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Advances in scientific production technology & post harvest management of Tamarind (*Tamarindus indica* L.)

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Abstract

Tamarind (*Tamarindus indica* L.), an extremely versatile tropical fruit tree belonging to the family Fabaceae (Subfamily: Caesalpinioideae), is indigenous to tropical Africa but is grown in India since ages. Being adaptable, long-lived, nutritious, medicinal and industrial, it has become one of the important fruit crops in the world. India is the largest producer as well as consumer of tamarind. Fruit pulp is rich in organic acids, dietary fibre, minerals, polyphenols, flavonoids, vitamins, and other bioactive compounds that have antioxidant, antimicrobial, anti-inflammatory, antidiabetic, and cardioprotective effects. In addition to being consumed in raw form, tamarind finds applications in food processing, beverages, pharmaceuticals, cosmetics, and nutraceuticals industries. Cultivation practices including superior cultivars, vegetative propagation, proper nutrition, irrigation, canopy management, pest and disease management etc enhance yield and quality. Because tamarind is harvested in seasons but is consumed through-out the year, post-harvest technologies including drying, grading, packaging, storage, and hygienic processing play an important role in minimizing losses and improving its shelf-life. Some major areas of value addition include pulp, concentrate, beverages, sauces, candies, powders, seed kernel products, pharmaceutical ingredients and biodegradable industrial materials. Seeds, shells, and residues obtained during processing also provide ample opportunities for circular bio-economy. This review highlights developments in cultivation, post-harvest management, processing, value addition, marketing and export of tamarind.

Keywords: *Tamarindus indica*, tamarind cultivation, post-harvest technology, value addition, tamarind pulp, tamarind seed kernel powder, processing, nutraceuticals

1. Introduction

Tamarind (*Tamarindus indica* L.) is among the most useful multipurpose fruit tree species grown in tropical as well as subtropical parts of the world. While most of the commercial fruit crops are utilized mainly in their fresh forms, tamarind is very versatile because almost all the parts of the tree including fruits, leaves, flowers, bark, wood, seeds, and roots are nutritious, medicinal and/or industrial. Because of its adaptability to drought, high temperatures, poor soils, and marginal ecosystems, tamarind has emerged as an important climate resilient fruit tree crop suitable for sustainable agriculture under the changing climate (El-Siddig *et al.*, 2006) [7].

Tamarind fruit pulp is distinguished by a unique sweet-sour flavour owing to the presence of tartaric acid, which constitutes about 8-18% of the pulp depending on the genotype and maturity stage. In addition to tartaric acid, pulp is rich in reducing sugars, pectin, dietary fibre, calcium, potassium, phosphorus, magnesium, iron, B complex vitamins, phenolics, flavonoids, and antioxidants (De Caluwé *et al.*, 2010) [5]. Tamarind is traditionally used in Ayurveda, Siddha, Unani as well as African medicine for treatment of digestion disorders, fever, constipation, inflammation, microbial infection, diabetes, high blood pressure, and liver diseases. Research studies have revealed that different parts of the tamarind plant have antioxidant, antimicrobial, anti-cancer, anti-inflammatory, hypolipidaemic, hepatoprotective, nephroprotective and anti-diabetic effects (Mani *et al.*, 2020) [11, 12].

India has a predominant role in global production of tamarind. Karnataka, Tamil Nadu, Andhra Pradesh, Telangana, Maharashtra, Odisha, Chhattisgarh, Madhya Pradesh, Jharkhand and some

parts of West Bengal are major producers of tamarind. In addition to commercial orchards, a major part of production comes from natural stands in forests, village commons, roadside, and homesteads (Mani *et al.*, 2020) ^[11, 12]. Despite favourable agroclimatic conditions and enormous genetic diversity, productivity is low in India due to dependence on seedlings, poor orchard management, irregular bearing, inefficient harvesting techniques, poor post-harvest practices, and absence of processing facilities (Coronel, 1991) ^[3].

International demand for natural food ingredients, functional foods, organic products, hydrocolloids, biodegradable industrial materials and nutraceuticals has created interest in the commercial cultivation of tamarind. Use of improved cultivars, clonal propagation, high density orchards, precision irrigation, integrated nutrient management, scientific pruning, efficient harvesting, value addition, FPOs, digital marketing, and export orientation will help increase farmer income besides ensuring food security and sustainable rural livelihoods (Pugalenth *et al.*, 2004) ^[17].

2. Origin, history and global distribution

Tamarindus indica L. is thought to have originated in the tropical savannahs of east Africa, particularly Sudan, Ethiopia, and Eritrea. It got dispersed to the Indian subcontinent thousands of years ago where it got fully naturalized and diversified into several indigenous landraces. It is evident from historical evidences that tamarind has been cultivated in India for more than 2500 years and has deep roots in its agriculture, cuisine, traditional medicine, and culture (Mani *et al.*, 2020) ^[11, 12].

Arabs took tamarind from India to the Middle East and North Africa, and the Arabic term Tamar Hindi ("Indian Date") was converted into the English name of tamarind. During the sixteenth century, the Portuguese and Spanish explorers extended its distribution to South America, Central America, the Caribbean, and Southeast Asia.

Now tamarind is widely grown in tropical Asia, Africa, Americas, Australia, and Pacific Islands. India leads the world in production of tamarind followed by Thailand, Myanmar, Indonesia, Sri Lanka, Bangladesh, Mexico, Nigeria, and other African and Latin American countries. Growing international demand for tamarind pulp, concentrates, seed products, and processed foods has increased its international trade. India has rich genetic diversity of tamarind with several elite and improved genotypes developed at ICAR, IIHR, and State Agricultural Universities. These varieties have higher pulp yield and fruit quality and are regular bearers with high productivity.

3. Botanical description, morphology and reproductive biology

Tamarindus indica is a member of the family Fabaceae (Caesalpinioideae subfamily). It is a long-lived evergreen to semi-evergreen tree that can continue producing fruit for more than 150-200 years depending on conditions. Adult trees usually grow up to 15-25 m tall with a large trunk, wide crown and lush foliage, thus being very good shade trees besides its commercial value. The root system is made up of a deep and powerful taproot combined with widespread lateral roots that can penetrate the deeper layers of soil. This feature allows tamarind to endure long drought periods as well as utilize water and nutrients effectively (Mani *et al.*, 2020) ^[11, 12]. The bark is grey-brown, furrowed, and abundant in tannins. Leaves are alternate, pinnately compound, 7-15 cm long, containing 10-20 pairs of oblong leaflets. Leaflets are dark-green and light-sensitive as well as exhibiting nyctinasty movement by folding at night time. The dense crown greatly

contributes to carbon fixation, soil conservation, and microclimate formation (Usha & Singh, 2017) ^[23].

Flowers are produced in terminal and axillary racemes. They are bisexual, zygomorphic, yellow with beautiful red or orange spots. Flowering usually takes place in spring to early summer depending on environmental conditions and variety. Despite the large number of flowers in the inflorescences, only a few of them will turn into mature fruits due to natural flower dropping and environmental factors (Usha & Singh, 2017) ^[23]. The fruit is an indehiscent pod 5-20 cm long with a brittle brown shell, which contains sticky brown pulp around hard shiny seeds. The fruit pulp originates from the mesocarp layer and accumulates sugars, tartaric acid, minerals, and polyphenolic compounds during fruit maturation (Mani *et al.*, 2020) ^[11, 12]. The mature fruits usually have 3-12 seeds depending on variety. Seeds are hard, flattened, dark-brown and highly viable but dormant due to an impermeable seed coat (De-Caluwé *et al.*, 2010) ^[5]. Seeds are rich in proteins and polysaccharides, especially xyloglucan, which constitutes tamarind seed kernel powder (TSKP), one of the most valuable industrial hydrocolloids used in textile, paper, pharmaceutical, cosmetic, food, mining, and adhesive industries (Ferrara, 2019) ^[8].

4. Flowering physiology, fruit set and fruit development

Flowering in tamarind depends on the genotype, tree age, environment, carbohydrate reserves, temperature, soil moisture, and nutrition. Flower initiation normally occurs during the dry period and then anthesis follows with the advent of favourable temperatures. Mature trees are capable of producing thousands of flowers during each flowering period, but only a few flowers will form mature fruits due to natural flower dropping and physiological fruit drop. The pollination process is mainly entomophilous. Honey bees (*Apis mellifera*, *Apis cerana*), stingless bees, butterflies, flies, and other insects are responsible for pollination. Cross-pollination results in better fruit set than self-pollination; although there is partial self-compatibility in some varieties (Usha & Singh, 2017) ^[23].

After successful fertilization, fruits rapidly elongate and become thicker with pulp development. During fruit ripening, chlorophyll breaks down, the pod shell becomes brown and brittle, the moisture content decreases, sugars accumulate, and the concentration of tartaric acid attains its characteristic level. Depending on variety and climate, fruits need 8-10 months after flowering for full ripening (Mani *et al.*, 2020) ^[11, 12]. Fruit retention depends on irrigation, nutrients, pests' incidence, carbohydrate reserves, temperature changes, and drought. The scientific orchard management by providing a balanced nutrition, proper irrigation, pollinators' conservation, and pruning improves fruit retention and productivity (Ferrara, 2019) ^[8].

5. Climatic Requirements

Tamarind is highly adapted to tropical and subtropical climate zones and is considered one of the most drought-resistant fruit trees grown commercially. The crop grows extremely well in hot semi-arid climate zone where the annual temperature ranges between 20 and 35°C. Mature trees endure temperatures above 45°C in summer and are productive even in drought conditions due to their deep root system and effective water use. The young seedlings are frost-sensitive, while mature trees are tolerant to mild frost periods. Flowering and fruit development require warm and relatively dry weather. Too much rain during flowering period adversely affects pollinator activity and flower dropping, resulting in fruit set reduction (De-Caluwé *et al.*, 2010) ^[5]. The crop can grow very well on annual rainfall between 500 and

1,500 mm. Despite the high drought tolerance of mature trees, the supplementary irrigation during flowering, fruit set, and pod development increases the productivity and fruit quality of the crop. The relative humidity 50-70% is usually favourable, while long humid conditions favour the development of fungal diseases of flowers and young fruits. Abundant sunshine is necessary for optimal flowering, photosynthesis, fruit development, and accumulation of sugars and organic acids. Dense shade negatively impacts flowering intensity and pod production; therefore, canopy management is important in commercial orchards (Mani *et al.*, 2020) ^[11, 12].

6. soil Requirements and land preparation

One of the key advantages of tamarind growing is its ability to grow on different soil types such as sandy loam, loam, red lateritic soils, alluvial soils, black cotton soils, gravelly soils, and even moderately degraded wastelands. However, maximum productivity and superior fruit quality are achieved on deep, fertile, well-drained loamy soils rich in organic matter. The crop grows best on soils with pH 5.5-7.5; though, mature trees tolerate slightly alkaline soils up to pH 8.5. Waterlogged soils are not suitable for growing tamarind as the root respiration is inhibited as well as the development of root diseases due to moisture stagnation. Heavy clay soils with poor drainage can be improved by using raised plant beds and proper drainage (Usha & Singh, 2017) ^[23].

Before planting the crop, the soil analysis should be carried out in order to find out the pH, organic carbon content, macro- and micronutrients, salinity, and soil-borne pathogens (Rao & Mary, 2001) ^[19]. The land preparation procedure involves clearing bushes, removal of stones, deep ploughing, harrowing, levelling, and application of organic manures. On slopes, contour planting, bench terracing, vegetative barriers, and cover crops reduce soil erosion and conserve moisture. Applying 20-30 tonnes per hectare of well-decomposed farmyard manure or compost during land preparation improves the soil structure, microbial activity, nutrients availability, and water-holding capacity.

7. Tamarind genetic diversity, types and commercial cultivars

Tamarindus indica L. displays a high degree of genetic variability due to its long history of propagation by seed. Genetic variability is observed among the species in terms of tree structure, canopy size, flowering, pod characteristics, pulp colour, acidity, sweetness, fibre content, number of seeds, pulp recovery, bearing habit, maturity period, and stress tolerance. India is one of the richest centres of diversity of tamarind, with the presence of many native landraces evolved through centuries of cultivation and natural selection. Rather than distinct botanical races, tamarind possesses local landraces, elite selections and improved cultivars identified through scientific evaluations. Criteria for selection include regular bearing, high pulp recovery, low fibre content, few seeds, proper balance of sweetness and acidity, good processability and high productivity (Mani *et al.*, 2020) ^[11, 12]. Various research institutions like ICAR-IIHR, ICAR-NBPGR, TNAU, UAS Bengaluru and Dr. Y.S.R. Horticultural University have contributed much to cultivar development (Ferrara, 2019) ^[8]. Among the cultivars released, PKM-1 is most popular in view of its early bearing, small canopy, 40-45% pulp recovery, low fibre content, and regular yielding of 250-300 kg of pods per tree. Urigam-1 is famous for its long pods, thick pulp, fine taste, high tartaric acid, drought tolerance, better keeping quality and suitability for rainfed conditions and processing. Elite selections like Prathisthan, Hasanur, DTS-1, DTS-2, DTS-4, GKVK-6, TH-1 and TH-2 have high yield and excellent pulp quality. Among

these, DTS-1 and DTS-2 have large pods with high pulp recovery, few seeds and regular bearing, making them more suitable for commercial orchards in southern India (Usha & Singh, 2017) ^[23]. For commercial cultivation of tamarind, vegetative propagation of elite cultivars is preferred over seed propagation since the latter gives highly variable progenies. Adoption of improved cultivars will help to get uniform plantations, higher productivity, good fruit quality and increased profit specially for the processing industry and premium domestic market (Rao & Mary, 2001) ^[19].

8. Propagation techniques

Propagation is an important aspect of scientific tamarind cultivation, as the productivity of the orchards depends upon the genetic quality of planting materials. Whereas seed propagation is used primarily for rootstock production, the commercial orchards prefer vegetative propagation techniques like softwood and veneer grafting, cleft grafting, budding and air layering for genetic uniformity, better fruit quality and earlier bearing (3-5 years) as compared to the seedling trees, which bear fruit after 8-12 years and are highly variable (Coronel, 1991) ^[3].

- a) **Seed Propagation:** Seed propagation is primarily used for rootstock production and germplasm preservation. Seeds of fresh fruits from elite trees are viable but do not retain their germination capacity during storage. Seeds need cleaning, shade drying for 1-2 days, fungicide or *Trichoderma* sp. treatment and scarification (acid, hot water or mechanical nicking) before sowing in raised beds or polybags or root trainers containing sterilised soil, sand and well-decomposed FYM. Germination starts in 10-20 days at 25-35 °C (Mani *et al.*, 2020) ^[11, 12].
- b) **Vegetative Propagation:** Vegetative propagation conserves the genetic identity of elite cultivars, shortens the juvenile phase and ensures high yielding orchards. Softwood and veneer grafting are the most widely adopted commercial methods because of their ease of practice, higher success and economical nature (Ferrara, 2019) ^[8].
- c) **Softwood Grafting:** Softwood grafting is the preferred commercial method. Healthy rootstocks of 8-12 month age (1-1.5 cm diameter of stem) are grafted with wedge shaped scions from elite mother trees and tied with polyethylene strips until the union is formed. Success rate is 70-90% and the plants become ready for planting in 6-8 months (Rao & Mary, 2001) ^[19].
- d) **Veneer Grafting:** Veneer grafting involves making slanted cuts on both the scion and the rootstock for proper cambial contact before tying. It forms strong graft unions and vigorous plants and is ideal for large scale nursery raising (Usha & Singh, 2017) ^[23].
- e) **Cleft Grafting:** Cleft grafting is done when scion and rootstock are of nearly same diameter. The wedge-shaped scion is inserted into the split rootstock and union is made with proper cambial alignment and favourable temperature and humidity (Ferrara, 2019) ^[8].
- f) **Budding:** The success rate of patch and shield budding is moderate in case of tamarind because of the bark characteristics and slow callus formation. Therefore, grafting remains the preferred method for commercial propagation.
- g) **Micropropagation:** Micropropagation by nodal explants, shoot tips, somatic embryogenesis and *in vitro* organogenesis can be useful for quick multiplication of elite and disease-free planting material and germplasm preservation, though its commercial application is still difficult due to cost and technical reasons (Sookying *et al.*, 2022) ^[22].

9. Nursery Management & Orchard Establishment

Scientific nursery management is crucial for getting vigorous, disease free and true to type tamarind plants for successful establishment and productivity of the orchards. The nurseries must be located on well drained sites with assured irrigation, good sunlight and shelter from strong winds, using sterilised growing media of soil, sand, compost, cocopeat and vermicompost (Rao & Mary, 2001) ^[19]. The grafts need maintenance under partial shade with regular irrigation, balanced nutrition, sanitization, weed control and IPM. Plants need hardening before planting in the orchard through gradual acclimatisation to sunlight and reduced irrigation. Only healthy plants with well-developed root system, straight stem, dark green foliage and proper graft unions should be selected for orchard establishment (Mani *et al.*, 2020) ^[11, 12].

Commercial production of tamarind starts with the correct establishment of orchards because the tree remains productive for more than 100 years. The mistakes that might include improper orchard site selection, poor planting materials, drainage, spacing, and soil preparation reduce the productivity of the trees (Sookying *et al.*, 2022) ^[22]. Therefore, proper planning before planting tamarind is necessary. A well-drained field with deep soils and mild slopes (1-5%) is the best place to cultivate because of its extensive taproot system and prevent waterlogging. Before planting, a field survey should be done to find out the suitability of the land concerning topography, soil fertility, irrigation, drainage, and accessibility before removing the weeds, stones, and stumps from the land (Ferrara, 2019) ^[8]. Deep ploughing and cross-harrowing increases soil aeration, root development, and moisture penetration while contour planting and bunding helps in reducing soil erosion and moisture conservation. Well decomposed FYM, compost, green manures, and bio-fertilizers increase soil fertility and microbial activities. Soil testing helps to identify and amend nutrient deficiency and soil pH levels before planting (Rao & Mary, 2001) ^[19]. It is necessary to protect the young grafts by windbreaks like Casuarina, Grevillea, and bamboo and construct irrigation channels, fencing, drainage, and water harvesting structures before planting. In modern orchards, GPS-assisted land levelling, digital mapping, precision irrigation, soil moisture sensors and rain water harvesting are becoming popular (Usha & Singh, 2017) ^[23].

10. Planting season and planting Systems

Healthy true to type grafted plants between 8-12 months old with a healthy root system, well-healed graft union, a straight stem, healthy foliage, and free from pests and diseases should be chosen. Nursery pots should be irrigated before planting to extract the plant from the pot without damaging it (Sookying *et al.*, 2022) ^[22]. The plants are to be placed in the center of the planting pit, and the graft union should remain above ground level at 15-20 cm above the ground surface to prevent the collar disease. After planting, soil should be pressed firmly around the root and irrigate immediately. Temporary staking is necessary for young plants especially if they have to withstand hot weather conditions. Organic mulches like dry grass, straw, or compost will conserve soil moisture, prevent weeds and improve soil health. Within the first two years, proper irrigation, weeding, nutrients management, and protection from pest and grazing animals are essential for successful establishment (Mani *et al.*, 2020) ^[11, 12].

The proper pit preparation ensures quick establishment of roots by improving soil aeration, moisture conservation, availability of nutrients and microbial activities. The pit sizes of 1×1×1m is suggested for commercial orchards (75×75×75cm in light soils) while large pits are better in compact soils. The pits should be prepared one to two months before planting where topsoil should

be kept separate and mixed with 20-30kg FYM/compost, 2-3kg vermi-compost, 1kg Neem cake, 500g Single Super Phosphate and required micronutrients. Beneficial microbes like Trichoderma and Pseudomonas are helpful in root development and raising mounds (30-50cm) in poorly drained areas (Ferrara, 2019) ^[8].

Spacing plays a significant role in canopy development, light interception, air circulation, nutrient uptake, irrigation efficiencies, and long-term orchard productivity. The standard spacing of tamarind is 10×10m with 100 trees per hectare which provides adequate canopy development space and allows mechanization. Wider spacing (12×12m) is suggested in fertile and high rainfall areas, while 8×8m spacing is preferable in semi-arid regions with proper canopy management (Sookying *et al.*, 2022) ^[22]. Square planting is the common planting system since it is convenient for irrigation and intercultural operation, whereas contour planting is preferable in sloping areas to conserve moisture (Keskar *et al.*, 1989) ^[9]. High density planting (6×6m to 8×6m) using dwarf or moderately vigorous grafted cultivars will improve early productivity, but proper pruning, fertigation, and precision irrigation are necessary. Future dwarf cultivars will improve orchard productivity and mechanization (Marles & Farnsworth, 1995) ^[13].

11. Pollination Biology and Pollinizer Management

Tamarind flower is bisexual, and it is mostly insect-pollinated. Although some genotypes are partially self-fertile, the cross-pollination helps to get a good number of fruits and pods. Major pollinators include honey bees (*Apis mellifera* and *A. cerana*), stingless bees, carpenter bees, butterflies, hover flies, and other insects with peak pollination activity during sunny warm mornings (El-Siddig *et al.*, 2006) ^[7]. Environmental factors such as heavy rainfall, high winds, extreme temperature, and drought affect the pollination activity, and adequate moisture in the soil during flowering helps in the production of nectar. Conservation of pollinators through proper insecticides usage, flowering cover crops, natural vegetation and introduction of 3-5 bee colonies per hectare during flowering period significantly improves pollination, production and sustainability of the orchard (Mani *et al.*, 2020) ^[11, 12].

12. Nutrient Management

Balanced nutrient management is very much important to sustain the growth, flowering, fruiting and long-term productivity of tamarind orchards. Though tamarind can thrive in marginal soils, the commercial cultivation of tamarind requires nutrient management depending upon the soil fertility, tree age, crop load and climatic conditions. The nitrogen promotes vegetative growth and flowering while phosphorus stimulates root development, flowering, and fruit set (Usha & Singh, 2017) ^[23]. The potassium improves pod size, pulp quality, sugar accumulation, drought resistance and storage life. Calcium, magnesium, and sulphur improve cell wall structure, photosynthesis, and protein synthesis. Zn, B, Fe, Mn, Cu, and Mo are equally important micronutrients and their deficiency negatively impacts flowering, fruit set, and leaf health (Rao & Mary, 2001) ^[19].

INM involving integrated use of organic manures, chemical fertilizers, compost, vermi-compost, green manures, crop residues, and bio-fertilizers (*Azotobacter*, *Azospirillum*, phosphate solubilizing and potassium mobilizing bacteria, arbuscular mycorrhizal fungi, and Trichoderma spp.) is the most effective system (Mani *et al.*, 2020) ^[11, 12]. An annual application of 25-50kg well-decomposed FYM per mature tree will improve soil fertility, organic carbon content, microbial activities, and

moisture conservation. General recommendation for bearing trees is 500-1000gN, 250-500gP₂O₅, and 500-1000gK₂O per tree annually to be applied in two splits, before flowering and fruit set. Soil and leaf analysis are of great help in optimizing nutrient application and fertilizer use efficiency (El-Siddig *et al.*, 2006) ^[7]. INM involving use of organic manures, chemical fertilizers, compost, vermicompost, green manures, crop residues, and biofertilizers (*Azotobacter*, *Azospirillum*, phosphate-solubilizing and potassium-mobilizing bacteria, arbuscular mycorrhizal fungi, and *Trichoderma* spp.) is the most sustainable option (Mani *et al.*, 2020) ^[11, 12]. Annual application of 25–50 kg well-decomposed FYM per mature tree will enhance soil fertility, organic carbon, microbial activity, and moisture conservation. The general recommendation for bearing trees is 500–1000 g N, 250–500 g P₂O₅, and 500–1000 g K₂O per tree annually to be applied in two splits, before flowering and after fruit set. Soil and leaf analysis is of great help in optimizing nutrient application, improving fertilizer use efficiency, and minimizing environmental losses (El-Siddig *et al.*, 2006) ^[7].

13. Irrigation and Water Management

Even though tamarind is highly drought-tolerant, appropriate irrigation and water management improve vegetative growth, flowering, fruit retention, pod development, and pulp quality. Irrigation of young grafted plants on alternate weeks (7-10 days) during dry periods for the first 2-3 years and irrigation of mature trees mainly during flowering, fruit set, and pod enlargement to minimize flower drop and improve yield are essential (Sookying *et al.*, 2022) ^[22]. Drip irrigation is the most suitable irrigation system as it will conserve water and improve fertigation efficiency. Mulching, rainwater harvesting, contour bunding, farm ponds, and micro catchment systems are important for conserving soil moisture in rain-fed orchards. Precision irrigation with soil moisture sensors and weather-based scheduling improve water-use efficiency. Avoid water logging through proper drainage as prolonged soil saturation negatively impacts root health (Rao & Mary, 2001) ^[19].

14. Weed Management

Weeds compete with young tamarind plants for water, nutrients, light, and space besides harbouring pests and diseases, and interfering with orchard operations (Mani *et al.*, 2020) ^[11, 12]. Basin weeding and manual hoeing are necessary for the establishment phase, while mechanical cultivation is suitable for large orchards. Organic mulching using paddy straw, dry grass, sugarcane trash, coconut husk, and compost effectively suppress weeds, conserve moisture, and improve soil fertility (Singh *et al.*, 2021) ^[21]. Leguminous cover crops such as cowpea, horse gram, green gram, and sunhemp will further help in suppressing weed growth while providing biologically-fixed nitrogen. Careful use of selective herbicides when labour is limited will prevent damage to young plants. Integrated Weed Management (IWM), combining cultural, mechanical, biological, and chemical methods is the most sustainable option (Usha & Singh, 2017) ^[23].

15. Intercropping

Intercropping increases land-use efficiency and generates additional income during the first 5-7 years of tamarind orchard establishment when tree canopies are not fully developed. Leguminous crops like green gram, black gram, cowpea, soybean, pigeon pea, and groundnut are ideal as they enrich soil through biological nitrogen fixation (Mani *et al.*, 2020) ^[11, 12]. In irrigated conditions, vegetables like onion, garlic, chilli, tomato, brinjal, cabbage, cauliflower, okra, carrot, radish, and leafy vegetables

can be cultivated. Medicinal and aromatic crops like turmeric, ginger, lemongrass, citronella, aloe vera, and ashwagandha are also suitable. With the expansion of canopies, intercrops must be stopped to avoid competition for light, water, and nutrients. Appropriate intercropping increases biodiversity, improves soil health, suppresses weeds, and generates diversified farm income (Donkor *et al.*, 2020) ^[6].

16. Mulching

Mulching is one of the most beneficial cultural practices in commercial tamarind cultivation. Application of organic mulch around tree basins conserves soil moisture, moderates soil temperature, suppresses weeds, prevents soil erosion, enhances microbial activity, and gradually adds organic matter through decomposition (El-Siddig *et al.*, 2006) ^[7]. Organic mulches normally used include paddy straw, sugarcane trash, dry grasses, coconut husk, wood chips, fallen leaves, compost, farmyard manure, and pruning residues. Mulch must be applied in a circular basin around the tree beyond canopy drip line leaving an interval of about 15-20 cm around the trunk to prevent collar rot (Usha & Singh, 2017) ^[23].

Mulching greatly improves water use efficiency during dry seasons through reduction of evaporation losses. Improved biological activity under the mulch will accelerate nutrient cycling, soil aggregation, and beneficial microbial population. In rain-fed orchards, mulching with rainwater harvesting will greatly improve tree survival and productivity during drought periods (Donkor *et al.*, 2020) ^[6].

17. Training, Pruning and Canopy Management

Scientific canopy management is an indispensable practice for maintaining balanced vegetative growth, optimum light interception, efficient harvesting, and consistent fruit production (Keskar *et al.*, 1989) ^[9]. If no pruning is done, tamarind trees develop excessive dense and spreading canopies which will affect light penetration and increase harvesting difficulty. Training starts immediately after planting through encouragement of development of strong central leader with 4-6 well-spaced scaffold branches around the trunk. Weak, diseased, crossing, inward growing, and competing branches must be removed during formative period to develop well-balanced structure (Mani *et al.*, 2020) ^[11, 12].

Pruning of bearing orchards involves removal of dead, diseased, broken and overcrowded branches. Light pruning of the canopy will improve air circulation, reduce humidity, increase photosynthesis, facilitate pesticide application, and flower formation. Rejuvenation pruning may be practiced for old, neglected and senile trees for rejuvenation. Excessive pruning stimulates development of vigorous shoots which will later form productive fruiting wood. However, pruning must be done with caution since excessive pruning of canopy reduces flowering in subsequent seasons. Modern orchard management increasingly uses mechanical pruning, canopy architecture modelling, and precision pruning (Marles & Farnsworth, 1995) ^[13].

18. Flowering Biology, Pollination, Fruit Set and Fruit Development

Tamarind has an abundance of attractive bisexual flowers borne in terminal and axillary racemes. The flowering usually takes place in spring depending on the genotype and climatic conditions. The initiation of flowering is influenced by carbohydrate stores, tree age, soil moisture, nutrients availability, temperature, and previous crop load (Donkor *et al.*, 2020) ^[6]. The flowers have abundant nectar attracting a variety of insect

pollinators, including honey bees, stingless bees, butterflies, and flies (Pugalenthi *et al.*, 2004) ^[17]. Though there is self-pollination, cross pollination helps in improving the fruit set, pod size, and seed development. After successful pollination and fertilization, there is rapid cell division and elongation resulting in the development of pods. During maturation process, moisture contents reduce gradually while sugars, tartaric acid, minerals, and phenolics get accumulated in the pulp (Rao & Mary, 2001) ^[19]. The pods become physiologically matured in about 8-10 months after flowering. Fruit retention is possible with good carbohydrate supply, balanced nutrition, irrigation, pollination and conducive environmental conditions. Flower and fruit drop due to drought, nutrient deficiency, and pest attack decrease the yield of the tree (Mani *et al.*, 2020) ^[11, 12].

19. Crop Regulation, Alternate Bearing and Crop Load Management

Alternate bearing is characterized by heavy and light crops in alternative years seen in seedling population of tamarind trees. Heavy cropping reduces the carbohydrate stores resulting in fewer flower initiation in the next year. Balanced nutrient management, irrigation, scientific pruning, harvesting, and healthy canopy maintain minimize alternate bearing. Removal of diseased, injured and crowded pods in heavy crop year reduces stress on the trees and improves the pod size and quality. Unlike other deciduous fruit crops, chemical thinning is not applied in tamarind due to natural physiological fruit drop regulating the crop load (Donkor *et al.*, 2020) ^[6].

20. Physiological Disorders

Physiological disorders usually occur due to environmental stress, nutritional imbalance and improper orchard management rather than due to any infectious pathogen (Mani *et al.*, 2020) ^[11, 12].

- A. **Flower Drop:** Overflower drop is usually caused by drought stress, nutrient deficiency, high temperatures, wind movement, poor pollination, and insect infestation. Balanced irrigation, boron applications, and conservation of pollinators help in fruit set.
- B. **Premature Fruit Drop:** Factors like water stress, potassium deficiency, insect infestation, and moisture fluctuations cause premature fruit drop. Balanced irrigation and proper nutrient supply help in minimizing losses.
- C. **Sun Scorch:** Young grafts suffer from sun scorch during extremely high summer temperatures. It is prevented with temporary shading, whitewashing trunks and irrigation.
- D. **Nutrient Deficiency Disorders:** The deficiency of zinc, boron, iron, magnesium, and nitrogen is indicated with chlorosis, reduced shoot growth, poor flowering, and reduced productivity. Periodic soil and leaf testing help to supply nutrients through soil or foliar applications.
- E. **Moisture Stress:** Long duration of drought causes reduced growth, flowering, pod development and quality of pulp. Rainwater harvesting, mulching, and irrigation are the most effective ways of management.

21. Pest Management of Tamarind

- A. **Tamarind Fruit Borer (*Cryptophlebia ombrodelta*):** Fruit borers are one of the major pests of tamarind. The adult moths lay eggs on the young pods and after hatching, larvae bore into fruits and feed on the pulp and immature seeds. The infested pods have entrance holes filled with frass, premature drying, poor pulp development, and fruit drop. The secondary fungal infection is common through feeding injury making the pods unfit for processing and marketing (Keskar

et al., 1989) ^[9]. The integrated management of the pests includes destruction of infested pods, harvesting in time, installation of pheromone trap for adult population estimation, conservation of parasitoids, especially *Trichogramma* spp., and *Bacillus thuringiensis* (Bt) formulations at the early larval stage. The application of chemicals should be done only above the economic threshold level and during the period of flowering to conserve the pollinators (Ferrara, 2019) ^[8].

- B. **Leaf Webber and Defoliators:** A number of lepidopterous larvae defoliate tamarind foliage by webbing the leaves together and eating the leaf tissue. The young plantations are more vulnerable as the defoliation reduces photosynthetic area and canopy development. The management of the pests involves periodic monitoring, manual destruction of webbed leaves, conservation of predacious insects and parasitoids, and biological control by using *Bacillus thuringiensis*. Light traps help in reducing adult population during the outbreak periods (Sookying *et al.*, 2022) ^[22].
- C. **Mealybugs (*Ferrisia*, *Planococcus* spp.):** The mealybugs feed on tamarind by sucking plant sap from tender shoots, leaves, flowers, and developing pods. Heavily infested trees have poor flowering, reduced growth, fruit drop, and weak growth. Honeydew excretions attract the development of sooty molds decreasing the photosynthesis and marketability of the fruit. The control of the pests is done by pruning of infested branches, controlling attendant ants protecting mealybugs, conservation of natural enemies like *Cryptolaemus montrouzieri* and parasitoids. The botanical insecticides using neem are quite effective against the early infestations (Keskar *et al.*, 1989) ^[9].
- D. **Scale Insects:** A number of scale insects infest the tamarind leaves, twigs, and branches sucking plant sap. The severe infestation leads to yellowing, premature leaf fall, dieback of branches, poor pod production, and honeydew secretion promoting the development of sooty mold. The biological control with the help of ladybird beetles, lacewings, predatory mites, and parasitoid wasps usually suppresses the pest. The pruning of overcrowded branches helps in improving the air movement and reduces favourable environment for the proliferation of scales.
- E. **Aphids:** The aphids infest the young nursery plants and new shoots causing curling of leaves, distorted shoots, reduced growth, and spread of certain viral diseases in associated host plants. The ladybird beetles, syrphid flies, lacewings, and parasitoid wasps are the natural enemies of the aphids maintaining the population below the damaging levels. Avoiding excessive nitrogen fertilizer prevents succulent growth favoured by aphid multiplication (Keskar *et al.*, 1989) ^[9].
- F. **Bark-Eating Caterpillar (*Indarbela quadrinotata*):** The bark-eating caterpillar is one of the important pests of mature tamarind trees. The larvae bore into the bark creating webbed galleries containing the frass and excreta. The feeding makes the branches weaker, disrupts the nutrient transport, and predisposes the tree to secondary fungal infections. The management of the pest is done with the help of mechanical removal of larvae by use of hooked wire, destruction of infested bark, inserting cotton soaked in approved insecticides into tunnels, if required, and orchard sanitation.
- G. **Stem and Branch Borers:** The stem borers bore the woody tissues causing dieback of branches, reduced vigour, canopy thinning, and sometimes killing the young trees. The early detection is very important in case of borer attack through

regular inspection. The integrated management involves the removal and destruction of infested branches, sealing of pruning sealing pruning wounds, maintenance of vigorous tree growth, and need-based insecticidal treatment of active galleries (Ferrara, 2019) ^[8].

- H. **Termites:** Termites occasionally cause damage to young transplant trees especially during dry conditions. Termite damage is severe in young orchards, where damage is caused to roots and lower stems of plants. Application of well decomposed organic matter, avoiding undecomposed crop residue near the trunk of the plants, biological agents like *Metarhizium anisopliae* and soil treatment if necessary are useful for termite management (Pugalethi *et al.*, 2004) ^[17].
- I. **Seed Beetles (Storage Pests):** Stored tamarind seeds used for industrial processing or as nursery seedlings are subject to attack by bruchid beetles. Seeds attacked by beetles are characterized by presence of holes, reduced germination and poor-quality seeds. Proper drying, storage in low moisture conditions, airtight containers and periodic examination help in reducing storage losses.

22. Diseases of Tamarind and Integrated Disease Management

- A. **Powdery Mildew (*Oidium* spp.):** Powdery mildew is usually found on young leaves, flowers and shoots during warm humid weather. The fungus forms white powdery coverings on affected organs, reducing photosynthesis and flower and fruit formation. Integrated management involves pruning to improve ventilation in the canopy, balanced nitrogen fertilization, removal of infected shoots and timely application of sulphur and other fungicides if necessary.
- B. **Leaf Spot (*Cercospora*, *Colletotrichum*, *Alternaria* spp.):** Leaf spots are formed by circular brown or black spots surrounded by chlorotic margins. Heavy infection leads to early shedding of leaves and weakens the plant vigour due to reduced photosynthesis. Integrated disease management practices include removal of fallen leaves, pruning of infected branches, balanced nutrition and fungicide application if weather remains warm and wet (Singh *et al.*, 2021) ^[21].
- C. **Anthraxnose (*Colletotrichum gloeosporioides*):** Anthracnose is observed in flowers, immature pods, mature fruits and post-harvest fruits. Infestation in fruits becomes evident only after maturation when black sunken spots appear on fruits. Warm and humid weather favours the spread of disease. Good sanitation practices, pruning, balanced fertilization, proper harvesting and hygienic post-harvest handling helps to reduce the disease occurrence.
- D. **Dieback:** Dieback occurs when the trees are infected with fungal organisms following pruning wounds, drought stress, mechanical wounds or insect attack. Symptoms include drying of twigs, branch dieback, reduced canopy and decreased productivity. Infected branches should be pruned far from the point of infection and disposed. The pruning wounds should be dressed with suitable wound dressing material to avoid re-infection (Singh *et al.*, 2021) ^[21].
- E. **Root Rot:** Young plants planted in poorly drained soil may suffer from root rots caused by soil borne fungi and oomycetes such as *Phytophthora* species. Symptoms include yellowing, wilting, root rotting, stunted growth and ultimately plant death. Proper drainage of the field, raised planting, biological control with *Trichoderma* spp. and avoidance of water logging are very effective management practices (Coronel, 1991) ^[3].

F. **Sooty Mould:** Sooty mould appears on honeydew formed by the insects such as aphids, scales and mealybugs. Even though the fungi do not infect the tissues of the plant, their black coloration interferes with photosynthesis and fruit quality. Disease management depends mainly on management of honeydew forming insects. Washing the affected parts and improving ventilation in the canopy reduce the disease incidence.

G. **Nursery Damping-Off:** Damping off may occur in seedlings in nurseries due to attack by *Pythium*, *Rhizoctonia* and *Fusarium* species. Symptoms include constricting of stems at the soil line level followed by death. Soil sterilization, proper drainage, seed treatment, biological antagonists like *Trichoderma harzianum* and avoiding excessive irrigation are useful to prevent the disease (Ferrara, 2019) ^[8].

23. Harvest Maturity and Harvesting

Proper harvesting of tamarind at the right time of maturity is important to get better quality pulp, higher levels of acidity and sugar, better processability, longer storage life and market value. Since the fruit is mainly processed and not consumed in fresh form, tamarinds should be harvested at physiological maturity. Unripe pods contain immature pulp with high water content and low sugar content, while delayed harvesting increases the risk of insect infestation, fungal infection, pod cracking and quality loss (Singh *et al.*, 2021) ^[21]. Under Indian conditions, the fruits usually mature 8-10 months after flowering and are harvested between January and April, according to the cultivars and climatic conditions. Pod maturity can be known by change in the pod colour from green to brown, brittle pod shell, low pulp moisture and appearance of reddish-brown pulp with pleasant sweet-acid taste. Mature pods contain 35-55° Brix total soluble solids, 8-18% titratable acidity and 18-30% pulp moisture, and these fruits are suitable for processing into concentrates, pulp, beverages, sauces and confectionery products (Mani *et al.*, 2020) ^[11, 12]. Fruit harvesting should be done during dry weather. Manual harvesting using ladders, fruit pickers or harvesting hooks is preferable to beating the branches which cause damage to future fruiting wood. Harvested pods should be collected properly and moved to the collecting centers for sorting and initial processing. Scientific harvesting will ensure minimum mechanical damage, lower post-harvest losses, maintenance of fruit quality and regular productivity in future harvests (Coronel, 1991) ^[3].

24. Post-Harvest Physiology

Tamarind is a non-climacteric fruit, therefore, it does not ripen after harvesting and has to be harvested at physiological maturity. The post-harvest changes include gradual reduction in moisture content, some pulp softening, stable soluble solids content and slower biochemical processes (Sookying *et al.*, 2022) ^[22]. Because of its high acidity and low moisture content, tamarind possesses low respiration rate, giving it relatively long storage life. Proper maintenance of optimum moisture level is essential because excess moisture favours fungal growth, fermentation and insect attacks, while excessive drying hardens the pulp and reduces processability (Keskar *et al.*, 1989) ^[9]. During storage, there will be gradual oxidation of polyphenolic substances leading to pulp darkening and slow reduction in vitamin C content. Proper drying, hygienic handling, moisture maintenance, proper packaging and cold storage will prevent microbial deterioration, preservation of nutritional quality and increase the storage life (Singh *et al.*, 2021) ^[21].

25. Post-Harvest Handling

- A. Grading:** Grading is an important post-harvest activity that guarantees uniformity of products, increases the market value and consumer satisfaction and makes the products competitive in international market (Donkor *et al.*, 2020) ^[6]. Tamarind is graded according to pod size and weight, pod length, shell integrity, pulp percentage, fibre content, number of seeds, pulp colour, moisture content and freedom from insect damage and fungal infections. The premium grade pods have uniform brown colour, intact shells, thick pulp, low fibre, good acidity and absence of contaminants. Processing industries usually grade deseeded pulp based on its moisture, colour, acidity and purity rather than the pod appearance. Modern grading techniques involve using vibrating screens, optical sorting, machine vision and image analysis with AI (Mani *et al.*, 2020) ^[11, 12].
- B. Packaging:** Proper packaging of tamarind helps to prevent mechanical damage, moisture absorption, insect infestations, microbial contamination and spoilage during storage and transport. Traditional packaging materials such as jute bags, bamboo baskets, wooden boxes, and palm-leaf baskets are relatively cheap but offer poor protection. Modern packaging of tamarind includes corrugated fibreboard boxes, food-grade polyethylene bags, vacuum and laminated foil packages, polypropylene bags, HDPE containers and plastic crates (Donkor *et al.*, 2020) ^[6]. Vacuum packaging and Modified Atmosphere Packaging (MAP) technologies increase the shelf-life of tamarind by reducing the levels of oxygen and inhibiting microbial activity. Industrial pulp of tamarind is usually pressed into blocks of 5 – 25 kg and packaged in polyethylene lined cartons. The packing material must be moisture proof, strong, pest-proof, food grade and tear-resistant. Package labels must have information about cultivar name, grade, weight, date of processing, batch number, storage conditions and traceability (Mani *et al.*, 2020) ^[11, 12].
- C. Storage:** Proper storage is important for maintaining quality of tamarind fruit since it is marketed round the year despite being a seasonal crop. Dried pods containing less than 20% moisture can be kept for 6 – 12 months under cool and dry storage conditions with reduced fungal growth and insect infestations. Proper storage conditions for tamarind fruit include a temperature of 5 – 10°C, relative humidity 60 -70%, good ventilation, darkness and protection from rodents and insects. Pulp of tamarind packaged using vacuum and stored in refrigeration facility remain acceptable for 12 – 18 months with minimal deterioration in quality. Regular inspections are necessary to check for signs of fungal infection, insect attacks, moisture migration and package damages. Adoption of Good Storage Practice (GSP), Hazard Analysis Critical Control Points (HACCP) and Good Manufacturing Practices (GMP) ensures food safety and export quality standards.
- D. Cold Chain Management:** Though tamarind is more stable than most of the tropical fruits, cold chain management is important to maintain quality of premium products, processed pulp, concentrate and exported consignments. In cold chain, tamarind is shifted to cooler places soon after harvest and stored at controlled temperatures. Continuous refrigeration at all stages of storage, transport and marketing prevents the losses of moisture, microbial growth, enzymatic changes and oxidative spoilage. Modern cold chains consist of refrigerated ware houses, insulated transport facilities, temperature and humidity monitoring, data loggers and digital traceability system. Cold storage is particularly useful

for vacuum-packed pulp, concentrates, ready-to-use ingredients and other value-added tamarind products for long storage and export (Mani *et al.*, 2020) ^[11, 12].

- E. Transportation:** Proper transportation is necessary to make sure that tamarind fruit after harvest reach the processing unit and markets without quality deterioration. Tamarind pods should be transported in clean and well-ventilated vehicle protected from rain, direct sunlight and mechanical vibrations. Plastic crates are better option than traditional gunny bags to reduce the risks of compression damage and better air circulation. Bulk processed pulp should be transported in closed food-grade containers in hygienic condition. For long distance exports of high-value processed products, use of refrigerated containers is necessary. Modern logistics which include GPS tracking, digital inventory management and real-time temperature monitoring systems further improve efficiency of the supply chain (De-Caluwé *et al.*, 2010) ^[5].

26. Advanced Post-Harvest Technologies for Tamarind

- A. Minimal Processing:** Minimal processing consists of cleaning, removing of shell, deseeding, removal of fibre, grading, compressing of pulp and hygienic packaging without compromising the natural quality of tamarind fruit. Modern stainless-steel equipment and adherence to GMP, GHP and HACCP principles result in safe, hygienic and uniform products with efficient processing, exportability and consumer convenience (Mani *et al.*, 2020) ^[11, 12].
- B. Vacuum packaging:** Vacuum packaging removes the air from the package, thus reducing oxygen concentration and delaying oxidation, microbial growth, insect infestation and moisture loss. It maintains colour, flavour, acidity and nutritional quality of tamarind pulp for 12 – 18 months at refrigeration conditions and therefore is suitable for pulp blocks, concentrates, powders and export products.
- C. Modified Atmosphere Packaging (MAP):** Modified Atmosphere Packaging extends the shelf life by lowering the oxygen and increasing carbon dioxide and nitrogen in the package. This technology reduces microbial growth, delays oxidation, maintains flavour and colour and improves storage stability and export quality of premium tamarind products.
- D. Controlled Atmosphere (CA) Storage:** Controlled Atmosphere storage controls oxygen, carbon dioxide, temperature and humidity level and thereby minimizes quality deterioration. While it is mostly used for processed tamarind products, concentrates and pharmaceutical grade raw materials, it increases long-term storage and export competitiveness.
- E. Edible Coatings:** Edible coatings made up of chitosan, alginate, pectin, starch, gum arabic, aloe vera and tamarind seed polysaccharides prevent moisture loss, oxidation and microbial contamination. These biodegradable coatings improve shelf life, quality and help in circular bio economy by utilizing tamarind processing by-products (Keskar *et al.*, 1989) ^[9].
- F. Active Packaging:** Active packaging contains oxygen scavenger, moisture absorber, antimicrobial sachets and antioxidant releasing films and reduces oxidation and microbial growth. It improves the shelf life and stability of processed tamarind products especially during long-distance transportation and export.
- G. Intelligent Packaging:** Intelligent packaging makes use of sensors, RFID tag, QR code and freshness indicators for monitoring storage conditions and product quality in real

time. It increases traceability, food safety, inventory management and consumer satisfaction in supply chain (Marles & Farnsworth, 1995) ^[13].

- H. **Cold Plasma Technology:** Cold plasma is a non-thermal technology that produces reactive species that eliminate bacteria, fungi, moulds and eggs of insect without affecting the nutritional quality. It is useful for surface decontamination, seed sterilization, packaging sanitation and extension of shelf life.
- I. **Ozone Treatment:** Ozone treatment uses gaseous or aqueous ozone to kill microorganisms and insect pests without any harmful chemical residues. It improves food safety, reduces microbial contamination and prolongs the shelf life and is therefore eco-friendly sanitization technique in tamarind processing (Keskar *et al.*, 1989) ^[9].
- J. **Food Irradiation:** Food irradiation uses gamma rays, electron beams or X-rays to control insects and microorganisms without changing nutritional quality. It is useful for quarantine treatment, reduction of mould growth, shelf life extension and improvement in export acceptance at approved safety limits.
- K. **High Pressure Processing (HPP):** High Pressure Processing (300–600 MPa) is a non-thermal technology that inactivates spoilage and pathogenic microorganisms while preserving natural colour, flavour, vitamins and bio-active compounds. It is particularly useful for premium tamarind beverages, concentrates, sauces and ready-to-use products.

27. Process of Tamarind

There has been an increased demand for tamarind processing because of various uses in the food, beverage, pharmaceutical, cosmetic, and industrial industries. Processing of tamarind improves food safety, prolongs shelf life, reduces post-harvest losses, and adds value according to GMP, HACCP, and ISO 22000 standards. The process starts from harvesting, cleaning, sorting, shell removal, fibre removal, de-seeding, pulp extraction, processing, packaging, storing, and marketing (Sookying *et al.*, 2022) ^[22].

The general process includes: Harvesting → Cleaning → Sorting → Shell Removal → Fibre Removal → De-seeding → Pulp Extraction → Concentration/processing → Packaging → Storing → Marketing

- A. **Tamarind Pulp:** Tamarind pulp is a major commercially produced product from tamarind fruits by cleaning, shelling, de-seeding, and pressing mature fruits into blocks or pastes. Commercial pulp usually has 18-25% moisture, 45-65° Brix TSS, 8-18% tartaric acid, and 25-45% total sugars. Vacuum-packed tamarind pulp can be stored for more than one year under refrigeration with minimal quality degradation (Sookying *et al.*, 2022) ^[22].
- B. **Tamarind Paste:** Tamarind paste is a product made through blending de-seeded tamarind pulp with water then filtration, concentrating, and pasteurization. It is used in sauces, curries, chutneys, pickles, ready to cook foods, and catering industries. The paste is normally packed in laminate pouches, glass bottles, or food grade plastic containers (Keskar *et al.*, 1989) ^[9].
- C. **Tamarind Concentrate:** Tamarind concentrate is made through vacuum evaporation which removes excess water without compromising its flavour and organic acids. It has increased shelf life, uniform quality, and lower transportation costs making it ideal for beverage production, sauces, food

production, and pharmaceuticals.

- D. **Tamarind Powder:** Tamarind powder is made through spray drying, drum drying, freeze drying or vacuum drying. This product has the advantage of easy handling, reduced storage space, long shelf life, and is extensively used in spices, instant soups, seasoning, snacks, and ready to eat foods.
- E. **Tamarind Beverages:** Ready to serve drinks, syrups, squashes, nectars, carbonated beverages, and functional drinks are being prepared from tamarind pulp with improved taste and nutrition. These products may also have added vitamin C, probiotics, herbal extract, and natural antioxidants.
- F. **Tamarind Chutney:** Tamarind chutney is traditionally produced value-added product made from tamarind pulp through blending with sugar or jaggery, salt, spices, ginger, garlic, cumin, and black pepper. Hygienic processing and proper packing improve its shelf life while maintaining its special flavour (Keskar *et al.*, 1989) ^[9].
- G. **Tamarind Candy:** Sweet tamarind variety is used to prepare tamarind candy through mixing with sugar and flavouring agent then molding, drying, and packing. Tamarind candy is liked by kids and has good domestic and export potentials (Mani *et al.*, 2020) ^[11, 12].
- H. **Jam, Jelly, Sauce, and Pickle:** Tamarind pulp is converted into jams, jellies, sauces, and pickles either alone or in combination with sugar, pectin, tomato, chilli, garlic, onion, vinegar, ginger, mango, or vegetables. These products have high consumer acceptance, increased shelf life, and high commercial value.
- I. **Tamarind Sauce:** Tamarind sauce is an important value-added product used as condiments in Asian, African, and Latin American cuisines. It is made by combining tamarind pulp with tomato, garlic, chilli, onion, sugar, vinegar, and selected spices. Tamarind sauce has high commercial demand (Keskar *et al.*, 1989) ^[9].
- J. **Tamarind Pickle:** Tamarind pickle is made through use of tamarind pulp either alone or in combination with mango, chilli, garlic, ginger or mixed vegetables. Proper fermentation, hygienic processing, and appropriate packing improves shelf life, flavor, and consumer acceptability.
- K. **Tamarind Seed Processing and Tamarind Seed Kernel Powder (TSKP):** Tamarind seeds constitute 30-40% of the fruit and are important industrial by-product with high content of protein, dietary fibre, minerals, and polysaccharide known as galactoxyloglucan. Roasting or mechanical decortications are used to remove the seed coat then kernel is milled to form Tamarind Seed Kernel Powder (TSKP), an important raw material in food, pharmaceuticals, textiles, paper, adhesives and other industries.

31. Economics of tamarind cultivation

Grafting tamarind is highly profitable and sustainable business because of its high longevity period of more than 100 years, low maintenance, excellent drought resistance, stable market, and value addition possibilities. As opposed to seedlings that take 8-12 years to fruit commercially, grafted plants start bearing fruits after 4-6 years. Under scientific management practices, matured grafted plants produce 150-300 kg of fruits per tree annually while elite varieties can produce even more. Major expenses in cultivation include land preparation, procurement of quality planting materials, irrigation, fertilizers, cultural practices, labour, harvesting, processing, and packing (Donkor *et al.*, 2020) ^[6]. However, these expenditures are covered through the long

productive period and relatively low maintenance expenses. Profitability can be increased by using scientific post-harvest management and value addition practices. Value addition through processing tamarind into products such as pulp, paste, concentrate, powder, beverages, sauces, chutney, candies, and seed kernel powder increase the value of the produce compared to the sale of raw pods. Increased demands from the food, pharmaceutical, cosmetic, and industrial sector besides export possibilities make tamarind cultivation profitable venture (Marles & Farnsworth, 1995) ^[13].

32. Marketing and export potential

India is the world's largest producer and exporter of tamarind and its value-added products, supplying both domestic and international markets. Major export destinations include the United States, United Kingdom, Canada, United Arab Emirates, Saudi Arabia, Malaysia, Singapore, Japan, South Korea, Australia, and several European Union countries. Exported products include whole pods, tamarind pulp, concentrate, paste, powder, tamarind seed kernel powder (TSKP), sauces, chutneys, and other processed food products. The increasing global demand for natural ingredients, functional foods, and processed fruit products has created significant opportunities for the tamarind industry. Establishment of Farmer Producer Organizations (FPOs), processing clusters, improved post-harvest infrastructure, GI tagging of region-specific cultivars, organic certification, branding, quality assurance, and e-commerce marketing can substantially enhance market access, export competitiveness, value addition, and farmers' income while promoting sustainable growth of the tamarind sector (Donkor *et al.*, 2020) ^[6].

33. Future prospects

Future prospects of tamarind production depend upon advanced breeding and sustainable agronomic and processing technologies. Some of the important fields for future research include development of high yielding dwarf and climate resilient varieties by means of genomic and marker assisted selection and use of orchard management techniques involving artificial intelligence, precision irrigation, remote sensing, drone based monitoring and robotic harvesting. Future research on tamarind cultivation should focus on post-harvest management, development of biodegradable packages using tamarind polysaccharides, carbon neutral processing and circular bio-economy approach with utilization of seeds, shells and other waste products of processing. Further development of organic production systems, block chain enabled traceability, export-oriented quality certification and value-added processing will help in ensuring better market access and competitiveness. Future sustainability of tamarind production would greatly depend upon integration of digital agriculture with sustainable value chains.

34. Conclusion

Tamarindus indica L. is a valuable multipurpose fruit tree with significant importance in food, nutrition, medicine, industry, and sustainable agriculture. Its drought tolerance, adaptability to marginal environments, and long productive life make it an ideal climate-resilient crop. Adoption of improved cultivars, vegetative propagation, scientific orchard management, balanced nutrition, precision irrigation, and integrated pest and disease management can significantly enhance productivity and fruit quality. Modern post-harvest technologies, including scientific harvesting, hygienic processing, improved packaging, and cold-chain management, reduce losses and improve shelf life. Value-added products such as pulp, paste, concentrates, beverages, sauces,

seed kernel powder, and nutraceuticals offer excellent opportunities for income generation and agro-industrial growth. Future emphasis on genetic improvement, climate-smart production, precision agriculture, sustainable processing, and circular bio-economy will further strengthen tamarind's role in sustainable horticulture, rural livelihoods, and the global bio-based economy.

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