. D í az-Maroto, M. S. Perez-Coello, and M. E. Alañón, "Comprehensive research on mango by-products applications in food industry," *Trends Food Sci. Technol.*, vol. 118, pp. 179–188, Dec. 2021, <https://doi.org/10.1016/j.tifs.2021.09.024>
- [35] A. C. Duran-Castaneda, S. Gonzalez-Moya, J. A. Sanchez-Burgos, S. G. Sayago-Ayerdi, and V. M. Zamora-Gasga, "Applications of vacuum impregnation as a technology to incorporate functional components in vegetal matrices," *Food Chem. Adv.*, vol. 4, p. 100579, June 2024, <https://doi.org/10.1016/j.focha.2023.100579>
- [36] B. Tovar, E. Montalvo, B. M. Damian, H. S. Garcia, and M. Mata, "Application of vacuum and exogenous ethylene on Ataulfo mango ripening," *LWT - Food Sci. Technol.*, vol. 44, no. 10, pp. 2040–2046, Dec. 2011, <https://doi.org/10.1016/j.lwt.2011.06.005>
- [37] M. Aguirre-García, P. Hernandez-Carranza, O. Cortes-Zavaleta, H. Ruiz-Espinosa, C. E. Ochoa-Velasco, and I. I. Ruiz-López, "Mass transfer analysis of bioactive compounds in apple wedges impregnated with beetroot juice: A 3D modelling approach," *J. Food Eng.*, vol. 282, p. 110003, Oct. 2020, <https://doi.org/10.1016/j.jfoodeng.2020.110003>
- [38] "Present and Future in Process Control and Optimization of Osmotic Dehydration: From Unit Operation to Innovative Combined Process: An Overview," vol. 48, pp. 173–238, Jan. 2004, [https://doi.org/10.1016/S1043-4526\(04\)48004-8](https://doi.org/10.1016/S1043-4526(04)48004-8)
- [39] J. Floury, A. Le Bail, and Q. T. Pham, "A three-dimensional numerical simulation of the osmotic dehydration of mango and effect of freezing on the mass transfer rates," *J. Food Eng.*, vol. 85, no. 1, pp. 1–11, Mar. 2008, <https://doi.org/10.1016/j.jfoodeng.2007.06.011>
- [40] M. Zhong, Y. Miao, Y. Lan, Q. Ma, K. Li, and W. Chen, "Effects of *Exidia yadongensis* polysaccharide as emulsifier on the stability, aroma, and antioxidant activities of fat-free stirred mango buffalo yogurt," *Int. J. Biol. Macromol.*, vol. 276, p. 133785, Sept. 2024, <https://doi.org/10.1016/j.ijbiomac.2024.133785>
- [41] E. de Oliveira Alves Sena *et al.*, "Calcium application via hydrocooling and edible coating for the conservation and quality of cashew apples," *Sci. Hortic.*, vol. 256, p. 108531, Oct. 2019, <https://doi.org/10.1016/j.scienta.2019.05.058>
- [42] S. Liu *et al.*, "Changes in volatile and nutrient components of mango juice by different Lactic acid bacteria fermentation," *Food Biosci.*, vol. 56, p. 103141, Dec. 2023, <https://doi.org/10.1016/j.fbio.2023.103141>
- [43] V. Khobragade, S. Pareek, H. Sati, P. C. Badgujar, A. K. Goswami, and D. Kamil, "Exogenous melatonin preserves mango fruit quality and reduces anthracnose disease progression by enhancing antioxidative defense mechanisms," *Plant Stress*, vol. 18, p. 101126, Dec. 2025, <https://doi.org/10.1016/j.stress.2025.101126>
- [44] A. Shukla, R. S. Shukla, C. Das, and V. V. Goud, "Gingerols infusion and multi-step process optimization for enhancement of color, sensory and functional profiles of candied mango," *Food Chem.*, vol. 300, p. 125195, Dec. 2019, <https://doi.org/10.1016/j.foodchem.2019.125195>
- [45] M. T. Fernandez-Ponce *et al.*, "Development of functionalized alginate dressing with mango polyphenols by supercritical technique to be employed as an antidiabetic transdermal system," *J. Supercrit. Fluids*, vol. 175, p. 105274, Sept. 2021, <https://doi.org/10.1016/j.supflu.2021.105274>
- [46] J. Banerjee, R. Singh, R. Vijayaraghavan, D. MacFarlane, A. F. Patti, and A. Arora, "Bioactives from fruit processing wastes: Green approaches to valuable chemicals," *Food Chem.*, vol. 225, pp. 10–22, June 2017, <https://doi.org/10.1016/j.foodchem.2016.12.093>
- [47] W. Wang *et al.*, "Preparation of sodium alginate/sodium carboxymethyl cellulose composite coating film and evaluation of its effects on mango preservation," *Food Chem.*, vol. 495, p. 146611, Dec. 2025, <https://doi.org/10.1016/j.foodchem.2025.146611>
- [48] L. R. Amado, K. de S. Silva, and M. A. Mauro, "Drying of mangoes (*Mangifera indica* L. cv. Palmer) at changeable temperature conditions—Effects on energy consumption and quality of the dehydrated fruit," *J. Food Process Eng.*, vol. 44, no. 2, p. e13615, 2021, <https://doi.org/10.1111/jfpe.13615>
- [49] P. R. Fernandez, R. H. Mascheroni, and L. A. Ramallo, "Ascorbic acid and calcium uptake in pineapple tissue through different sucrose concentrations of impregnation solution," *J. Food Eng.*, vol. 261, pp. 150–157, Nov. 2019, <https://doi.org/10.1016/j.jfoodeng.2019.06.012>
- [50] R. A. Batista de Medeiros *et al.*, "Effect of different grape residues polyphenols impregnation techniques in mango," *J. Food Eng.*, vol. 262, pp. 1–8, Dec. 2019, <https://doi.org/10.1016/j.jfoodeng.2019.05.011>
- [51] L. C. López and G. A. Hincapié-Llanos, "Comparison of Mango (*Mangifera indica*) Dehydration Technologies: A Systematic Review," *AgriEngineering*, vol. 6, no. 3, pp. 2694–2717, Aug. 2024, <https://doi.org/10.3390/agriengineering6030157>
- [52] A. G. Parente, W. da S. Soares, H. P. de Oliveira, S. T. de Freitas, and D. F. de M. Neri, "Polymers and mango (*Mangifera indica* L.): a systematic literature review on potential value and application," *J. Food Meas. Charact.*, vol. 18, no. 1, pp. 168–183, Jan. 2024, <https://doi.org/10.1007/s11694-023-02128-8>

Biography



Abdoulaye Tamba is a senior food scientist and specialist in agro-food processing technologies. He earned his PhD in Agro-food Process Engineering from Cheikh Anta Diop University (Dakar, Senegal), following a Master's degree in Food Technology and a Bachelor's degree in Food Science. His research focuses on post-harvest technology, food dehydration processes, food quality and safety, and the valorization of local agricultural resources such as mango, cactus pear. He has contributed to several scientific and technical initiatives aimed at improving food processing practices in West Africa, notably through innovation in drying processes, process optimization, and tech-

nology transfer for SMEs. He currently serves as Senior Technological Referent and Operational Lead for the youth insertion and industrial support program implemented by GINDI (www.gindi.sn), where he works closely with food industries, academic institutions, and development partners to strengthen technical capacity, promote innovation, and support industrial transformation in the agro-food sector.

Research Field

Abdoulaye Tamba: Food Process Engineering; Post-Harvest Technology; Preservation of Tropical Fruits; Food Quality; Agro-Industrial Innovation and SME Technology Transfe.