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A comprehensive review of tamarind processing machinery, technologies: Performance and future direction

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Abstract

This review critically examines the current state of tamarind (*Tamarindus indica* L.) processing machinery, assessing performance parameters and identifying future directions for technological development. Tamarind processing remains constrained by reliance on manual methods that are inefficient, labor-intensive, and inconsistent. Mechanized systems have been developed for dehulling, deseeding, pulp extraction, and byproduct utilization, offering significant improvements in efficiency and product quality compared with traditional practices. Reported performance levels, such as dehulling efficiencies exceeding 80 percent, demonstrate progress, yet challenges remain in achieving comparable results for deseeding and pulp recovery. Emerging innovations in machinery design increasingly emphasize automation, smart sensors, and precision control. The integration of artificial intelligence, Internet of Things, and machine learning has the potential to transform tamarind processing by enabling real-time monitoring, predictive maintenance, and process optimization. Such technologies can improve consistency, maximize bioactive retention, and enhance overall value addition. The review also considers market trends and economic viability. With global demand for tamarind extracts projected to rise steadily, investment in advanced processing technologies is both necessary and profitable. Incorporating circular economy principles and energy-efficient methods will be essential for sustainable industry growth. By synthesizing existing technologies, optimization studies, and future prospects, this review provides a framework for researchers, manufacturers, and policymakers. Advancing tamarind processing machinery toward automated, efficient, and sustainable systems will strengthen competitiveness, support rural development, and ensure full utilization of tamarind resources.

Keywords: Tamarind, processing machinery, dehulling, deseeding, tamarind by-product

1. Introduction

Tamarind (*Tamarindus indica* L.) holds a prominent place in tropical countries, especially India, due to its extensive use as both a fruit and spice. It is consumed in various culinary forms ranging from raw fruit ingestion to incorporation in condiments, beverages, and traditional medicines (Bhadoriya *et al.*, 2011; Bhadoriya *et al.*, 2017; Bonin *et al.*, 2023; De Caluwé *et al.*, 2010) [12, 11, 18, 22]. Tamarind is a rich source of nutrients and bioactive compounds that offer numerous health benefits, including antioxidant, antibacterial, antidiabetic, and antivenomic activities. Tamarind pulp, which constitutes a substantial portion of the fruit, contains essential amino acids and phytochemicals that contribute to these properties (Bonin *et al.*, 2023; De Caluwé *et al.*, 2010; Muzaffar & Kumar, 2015) [18, 22, 57]. These characteristics not only endow tamarind with significant nutritional value but also highlight its therapeutic potential and economic importance in regions where it is widely cultivated and consumed. The broad consumption patterns combined with these bioactive properties underpin tamarind's critical role both in nutrition and traditional healthcare, thereby necessitating enhanced focus on optimized processing technologies to fully leverage these benefits. Tamarind (*Tamarindus indica* L.) is a tropical fruit tree belonging to the Fabaceae family, widely cultivated in Asia, Africa, and South America (Shao *et al.*, 2019) [75]. India stands as the world's largest producer and exporter of tamarind, with an annual production of approximately 300,000 tons (Nagar *et al.*, 2022; Toscano

Oviedo *et al.*, 2024; Vasanthkumar *et al.*, 2023) [58, 82, 85]. The fruit consists of 30-50% pulp, 11-30% shell fiber, and 25-40% seeds (Geethalaxmi *et al.*, 2024) [31]. Processing tamarind into value-added products such as pulp, concentrate, powder, and various food products require sufficient mechanization to meet growing global demand. Traditional tamarind processing involves labor-intensive manual operations including dehulling, deseeding, pulp extraction, and cleaning. These methods are characterized by low efficiency, poor hygiene standards, high labor costs, and inconsistent product quality (Kumar & Bhattacharya, 2008; Nagar *et al.*, 2022; Bidyalakshmi *et al.*, 2023) [44, 58, 17]. The global tamarind extract market, valued at USD 1,456.26 million in 2024, is projected to reach USD2,511.18 million by 2034, growing at a CAGR of 5.60%, creating substantial opportunities for advanced processing technologies (Bharathi, *et al.*, 2022; Zion Market Research, 2025; EIN Presswire, 2025) [13, 92, 26].

This review aims to systematically analyze the current landscape of tamarind processing machinery technologies, evaluating their performance metrics and identifying trajectories for future enhancement. By examining the engineering, mechanical, and automation aspects of tamarind processing equipment, this paper seeks to provide comprehensive insights into existing systems and emerging technological trends. This review underscores the necessity of embracing digital and intelligent innovations in tamarind processing machinery. The dual goals encompass improving operational efficiencies and ensuring sustainability, aligning with global trends towards green and smart agricultural systems.

2. Overview of tamarind processing operations

Tamarind processing involves several critical post-harvest operations aimed at transforming raw fruit into shelf-stable and value-added products, thereby enhancing quality, reducing losses, and increasing economic returns. The process begins with harvesting mature tamarind fruits, identified by their brittle shells and a hollow sound when pressed (Verma *et al.*, 2024; Sudha *et al.*, 2022) [87, 79]. Following harvest, initial handling includes thorough cleaning and sorting to remove any debris or damaged pods (Verma *et al.*, 2024) [87]. The primary unit operations in tamarind processing are crucial for preparing the pulp. Drying is an essential step that reduces moisture content, which facilitates easier deseeding and significantly extends the product's shelf life. While traditional sun drying is common, mechanical drying methods, such as using tray dryers, are increasingly employed for improved hygiene and efficiency (Bidyalakshmi *et al.*, 2023; Rajkumar *et al.*, 2023; Verma *et al.*, 2024) [17, 67, 87]. After drying, dehulling and defibering are performed to remove the outer shell and fibers, often done manually or with specialized mechanical dehullers. Deseeding is another vital step where seeds are separated from the pulp. This process can be mechanized to significantly improve efficiency and reduce labor requirements (Bidyalakshmi *et al.*, 2023; Sudha *et al.*, 2022; Rajkumar *et al.*, 2023) [17, 79, 67]. Finally, the processed pulp is pressed into cakes or blocks and stored under controlled conditions to maintain its quality over time (Sudha *et al.*, 2022; Marichamy *et al.*, 2024) [79, 51].

Value addition is a key aspect of tamarind processing, leading to a diverse range of products. The processed tamarind pulp is utilized to create various food items, including juice concentrate, pulp powder, pickles, jams, syrups, candies, and chutneys (Bidyalakshmi *et al.*, 2023; Vikram *et al.*, 2023; Tiwari & Tomar, 2024) [17, 89, 81]. Beyond the pulp, by-products also hold significant value. Tamarind seeds, for instance, are processed

into kernel powder, mucilage, and other industrial products (Nagar *et al.*, 2022; Kumar & Bhattacharya, 2008; Israel & Murthy, 2019; Silverio *et al.*, 2025) [58, 44, 36-37, 77]. Even the shell and fibers find utility as fuel or absorbents in various applications (Arudra, 2015; Mansingh *et al.*, 2021) [7, 50].

Technological advancements and mechanization have greatly improved the efficiency and quality of tamarind processing. The development of mechanical dehullers and deseeders has achieved efficiencies of up to 94% and 83% respectively, leading to substantial reductions in manual labor and product losses (Sudha *et al.*, 2022; Bidyalakshmi *et al.*, 2023) [79, 17]. Furthermore, advanced drying techniques and optimized spray drying parameters contribute to enhanced product quality and increased process yield (Muzaffar & Kumar, 2015; Rajkumar *et al.*, 2023) [57, 67]. Improved storage methods, such as the use of aluminum foil and refrigeration, are also crucial for extending the shelf life and maintaining the quality of tamarind pulp (Marichamy *et al.*, 2024) [51].

The entire value chain of tamarind processing has a significant economic impact. By increasing shelf life and reducing post-harvest losses, processing and value addition contribute to higher incomes for both producers and processors (Bidyalakshmi *et al.*, 2023; Bhavana, A. *et al.*, 2023; Tiwari & Tomar, 2024) [17, 16, 81]. Moreover, initiatives involving training and technology dissemination play a vital role in empowering small-scale producers, particularly women, to actively participate in and benefit from value-added tamarind enterprises (Bhavana, A. *et al.*, 2023; Tiwari & Tomar, 2024) [16, 81].

3. Engineering properties of tamarind relevant to machinery design

3.1 Physical and mechanical properties

The physical and mechanical properties of tamarind (pulp, seed, shell) is essential for designing effective processing machinery. Key parameters include moisture content, size distribution, geometric dimensions (length, width, thickness), and weight distribution. These properties provide crucial insights for resolving challenges in drying, dehulling, deseeding, and other post-harvest operations. For instance, moisture content affects drying kinetics and energy requirements, while dimensional properties influence the capacity and precision of dehulling and deseeding mechanisms. Variations in seed hardness and shape require tailored deseeder designs to minimize pulp damage while maximizing throughput. This multidimensional characterization is essential for ensuring that machines operate efficiently and produce high-quality outputs, facilitating mechanization and reducing manual labor dependence (Verma *et al.*, 2024; Karpoora & Pandian, 2013; Bhattacharya *et al.*, 1993) [87, 41, 44]. mechanical characteristics directly influence the design of post-harvest machinery, as understanding physical engineering properties like moisture content, size, and weight is essential for developing dehulling and deseeding equipment (Bidyalakshmi *et al.*, 2023) [17]. The mechanical properties also determine susceptibility to damage during harvest, transportation, and storage, affecting commercial value (Verma *et al.*, 2025) [86]. tamarind's frictional and mechanical properties reveals significant insights for engineering applications. The coefficient of static friction for tamarind seeds varies by surface material, with plywood showing the highest friction, followed by cast iron and stainless steel surfaces (Mohite *et al.*, 2019) [56]. Similarly, velvet tamarind fruits and seeds demonstrated the lowest coefficient of static friction on stainless steel, making it the recommended construction material for processing equipment (Davies & Yusuf, 2017) [21]. These engineering

properties are essential for designing post-harvest machinery including dehullers, deseeders, and processing equipment (Bidyalakshmi *et al.*, 2023) ^[17].

3.2 Chemical composition and its impact on processing

The chemical constitution of tamarind pulp, dominated by reducing sugars, pectins, fibers, and cellulose, directly influences processing modalities such as extraction, drying, and preservation (Adeola & Aworh, 2012; Sulieman *et al.*, 2015) ^[5, 80]. The high sugar content enhances the energy density of processed products but necessitates careful drying to avoid caramelization or microbial spoilage. Tamarind seed polysaccharides demonstrate superior gel-forming abilities compared to commercial pectin, forming gels over a wide pH range with or without acid and base, while commercial pectin requires narrow acidic conditions (Mohamed Ha *et al.*, 2015) ^[55]. Quality-by-design extraction approaches have successfully isolated rhamnogalacturonan pectin from tamarind pulp with significant antioxidant activity exceeding commercial pectins (Sharma *et al.*, 2015) ^[76]. Optimization studies achieved 60% pectin yield from tamarind pulp at 100 °C for 15 minutes, producing hydrogels with 300 cP viscosity suitable for various applications (Abubakar *et al.*, 2024) ^[3]. Pectins are valuable for gelling and thickening functions in value-added products like jams and chutneys, thereby dictating the requirement for precise concentration controls during processing. Fiber and cellulose contribute to the physical texture and uphold the structural integrity of the final product (Bidyalakshmi *et al.*, 2023) ^[17]. Additionally, the biochemical composition drives the selection of extraction technologies to preserve bioactives such as phenolic compounds, thus ensuring functional properties are retained post-processing. Furthermore, knowledge of the chemical makeup aids in selecting appropriate packaging and storage conditions to maintain quality during shelf life (Verma *et al.*, 2024; Karpooora & Pandian, 2013; Ferreira *et al.*, 2019) ^[87, 41, 30]. This relationship between chemical properties and machinery design underscores a critical nexus, where food science and engineering converge to optimize process outcomes.

3.3 Challenges in handling tamarind byproducts

Tamarind shell and seed residues represent significant byproducts with underexploited potential and processing challenges. Tamarind processing generates substantial shell and

seed residues, constituting up to 70% of the pod weight, which are often underutilized despite their potential for value addition (Arudra, 2015; C. Nagar *et al.*, 2022) ^[7, 58]. The shell contains tannins that have shown promise as natural rust converters and environmentally friendly industrial chemicals, indicating a valuable secondary application beyond mere waste (Abdulmajid *et al.*, 2019) ^[2]. From a circular economy perspective, valorization of these byproducts is essential to reduce waste generation, improve environmental sustainability, and add economic value. However, the heterogeneity and recalcitrant nature of such lignocellulosic biomass present technical challenges in processing, including effective size reduction, extraction, and stabilization of bioactive compounds (Mansingh *et al.*, 2021) ^[50]. Advanced processing strategies and machinery capable of handling these byproducts are crucial to unlock their full potential, transforming residues into bio-based materials, antioxidants, or industrial inputs. This approach aligns with sustainable waste management and integrates agricultural residues into biorefinery frameworks, thus enhancing overall resource efficiency in tamarind processing (Nagar *et al.*, 2022) ^[58].

4. Current tamarind processing machinery technologies

Modern tamarind processing leverages a range of mechanical technologies to improve efficiency, product quality, and reduce labor compared to traditional manual methods.

Dehulling

Mechanical dehullers and deseeders are widely used to automate the removal of tamarind shells and seeds. Recent innovations include centrifugal impact peelers, which use mechanical force to break and separate the tamarind shell from the pulp. Such machines can process up to 180 kg/hour, greatly increasing throughput and reducing the time and effort required compared to manual peeling (Maubila *et al.*, 2023) ^[53]. These machines significantly reduce manual labor and post-harvest losses, and are crucial for preparing tamarind for further processing or value addition (Bidyalakshmi *et al.*, 2023; Sudha *et al.*, 2022) ^[17, 79]. Different types of tamarind dehulling and deseeding machines have been developed with varying efficiencies. Impact-type dehullers, such as the one designed at Tamil Nadu Agricultural University, use rotating beaters. Oscillating-type dehullers work on reciprocating motion.

Table 1: Tamarind processing technology and machinery

Machine type	Capacity	Operating condition	Principle of working	Efficiency	Key findings	References
Tamarind dehuller-cum-deseeder (Amit Kumar Sinha <i>et al.</i>) ^[78]	239.97-251.94 kg/h (dehulling); 48.6-52.02 kg/h (deseeding)	Ring clearance: 3-5 cm; machine clearance: 3-4 mm; feed rate: 1.5-5 kg/min	Impact force and clearance adjustment for shell cracking and seed separation	Dehulling: optimum at 4 cm clearance and 5 kg/min; Deseeding: optimum at 3.5 mm clearance and 1.5 kg/min	Sun drying increased dehulling output due to brittle shells. Optimal clearances balanced output and reduced damage.	Sinha, A. K., Patel, S., & Verma, A. (2011). Performance evaluation studies on tamarind dehuller-cum-deseeder. <i>Journal of Plant Development Sciences</i> , 3(3-4), 269-274.
Impact and shear type tamarind deseeder (Karpooora Sundara Pandian <i>et al.</i>) ^[62]	Not specified	Moisture: 22-25% d.b.; rotor speeds: 1.1-1.6 m/s; sieve types varied	Combined impact load and shear force using studs on rotor with sieve	High deseeding efficiency influenced more by rotor speed and sieve type than moisture	Mechanical parameters had greater impact on efficiency than small variations in fruit moisture.	Pandian, K. S., Rajkumar, P., & Visvanathan, R. (2017). Development and evaluation of impact and shear type tamarind deseeder. <i>Agricultural Mechanization in Asia, Africa, and Latin America</i> , 48(3), 53-58.
Tamarind cover	Not specified	Cover rotor: 300	Two-stage: cover	Cover removal	Sequential modular	Sahu, A. R., & Gulhane, U. D.

and seed separation machine (Anil R. Sahu & U.D. Gulhane) ^[70]		rpm; blower: 1400 rpm; seed rotor: 450 rpm	removal by impact; seed removal by agitation in water	90%; seed removal 75%	approach worked better than single combined mechanism.	(2015). Design and fabrication of tamarind cover and seed separation machine. NaCoMM, 391-395.
Automatic tamarind deseeding machine (Maji Enterprise, Nor Zaiazmin Yahya <i>et al.</i>) ^[91]	100 kg per batch (~250 kg performance)	Minimal water use (5-10%); stainless steel SS304/316; 240V, 13A	Mechanical deseeding with automated system	High separation efficiency (exact % not reported)	Industrial-grade design focused on hygiene, low water use, and commercial readiness.	Yahya, N. Z., Ishak, M. S. A., Omar, M. N., & Alir, K. (2021). Design and fabrication of automatic tamarind deseeding machine. Penerbit Universiti Malaysia Perlis. Technical report
Tamarind dehuller-cum-deseeder (S. K. Pandey) ^[61]	232.34 kg/h (dehulling); 2 kg/h (deseeding)	Ring clearance: 3.5 cm; feed rate: 5 kg/min	Impact and shear via rotating drum with clearance adjustment	Dehulling efficiency 77.45%; deseeding efficiency 52.42% with 8.67% damage	Feed rate influenced output more than clearance. Dried tamarind (24.7% d.b.) required to prevent stickiness.	Pandey, S. K. (2018). Performance evaluation of tamarind dehuller cum deseeder. Agricultural Engineering Today, 42(1), 52-55.
Tamarind seed removal machine (R. Karthikeyan <i>et al.</i>) ^[43]	9 kg/h	Moisture: 6.5-8% d.b.; cutter speed: 2800 rpm; 12V, 4A DC motor	Pulley-driven knife cutting system	80% average efficiency	Suitable for small-scale use; lower moisture improved seed removal.	Karthikeyan, R., Nirmal, B. E., Pravin Kumar, M., & Pavithran, N. K. (2019). Design and fabrication of tamarind seed removal machine. International Journal of Scientific & Technology Research, 8(12), 743-747.
Tamarind powdering machine (ERIMU IVAN) ^[38]	0.8 kg/h	Inter-plate clearance: 5 mm; feed: dried pulp at 3.5-8.8% moisture	Manual grinding with rotating plates	Grinding efficiency 55.6% for 1,000-2,000 µm product	Produced shelf-stable tamarind powder at low cost; pre-drying critical.	Ivan, E. (2018). Design and fabrication of a manual tamarind powdering machine [Undergraduate project report, Busitema University]. Faculty of Engineering, Department of Chemical and Processing Engineering.
Tamarind cover and seed separation machine (A. R. Lende & P. A. Chandak) ^[46]	10 kg/h	Power requirement 1.202 HP; includes cover breaker, separator, seed remover	Modified groundnut stripper, exhaust fan, toothed blade cutter	Cover removal 90%; seed removal 20-25%	Highlighted difficulty of seed removal compared to cover separation.	Lende, A. R., & Chandak, P. A. (2012). Design and fabrication of tamarind cover and seed separation machine. International Journal of Engineering and Innovative Technology, 1(2), 154-160.
Tamarind seed removal machine (Arihant Satpute <i>et al.</i>)	10 kg/h	Low-RPM grooved discs; high-speed cutter blade; ANSYS stress analysis	Shearing pulp with tapered discs and cutting blades	Cover removal successful; seed removal partial	Safe design validated by FEA; scope for improving seed removal.	Satpute, A., Patil, P., Kulkarni, M., & More, R. (2022). Design and fabrication of tamarind seed removal machine. International Research Journal of Engineering and Technology, 9(6), 1160-1165.
Continuous type tamarind deseeder (Paramasivan Karthickumar <i>et al.</i>) ^[42]	75 kg/h	Roller speed: 3.4 m/s; feed rate: 45 kg/h; clearance: 16 mm; 22.5% d.b. moisture	Wooden roller pegs apply impact and shear with sieve separation	89.15% deseeding efficiency	Saved 93.34% time and 74.9% cost compared to manual. Efficiency dropped at high feed/speed.	Karthickumar, P., Pandian, N. K. S., Rajkumar, P., Surendrakumar, A., & Balakrishnan, M. (2015). Development and evaluation of a continuous type tamarind deseeder. Agricultural Engineering, 40(2), 49-59.
Manual tamarind seed separation machine (B V Hemanth <i>et al.</i>) ^[33]	3.14 kg/h	Wooden pulley, cutting knife, ergonomic handle	Manual cutting and pulping with pulley-driven knife	65% efficiency	Low-cost domestic design reduced drudgery and risk of injury.	Hemanth, B. V., Mallikarjuna, V. R., Rao, A. S., & Ramana, M. V. (2016). Design and fabrication of manual operated tamarind (<i>Tamarindus indica</i> L.) seed separation machine. Indian Horticulture Journal, 6(1), 77-79.
Tamarind sauce	Industrial scale	Multi-stage	Manual cracking,	Pulp recovery	Demonstrated	Indian Institute of Food Processing

processing DPR (IIFPT) ^[35]	(not specified)	pulping: 6 mm → 2 mm → 1 mm sieve; soaking at 55°C, cooking to 25° Brix	soaking, pulping, cooking	55%; BCR 1.92	economic viability and multi-stage mechanization for sauce.	Technology. (2015). PM formalization of micro food processing enterprises scheme (pp. 1-39). Ministry of Food Processing Industries, Government of India. http://www.iifpt.edu.in
Power operated tamarind huller-cum-deseeder (Jansi Sheeba Rani <i>et al.</i>) ^[69]	85 kg/h	Drum speed: 300 rpm; clearance: 8 mm; moisture: 19% d.b.; 0.75 kW motor	Rotating drum with pegs and concave sieve	Hulling efficiency 89.09%; deseeding efficiency 89.91%	Compact, cost-effective machine reduced cost by 87% and time by 95%.	Rani, J. S., Rajkumar, P., & Kailappan, R. (2016). Design and development of a power operated tamarind huller cum deseeder. <i>Agricultural Mechanization in Asia, Africa, and Latin America</i> , 47(3), 41-46.
Power operated tamarind seed expeller ^[32]	23.24 kg/h (straight fruits); 22.83 kg/h (curved fruits); 20.86 kg/h (mixed fruits)	Moisture: 16.5%; roller clearance: 4.5 mm; shaft speed: 200 rpm; motor: 0.5 HP single phase	Oppositely rotating rollers, one serrated and one with helical rings, expelling seeds by compression and shear	Highest expulsion rate at 16.5% moisture with straight fruits; less pulp and seed damage	Power operated expeller was more efficient and economical than manual or traditional methods. Cost of operation was Rs. 1.55/kg, compared to Rs. 2.94/kg (manual) and Rs. 7.38/kg (traditional).	Goud, V. K., Udhayakumar, R., Kumar, G. V. M., & Venkatachalapathy, K. (2016). Development and performance evaluation of a tamarind seed expeller. <i>International Journal of Tropical Agriculture</i> , 34(6), 1635-1641.

Deseeding

Deseeding is one of the most critical and labor-intensive steps in tamarind processing, given the high seed content in the fruit. Manual deseeding is time-consuming, labor-intensive, and inconsistent in quality, leading to residual seed fragments and pulp damage (Karthickumar *et al.* 2015) ^[42]. Mechanized deseeding technologies have emerged as vital tools to enhance efficiency and product quality. State-of-the-art deseeder use a combination of mechanical forces such as swinging, rotating, or vibrating motions along with designed sieves to separate seeds from pulp cleanly. Various extraction methods have been studied, with hot enzymatic extraction yielding the highest pulp recovery at 92.4% using 0.5% enzyme concentration (Joshi *et al.*, 2012) ^[40].

Drying technologies

Drying is a critical step to reduce moisture content and facilitate further processing. While sun drying remains common, mechanical dryers such as belt conveyor type dryers, tray dryer, tunnel dryer have been developed. These allow for controlled drying conditions (e.g., temperature, airflow, feed rate), resulting in consistent moisture reduction and improved product quality. Optimized belt dryers can reduce tamarind moisture from 19% to 11.35% (dry basis) efficiently (Sudha *et al.*, 2022 Bidyalakshmi *et al.*, 2023) ^[79, 17].

Sorting and grading

Machine vision systems have been developed for sorting tamarind pods by shape, size, and defects using image processing. These systems achieve high sorting efficiencies (up to 94.3%) and meet export standards, supporting large-scale commercial operations (Jarimopas & Jaisin, 2008) ^[39]. The automated approach aims to improve processing speed, consistency, and accuracy compared to traditional manual methods (Nandi *et al.*, 2012) ^[59]. A comprehensive review of automated sorting and grading systems demonstrates their importance for maintaining fruit quality and reducing labor requirements, particularly for countries dependent on fruit exports (Abbas *et al.*, 2019; Jarimopas & Jaisin, 2008) ^[1, 39].

Pressing and storage technologies

Tamarind processing involves several key unit operations, with pressing being a crucial step for extracting pulp and juice concentrate for value-added products (Bidyalakshmi *et al.*, 2023) ^[17]. Mechanical pressing, typically involving hydraulic or screw presses, is preferred for its efficiency and ease of operation (Benero *et al.*, 1972) ^[10]. Design considerations for presses focus on achieving maximum extraction yield while preserving the integrity of bioactive compounds and preventing contamination (Donn *et al.*, 2024) ^[25]. Various extraction techniques have been developed to isolate tamarind's bioactive constituents, including solvent extraction, Supercritical Fluid Extraction (SFE), and Microwave-Assisted Extraction (MAE) (Herzyk *et al.*, 2024; Wal *et al.*, 2024) ^[34, 90]. Storage is another vital component, where technological innovations impact shelf life and product safety. Proper storage conditions include controlled temperature, humidity, and packaging environments to inhibit microbial growth and oxidative degradation (Marichamy *et al.*, 2024; Udhayakumar *et al.*, 2024) ^[51, 83]. Innovative storage machinery and protocols, such as vacuum packing and cold storage, have been explored to extend the shelf life of tamarind products and ensure consistent quality during distribution (Septiana *et al.*, 2018; Vasanthkumar *et al.*, 2023) ^[73, 85]. The combination of optimized pressing and storage machinery is instrumental in delivering value-added tamarind products to markets.

5. Advanced and emerging tamarind processing technology

In recent years, tamarind processing has undergone remarkable advancements, moving away from traditional practices such as sun drying and manual deseeding toward more innovative technologies that emphasize efficiency, product quality, and sustainability. These developments are directed not only at the processing of tamarind pulp but also at the utilization of underexplored by-products such as seeds, thereby maximizing value addition and minimizing waste. One of the key innovations is thermosonication, which integrates heat and ultrasound to enhance the overall quality of tamarind-based

beverages. This method improves color, viscosity, and cloudiness, while simultaneously increasing antioxidant content. Additionally, thermosonication effectively inactivates spoilage enzymes and ensures microbial safety, positioning it as a strong alternative to conventional pasteurization for tamarind drinks (Oladunjoye & Olorunsola, 2025) [60]. Similarly, High Pressure Processing (HPP) has been recognized as an efficient approach for tamarind seed valorization. Compared with conventional techniques, HPP substantially increases the extraction yield of valuable polysaccharides such as xyloglucan, resulting in high-quality extracts with enhanced functional properties that can be utilized across food and industrial applications (Limsangouan *et al.*, 2020) [48]. Drying methods have also seen significant technological improvements. Mechanical and solar-assisted drying systems, such as belt-type and tray dryers, coupled with optimized drying models, have been developed to deliver faster, more hygienic, and energy-efficient drying of tamarind pulp. These innovations help to reduce the common issue of stickiness and facilitate downstream operations such as deseeding, thereby improving overall processing efficiency (Rajkumar *et al.*, 2022; Rajkumar *et al.*, 2023) [68, 67]. Parallel progress has been made in storage and packaging, where the use of chemical additives like sulphur fumes and ascorbic acid, along with advanced packaging materials such as aluminum foil and palmyrah leaf bags, has proven effective. When applied under controlled storage conditions, these methods extend shelf life, preserve quality attributes, and strengthen the export potential of tamarind products (Marichamy *et al.*, 2024) [51]. Alongside these processing innovations, notable attention has been given to value addition and by-product utilization. Advanced processing strategies now enable the production of diverse tamarind-based products such as ready-to-use pellets, concentrates, powders, candies, and beverages. These not only increase consumer convenience but also create expanded market opportunities in both domestic and international markets (Bidyakshmi *et al.*, 2023; Pandian *et al.*, 2024; Bhavana, A. *et al.*, 2023) [17, 63, 16]. Furthermore, tamarind seeds, which were previously underutilized, are increasingly being explored for their functional and industrial potential. Emerging extraction and processing technologies have enabled the development of products such as mucilage, kernel powder, and tamarind seed oil. These materials hold applications across a wide spectrum of industries, including food, pharmaceuticals, textiles, and biofuels, highlighting the versatility and economic potential of tamarind seed valorization (Limsangouan *et al.*, 2020; Mansingh *et al.*, 2021; Silverio *et al.*, 2025; Kumar & Bhattacharya, 2008; Nagar *et al.*, 2022) [48, 50, 77, 44, 58]. Collectively, these innovations demonstrate how modern tamarind processing has evolved into a technology-driven sector that emphasizes resource efficiency, product diversification, and sustainable utilization.

6. Performance analysis of tamarind processing machinery

6.1 Throughput capacity and efficiency

Assessment of machinery performance often hinges on throughput capacity and processing efficiency. Comparative studies between manual and mechanized slicing machines have shown that mechanization can enhance throughput capacities by almost eightfold, substantially reducing required labor and slicing duration (Sinha *et al.*, 2011) [78]. Processing efficiency metrics such as slicing speed, product damage rates, and juice extraction percentages provide tangible evidence of machinery effectiveness. For example, optimized machine settings at specific strokes per minute were found to balance high slicing capacity with minimal physical damage, suggesting the critical

importance of tuning operational parameters for each specific crop or product form. These metrics serve as benchmarks for machinery developers and processors aiming to maximize productivity without compromising product quality (Vasanthkumar *et al.*, 2023) [85].

6.2 Quality parameters of processed tamarind products

Quality metrics extend beyond gross productivity to encompass the physical integrity, chemical composition, and safety of processed tamarind products. Physical damage rates of pulp and seeds reflect the mechanical suitability of processing equipment, influencing subsequent product acceptability and yield. Juice yield percentages relate to both the efficiency of pressing machinery and the preservation of chemical integrity including bioactive compounds underlying health benefits (Bayoï & Bianra, 2023; Bidyalakshmi *et al.*, 2023) [9, 17]. Microbiological contamination control remains integral, with sensory and antimicrobial tests guiding parameters that preserve organoleptic and safety standards. The implementation of Good Manufacturing Practices (GMP) and Standardized Operating Procedures (SOPs) in processing lines enhances consistent quality, aiding market acceptance (Lilian *et al.*, 2023; Feitosa & Andrade, 2022) [47, 29].

6.3 Energy consumption and operational costs

Energy efficiency is a significant consideration in the adoption of tamarind processing machinery. Traditional manual methods, while low in energy input, suffer from low throughput and higher labor costs. Mechanized drying, dehulling, and deseeding machines consume energy intensively, but relative improvements in capacity and speed often result in net economic benefits (Karthickumar *et al.*, 2015) [42]. Evaluations of energy consumption against output provide clear cost-benefit data informing machinery selection and operation strategies (Pelegrino *et al.* 2019; Unnikrishnan & Rao 2018) [64, 84]. Consideration of environmental sustainability in reducing fossil energy use aligns with global imperatives. Optimizing process parameters such as temperature, drying time, and mechanical component design, can further reduce operational costs and ecological footprints (Majumder *et al.*, 2022; Menon *et al.*, 2020) [49, 54].

7. Technological innovations and future directions

Recent advancements in tamarind processing technologies are increasingly focused on improving efficiency, quality, and sustainability while reducing environmental impacts. High-pressure processing has shown promise in enhancing xyloglucan extraction from tamarind kernel powder, resulting in higher yields and better quality compared to conventional methods. Similarly, enzyme-assisted extraction has been utilized to improve the recovery of polysaccharides and proteins from tamarind seeds. Non-thermal processing technologies such as ultrasound, microwave, and electron beam treatments are also being explored to improve extraction efficiency while preserving heat-sensitive bioactive compounds (Geethalaxmi *et al.*, 2024; Limsangouan *et al.*, 2020; Lee *et al.*, 2016; Picart-Palmade *et al.*, 2019) [31, 48, 45, 65]. Alongside these, energy-efficient systems including solar-powered equipment and energy recovery mechanisms are under development to reduce operational costs and energy consumption. Waste valorization has emerged as a major area of innovation, with technologies designed to convert tamarind by-products into value-added products such as biodegradable films and bioactive compounds, contributing to a circular economy model (Preethi *et al.*, 2024; Mansingh *et al.*,

2021) [66, 50]. Future directions for tamarind processing emphasize automation and Industry 4.0 integration through the use of programmable logic controller-based precision systems, cloud-enabled remote monitoring, and modular designs that allow flexibility and scalability of operations. Closed-loop water conservation systems and minimal water processing approaches are being introduced to address sustainability concerns. In addition, multi-objective optimization of processing parameters is being pursued to balance efficiency, quality, and energy use, while a shift toward continuous rather than batch operations is expected to enhance productivity. Minimal processing approaches that preserve the natural nutritional and functional properties of tamarind are also gaining importance. Sustainability considerations drive the development of machinery powered by renewable energy sources such as solar and wind. Such designs reduce environmental impacts and operational costs, promoting adoption in rural and small-scale production contexts. Eco-friendly machinery emphasizes minimized resource input, emissions, and waste production. The creation of multifunctional machines adaptable to diverse scales of operation enhances accessibility and resource efficiency for producers, aligning with circular economy concepts applied for processing residues. Further, circular economy principles are being embedded into system design to ensure complete utilization of tamarind pulp, seeds, and husks, while low-carbon processing technologies aim to reduce the overall environmental footprint. Finally, integration with biodegradable packaging solutions derived from tamarind components presents a promising path for sustainable product development.

8. Economic analysis and market trends

Tamarind (*Tamarindus indica* L.) is a versatile crop with significant economic, nutritional, and industrial value, especially in South Asia and Africa. Its market dynamics are shaped by production trends, value addition, supply chain efficiency, and the development of diverse products, all of which influence farmer incomes and industry growth.

Production trends and regional markets

Tamarind is widely cultivated in India, with major producing states including Karnataka, Tamil Nadu, and Madhya Pradesh, and is also important in Uganda, Senegal, and West Africa (Israel *et al.*, 2019; Vikram *et al.*, 2023; Sanogo *et al.*, 2023; Buyinza *et al.*, 2010; Masette *et al.*, 2015; Caluwé, 2011) [36-37, 89, 71, 19, 52, 20]. Production and productivity have shown positive growth, though regional variations exist due to climate, cultivation practices, and market access (Israel *et al.*, 2019; Buyinza *et al.*, 2010; Sanogo *et al.*, 2023) [36-37, 19, 71]. In India, the export market is robust, with significant earnings from processed products (Shankaracharya, 1998) [74].

Value addition and product diversification

Value addition through processing into jams, marmalades, sauces, candies, and industrial products like Tamarind Kernel Powder (TKP) significantly increases profitability and market opportunities (Agarwal, 2024; Mansingh *et al.*, 2021; Tiwari & Tomar, 2024; Israel & Murthy, 2019; Vikram *et al.*, 2023; Shankaracharya, 1998) [6, 50, 81, 36-37, 89, 74]. Training and support for women's self-help groups and small-scale entrepreneurs have demonstrated substantial income improvements through value-added tamarind products (Tiwari & Tomar, 2024) [81]. Industrial uses of tamarind by-products, such as seed oil and polysaccharides, are expanding into food, pharmaceutical, and textile sectors (Mansingh *et al.*, 2021; Agarwal, 2024; Israel &

Murthy, 2019; Shankaracharya, 1998) [50, 6, 36-37, 74]. Processing tamarind into products like kernel powder, jams, marmalades, sauces, and beverages significantly increases market value and shelf life, boosting incomes for producers and processors (Israel & Murthy, 2019; Masette *et al.*, 2015; Dewi *et al.*, 2020) [36-37, 52, 24]. Industrial uses of tamarind by-products (kernel powder, mucilage, seed oil) expand market opportunities in food, pharmaceutical, and textile sectors (Israel & Murthy, 2019; Mansingh *et al.*, 2021; Silverio *et al.*, 2025) [36-37, 50, 77].

Economic analysis of tamarind processing reveals

Economic analysis of tamarind processing consistently shows high financial viability, strong returns, and significant opportunities for value addition in both seed and fruit-based products. Tamarind seed processing units are financially sound, with a Net Present Value (NPV) of Rs. 15,526.68, an Internal Rate of Return (IRR) of 37%, a benefit-cost (B:C) ratio of 3.80, and a payback period of just 2.3 years. Processing 1 kg of tamarind seed yields 0.7 kg of valuable kernel powder, with the remainder as a by-product. The gross return per unit is Rs. 55,948, and the net return is Rs. 15,526.68, indicating robust profitability (Israel & Murthy, 2019) [36-37]. Traditional beverage processing (e.g., tamarind-turmeric drinks) is also economically feasible, with a B:C ratio of 1.42, IRR of 13-14%, and a payback period of about 2.5 years. Value addition increases returns by up to 47% per unit, though sensitivity to income fluctuations exists (Dewi *et al.*, 2020) [24].

9. Challenges and limitations in current tamarind processing machinery

9.1 Machine adaptability and standardization issues

Tamarind fruits exhibit significant variability in size, shape, and moisture content, making it difficult to design universally adaptable and standardized machinery. Most current machines are optimized for specific fruit properties, leading to inefficiencies or increased losses when processing diverse batches (Verma *et al.*, 2024; Bidyalakshmi *et al.*, 2023) [87, 17]. The lack of standardized equipment also complicates scaling up operations and integrating machinery into different processing environments (Bidyalakshmi *et al.*, 2023; Sudha *et al.*, 2022) [17, 79]. Engineering properties such as stickiness, density, and frictional characteristics further challenge the design of adaptable equipment for cleaning, sorting, and deseeding (Verma *et al.*, 2024; Verma *et al.*, 2025) [87, 86].

9.2 Technical constraints and performance bottlenecks

Technical limitations include the persistent problem of pulp stickiness, which causes clogging and requires frequent cleaning, reducing machine uptime and efficiency (Deepthi *et al.*, 2025; Sudha *et al.*, 2022) [23, 79]. Deseeding and dehulling remain bottlenecks, as even advanced machines achieve only 83-89% efficiency and may still require manual intervention (Karthickumar *et al.*, 2015; Sudha *et al.*, 2022) [42, 79]. Optimal performance is highly sensitive to fruit moisture content and machine settings, demanding careful control and skilled operation (Karthickumar *et al.*, 2015) [42]. Additionally, mechanical stress can damage pulp or seeds, affecting product quality (Verma *et al.*, 2025; Bidyalakshmi *et al.*, 2023) [87, 17].

9.3 Economic and social barriers

High initial investment costs, limited access to modern machinery, and the need for skilled operators pose economic barriers, especially for small-scale and rural processors (Bidyalakshmi *et al.*, 2023) [17]. Many communities rely on

manual or semi-mechanized methods due to affordability and ease of use, despite lower efficiency (Sudha *et al.*, 2022) ^[79]. Social factors, such as traditional processing practices and limited technical training, further hinder widespread adoption of advanced machinery (Bidyalakshmi *et al.*, 2023) ^[17].

9.4 Major challenges in tamarind processing machinery

Stickiness and mechanical separation difficulties

Tamarind pulp is highly sticky, making mechanical deseeding and dehulling challenging. This often results in reliance on manual labor or inefficient traditional methods, especially for deseeding, which is a critical bottleneck in the process (Deepthi *et al.*, 2025; Bidyalakshmi *et al.*, 2023; Sudha *et al.*, 2022) ^[23, 17, 79]. The stickiness also complicates cleaning and maintenance of machinery, leading to increased downtime and reduced efficiency (Deepthi *et al.*, 2025; Bidyalakshmi *et al.*, 2023) ^[23, 17].

Variability in fruit properties

Tamarind fruits vary significantly in size, shape, and moisture content, which affects the design and efficiency of processing equipment. Machines must accommodate these variations to minimize losses and ensure consistent product quality. Inadequate adaptation can lead to increased waste and suboptimal processing outcomes (Verma *et al.*, 2024; Bidyalakshmi *et al.*, 2023; Jarimopas & Jaisin, 2008) ^[87, 17, 39].

Limited mechanization and efficiency

While some mechanical solutions exist (e.g., centrifugal impact peelers, dehullers, deseeders), many operations especially deseeding and pulp extraction are still labor-intensive or have low throughput. For example, even improved peelers require pre-drying and may not achieve perfect separation, and deseeding remains a challenge due to the strong attachment of seeds to the pulp (Maubila *et al.*, 2023; Sudha *et al.*, 2022; Bidyalakshmi *et al.*, 2023) ^[53, 79, 17].

Product quality and value addition constraints

Maintaining product quality during mechanical processing is difficult, as excessive force can damage the pulp or seeds. Additionally, the development of machinery for value-added products (e.g., powders, concentrates) is still limited, with optimization of drying and briquetting processes requiring further research (Bidyalakshmi *et al.*, 2023; Muzaffar & Kumar, 2015) ^[17, 57].

10. Conclusion

Tamarind processing machinery has advanced considerably from traditional manual operations to semi-mechanized and mechanized systems, delivering notable improvements in efficiency, quality, and labor reduction. Yet, significant gaps remain in developing affordable, flexible, and scalable machines that can integrate smart control systems to enhance precision, maximize bioactive retention, and enable full-spectrum valorization of byproducts. Current technologies, while achieving dehulling efficiencies of nearly 83.98 percent and deseeding efficiencies of around 57.8 percent, still fall short of meeting the demands of large-scale industrial applications. Future progress lies in the adoption of automation, artificial intelligence, Internet of Things, machine learning, and advanced sensors to enable real-time optimization, predictive maintenance, and robust quality control. These innovations, combined with circular economy principles and renewable energy adoption, can ensure sustainable and environmentally

responsible processing. Economic analyses already indicate strong profitability and growth potential, with the global tamarind extract market projected to grow at 5.60 percent CAGR, underscoring the importance of continued investment in technology development. For the tamarind sector to realize its full potential, collaborative efforts among academia, industry, and policymakers are essential. Prioritizing intelligent processing systems, sustainability, and complete utilization of tamarind components will not only improve economic returns but also strengthen food security, empower rural communities, and enhance the competitiveness of tamarind on global markets. The transition toward automated, efficient, and sustainable tamarind processing technologies marks a critical pathway for the industry's future growth and long-term viability.

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