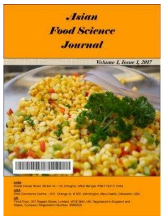

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Tamarind (*Tamarindus indica* L.), an Underutilized Fruit Crop with Potential Nutritional Value for Cultivation in the United States of America: A Review

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Authors' contributions

This work was carried out in collaboration between both authors. Author SSSN researched cultural practices, reviewed the literature and wrote the first draft of the manuscript. Author CJC edited the manuscript and served as consultant. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Tamarind is a perennial fruit crop revealing its potential as a viable resource vegetable of excellent nutrition. The late flowering types of tamarind are best suitable for cultivation in USDA Hardiness Zones 9-11, which include the warmer portions of California, Arizona, Alabama, Mississippi, New Mexico, Louisiana, Texas, and Florida. Germplasm introduction and evaluation trials will help to enhance cold hardiness, create variability in available genetic resource, and enable increased production of tamarind for various purposes.

Keywords: Indian date; cultivation; perennial; fruit; vegetable; ornamental; nutritional value.

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ABBREVIATIONS

µg (micrograms); g (grams); mg (milligrams); kg (kilograms); cm (centimeters); m (meters); % (percent); IU (International Units); USDA (United States Department of Agriculture); USA (United States of America); WHO (World Health Organization); NOAA (National Oceanic and Atmospheric Administration); PDSI (Palmer drought severity index); Codes for states of USA- AZ (Arizona), AL (Alabama), CA (California), FL (Florida), LA (Louisiana), MS (Mississippi), NM (New Mexico) TX (Texas), Virginia (VA).

1. INTRODUCTION

Vegetables provide nutritional benefits for humans, pets and livestock. They provide essential phytonutrients in the form of carbohydrates, proteins, and essential fatty acids to overcome nutritional deficiencies in rural and urban populations. Humans benefit from a year-round supply of nutritious vegetables, fruits and flowering ornamental crops [1]. The World Health Organization's (WHO) recommends a dose of 400 g of vegetable consumption per day [2].

Annual vegetable production is seasonal and often requires: 1) regular irrigation, 2) fertilizer and pesticide applications, 3) labour-intensive farming operations from planting through harvesting and marketing, and 4) postharvest processing and storage. Cultivation of perennial vegetables reduces yearly investment on labour and inputs. Furthermore, one-time investment of perennial crop establishment provides the producer with an advantage of concentrating on diversified farming operations without the requirement of yearly replanting.

In developing countries, government, public and private sectors are concentrating mainly on the production of commercially important seasonal vegetable crops like cucurbits, okra, tomato, onion, green beans, peppers, lettuce, and garlic to earn income from domestic and global markets and to sustain processing industries. In developed countries like the United States of America (USA), farmers are adapted to grow collards, cole crops, peas, beans, mustard greens, turnip greens, chard, spinach and kale produced in greenhouses or in the field to supply local markets (www.hort.purdue.edu).

Reasons for not growing any new or promising vegetable crops may include: 1) lack of market demand, 2) lack of awareness of potential for profit, 3) lack of knowledge on cultivation practices, including potential sources of planting material, 4) lack of suitable land [3,4,5]. In USA, the undercultivation of nontraditional crops results in it being dependent on developing countries to supply these crops as either raw food materials or processed functional foods.

Tamarind (*Tamarindus indica* L.) is a diploid (2n=24), under-cultivated, unimproved, dicotyledonous, vegetable legume belonging to the family Fabaceae, sub-family Cesalpinoideae. Tamarind is a perennial leaf and fruit vegetable with profuse flowering habit having ornamental value. Tamarind consumption prevents malnutrition and chronic human diseases, and supplies necessary macronutrients (carbohydrates, proteins and fats), micronutrients (calcium, iron, iodine, manganese, magnesium, zinc), fiber, vitamins A, C, D, folic acid, and other vital compounds [3,5,6,7].

Tamarind is a heterozygous and highly cross-pollinated crop. It is known for its wide distribution, adaptability to marginal land, freedom from pests and diseases, meagre demands in terms of input and attention for its cultivation. The fruit is the most commonly used part (100%). Tamarind fruit beverage made from pulp is the most popular drink (100% citations) indicating that pulp is consumed by all respondents in west Africa. Tamarind fruit was eaten as a snack and has most (98.3%) citations. The lowest percent citations were on ethno-medicinal (13%) and ethno-veterinary (15%) uses of tamarind (Table 1) [5]. Here the per cent citations indicate the potential benefits of direct consumption of fruit.

A single raw fruit (100 g) of tamarind provides 239 kcal of energy, carbohydrates (62.5 g), protein (2.8 g), 0.6 g total fat (0 cholesterol), dietary fiber (5.1 g); vitamins like folates (14 µg), niacin (1.94 mg), pantothenic acid (0.14 mg), pyridoxine (0.07 mg), thiamin (0.43 mg), vitamin A (30 IU), vitamin C (3.5 mg), vitamin E (0.1 mg), and vitamin K (2.8 µg); electrolytes - sodium (28 mg), potassium (628 mg), minerals such as calcium (74 mg), copper (0.86 mg), iron (2.8 mg), magnesium (92 mg), phosphorous (113 mg), selenium (1.3 µg), zinc (0.10 mg), and 18 µg of beta carotene (USDA nutrient database).

Compared to 100 g of raw fruit, the ripe fruit pulp provides 30-40% inverted sugars, more folates (59.35 µg), tartaric acid (18.52 g/100 g), soluble solids (44 ^{o}Brix) and vitamin E (108.78 µg/g), but less dietary fiber (4.13 g/100 g), vitamin C (4.79 mg/100g) and carbohydrates (50.07g/100g). Red pulp is sweet, while brownish green pulp is acidic in taste [7].

Tamarind fruit supplies vitamin A in the form of pro-vitamin A containing carotenoids and is bioavailable to supply the required amount of recommended retinol equivalents (500-600) per day [8]. Dark green mature leaves are sour and young foliage with immature leaves is sweetish sour in taste. On India's southeastern coast, fresh young and immature foliage is consumed either with other vegetables or with meat, fish or shrimp (S Narina, survey on tamarind cultivation, constraints, practices from local communities, farmers in villages of East Godavari District, Andhra Pradesh, India during January and February, 2018). The seed, seed powder, fruit pulp and ripe fruit cakes are exported for industrial, medicinal and culinary purposes (Table 1). A single tamarind tree can yield 200-1000 kg of unprocessed fruits per year and net return from one-acre is $207 in one year in India [9].

Little research has been published on tamarind cultivation. The tamarind tree is long lived, with the ability to survive for more than 200 years. The plantations that were in South Asia today are planted in periods of times unknown. In southeastern Asia and west Africa, tamarind has been self-propagated (52%), 45% was planted and the remaining 3% was unknown [9,3,5]. Tamarind is a slow growing tree used in home gardens, roadsides, farm boundaries, and as an intercrop (87%) in between commercial mango or coconut orchards in the past [3,5]. Cultivation since the 1990s has been primarily for pulp production (S Narina, survey on tamarind cultivation, constraints, practices from local communities, farmers in villages of East Godavari District, Andhra Pradesh, India during January and February, 2018).

Tamarind has been introduced to south Florida, cultivated mainly as a shade tree along roadsides and was stored in herbaria at several counties for educational purposes (www.plantsinusa.com, www.usda.gov).

Being fruit with several food and medicinal values, the scientific literature is limited to bio-medicinal, food and nutritional journals and deals mostly with functional compounds and bio-fortified foods or herbal phytomedicines made from its pulp extract, fruit, root and leaves (Table 1).

Tamarind is widely distributed in tropical and subtropical regions of the world including parts of Europe, India, Southeast Asia, the Middle East, the Sahel region of Africa, the Caribbean and the South and Central America [7]. In tropical Asia, where tamarind is commonly seen, the temperatures range between 25°C and 30°C.The

Table 1. Tamarind plant parts and their uses

Mode of use	Plant parts/products and uses
Food	Fruit pulp and fried seeds are eaten raw as snack; raw fruit, flower, leaves as salad; pulp used as preservative, and to prepare several culinary dishes, chutney, tamarind juice concentrate, pulp powder, pectin, jams, syrups, candy, and for making souring porridge, tartaric acid, alcohol, summer refreshing drink, seasoning, flavouring.
Fodder	Foliage and cooked seeds used as animal feed.
Agriculture	Flowers used for honey production; roots fix nitrogen in soil.
Fuel	Tamarind wood is good firewood (4850 kcal/kg) and excellent charcoal. But no one uses for firewood in general in Southeast Asia.
Timber	Sapwood is light yellow and heartwood is dark purplish brown, very hard, durable and strong used to make a variety of tools, furniture and utensils, poles, posts, boats, building materials; it is sold in USA as "madeira mahogany".
Tannins	Both leaves and bark are rich in tannins to yield ink and dye.
Lipids	Seed oil for paints, varnishes and for oil burning lamps.
Medicine	Leaves, twigs, bark and roots have medicinal value; bark decoction used for asthma, amenorrhea, used as a febrifuge and a digestive tonic, used to treat sores, rashes, ulcers, boils; leaf decoction is used to treat throat infection, rheumatism, cough, fever, intestinal worms, conjunctivitis; pulp is a mild laxative and used to treat scurvy; seeds used to cure dysentery and diarrhea [6] .
Other uses	Pulp is used to clean copper and brass utensils; seed pectin used for sizing textiles; tree is a host for wild silk worms; tree is a windbreak, live fence, ornamental plant in parks, roads and river banks for aesthetic value and shade; wood is ground and used as mulch for flower beds.

[5,6,7], and primary author's survey, 2018

relative humidity is above 80% throughout the year with high humidity during night and low humidity in day during the dry season [10].

Tamarind is a unique and relatively non-perishable food crop with many additional uses of the plant. Introduction of tamarind in hardiness zones 9-11 of the USA (Fig. 1) has the potential to enhance the agriculture, silvipastural, ornamental horticulture and landscaping, food and pharmaceutical industries. The cold hardiness and other potential genetic traits can be enhanced through selection and breeding.

Therefore, the presented review was done with the following objectives: 1) provide necessary resources for possible cultivation of tropical and subtropical tamarind germplasm lines in plant hardiness zones 9-11 of the USA, which includes the warmer parts of the states of Arizona (AZ), Alabama (AL), California (CA), Florida (FL), Louisiana (LA), Mississippi (MS), New Mexico (NM), Texas (TX), and Virginia (VA) 2) investigation of fruit and/or vegetable leaf production in these regions using either field production or protected cultivation, and 3) investigation of ornamental and landscaping uses.

2. DATA COLLECTION FOR LITERATURE ON TAMARIND, SOIL AND CLIMATIC RESOURCES OF USA

The literature on tamarind available online on July 25, 2018 in Google was downloaded with search terms: tamarind, cultivation, perennial, fruit, propagation materials, methods, vegetable, uses, production, processing, nutritional, industrial use, economics, medicinal values and other details as necessary for the objectives and purpose of the review. The articles were read thoroughly, the important points noted and organized.

The prevailing soil and climatic conditions that were suitable for cultivation of tamarind in USA are described in detail below.

2.1 Soil Type Compatibility

The soils are taxonomically classified into orders, suborders, groups, subgroups, families and series. There were 19,000 soil series among which Alfisols (13.9%) and Inceptisols (9.7%) are most commonly seen in USA. Great Plains are with black earth comprised of Mollisols (21.5%), and western US has Aridisols (extremely dry 8.3%). North eastern parts, higher elevations of western parts, Florida and other coastal regions of US are with Spodosols (3.5%) containing illuviated soils with organic matter in B-horizon. These are similar to the podzols of Eurasia and Canada. Ultisols (9.2%) are extensive in warm humid regions and Oxisols (0.02%) are in limited occurrence in tropical environments in USA. Entisols (12.3%) are newly formed alluvium, Histosols are organic soils lacking permafrost within 100 cm unlike Gelisols (8.7%) of Alaska [11].

2.2 Climate Compatibility

The climatic data retrieved on July 19, 2018 was averaged for a period of 123 years from 1895 to 2018 [11]. The range of mean monthly temperatures in degrees Fahrenheit (^{o}F) were listed in parentheses for each month: January (26-36), February (25-41), March (35-50), April (48-55), May (58-66), June (66-72), July (71-77), August (69-75), September (62-69), October (49-59), November (37-48), December (26-37).

The range of mean monthly precipitation in inches (") were listed in parentheses for each month: January (0.98-3.79), February (1.03-3.32), March (1.02-4.00), April (1.46-3.65), May (1.81-4.44), June (1.45-4.28), July (1.79-3.86), August (1.88-3.55), September (1.44-3.59), October (0.54-4.29), November (0.95-3.92), December (1.28-4.06).

The range of mean monthly heating degree days in Fahrenheit (^{o} F) were listed in parentheses for each month: January (685-1184), February (555-974), March (381-840), April (251-475), May (86-285), June (20-77), July (3-19), August (6-40), September (31-132), October (171-412), November (406-679), December (585 -1057).

In USA, the southern and south-eastern states (TX, LA, FL, part of MS, AL, GA, SC, NC) were hot and humid, middle-east and south-eastern states (OK,KY,WV,VA,TN,DE, Part of IN, AR, MS, GA, SC, NC) with mixed humid climate, upper north east and north western states (WA, OR, NV, UT, ID, MT, WY, ND, SD, NE, MN, IA, WI, MI, PA, MD, NY, NH, MA, ME, NB, part of IL, IN, OH) with cold and extremely cold climate, south western states (CA, AZ, NM, TX) with hot-dry or mixed dry climate and limited regions of pacific coast (CA,OR,WA) had marine climate (Fig. 1) [11].

The Palmer drought severity index (PDSI) revealed occurrence of severe drought in 2010 after 1997 with PDSI index ranging from 1.72 to 4.65 and 3.38 to 5.62 respectively. There was also an observed decrease in incidence of drought from 1895 to today with intermittent trend (+ 0.03) drought spell per decade [11].

3. INFORMATION ON CULTIVATION OF TAMARIND

Most published work on tamarind has dealt with vegetative propagation methods, including budding and grafting [12]. Post-harvest pulp nutritional quality analysis was conducted for medicinal and food use [6]. One set of studies deal with dynamics of plant growth [3]. No information is available on genomic studies, germplasm resources or crop improvement.

3.1 Cultivation Requirements

3.1.1 Soil type

Tamarind can grow in almost all soil types but prefers well drained deep alluvial soils at pH 6.3. It was also seen in coastal sands, and rocky soils. Poor growth on shallow, and soils having calcareous hardpan was reported [3,13].

US soils are relatively fertile silts and clay that include loess, dune sands, alluvial sand, silt and glacial till with significant amounts of organic matter with particle size 0.002-0.05 mm in diameter with larger surface area. The clay soils have ability to retain many plant nutrient cations (e.g. Ca^{2+}, Mg^{2+}, K^{+}, NH_4^{+}) and make them readily available to plants [11]. It is likely that soils with even relatively low levels of cation

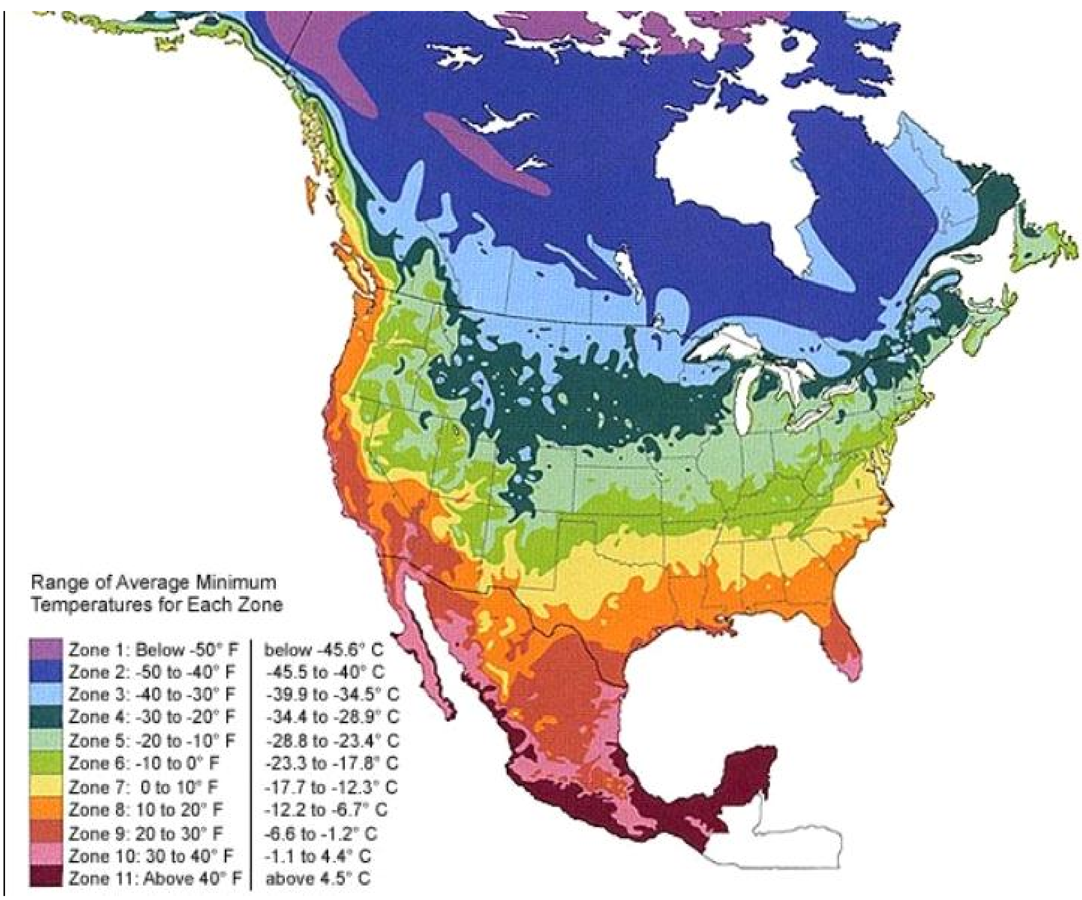

Fig. 1. Range of Plant Hardiness Zones in the United States of America Based on Average Minimum Winter Temperatures

Source: Climate Zone Map of North America retrieved on June 18,2018 from http://horticultureandsoilscience.wikia.com/wiki/Climate_Zone_Maps exchange capacity are suitable for tamarind, as its cultivation does not require high fertility levels, high soil water availability, or other inputs once trees are established.

3.1.2 Environmental conditions

Tamarind cultivation is most successful in environments similar to its native eastern Africa, which has extended dry season and warm climate in altitudes ranging from 0-1500 m above mean sea level (msl) with average temperatures ranging between 68°F and 91.4°F (20 and 33°C) and average rainfall ranging between 350 and 2700 mm [13] (John, 1990). In India, it grows in areas receiving 900 mm rainfall, temperature of 53.6°F - 98.6°F (12 - 37 °C) with an average relative humidity of 40-80%, at an altitude of 930 m above msl [3].

Tamarind is found in a wide range of biomes, including low altitude wooded lands, dry savannas and semi-arid grass lands. It was most common in indoor yards, parks, rivers and road sides, and on small stream banks. There were no reports about its occurrence in deep rainforests [13].

As a tree with large, strong branches and a deep root system, tamarind can tolerate severe drought, strong winds and tropical storms. It can also tolerate fog, cold, and coastal saline climate. However, subfreezing weather often results in damage or death, with young trees being most sensitive to cold damage [3,13,12].

Mature trees have been reported to withstand brief periods of 28°F (-2°C) without serious injury. From climate data, it was revealed that US has a range of 26°F to 77°F (-11.7°C to 21°C and above) temperature, 0.54" to 4.29" rainfall, 3 to 1184 ° Df heating degree days and a range of PDSI from -7 to 7 during a year [11]. Thus, it is likely that the range of cultivation in the USA would be limited to USDA Hardiness Zones 9-11.

A humid tropical climate receiving continuous rainfall has severe negative impact on growth and yield. Dry weather is important during fruit development, which occurs from late spring to early summer. Thus, the southwestern portions of the USA may be more conducive for tamarind grown for fruit production than states such as Louisiana and Florida, which do not have a dry season.

3.2 Planting Material

Trees propagated from seed are variable in quality. Grafting, budding and air layering are successful methods of asexual propagation. Under optimum growing conditions, seedlings begin to produce fruit in 6-8 years, while vegetatively propagated trees may begin to produce fruit in half that time.

Cultivars with red and brownish pulp types are popular in India. The red-fruited variety grown most commonly in India is *T. indica* var. *rhodocarpa* [13]. Cultivars that include ‘PKM-1’, ‘Prathisthan’, ‘Urigam’, ‘Tumkur’, ‘Yogeshwari’, ‘Makham Waan’ and ‘Manila Sweet’ have been selected and introduced [14]. Selected forms may have sweeter pulp than the species, early (fifth year) bearing, high yield potential, or attractive fruit qualities [15].

Selection of mid- and late flowering tamarind types is most beneficial due to their extended duration of maturity, to avoid alternate bearing and pollination uncertainties (unlike early flowering types), to overcome unpredictable environmental conditions and to reserve food resources in its past season's wood for maximum fruit set.

3.2.1 Sources for vegetative propagation material

Location: In India, agricultural research organizations were potential suppliers of vegetative propagation material. The research stations were located in Mahatma Phule Krishi Vidyapeeth, Rahuri and Horticultural Research Station, Andhra Pradesh Agricultural University, Pandirimamidi, Rampachodavaram.

Selection of propagation material: Propagation by cuttings, air layering, arch grafting, mound layering, cleft grafting, T-patch or chip budding, veneer and softwood grafting was attempted with varying rates of success [16]. Of the methods tested, softwood grafting and patch budding produced the highest number of propagules within 2-3 weeks.

Freshly defoliated (at the time of grafting) or naturally defoliated scion shoots (10 cm thick, 8-10 cm length) of red pulped genotypes having 3-4 buds were used for wedge and soft wood grafting in a grove that was cut at 15 cm height on six-month old root stock. In Andhra Pradesh, veneer and soft wood grafting were successful with 68% and 49% graft-take during October to December [12], while softwood wedge grafting and patch budding were most successful in

Rahuri with 50-60% survival during mid-April to mid-June and mid-October [16].

3.2.2 Sources of seed

Tamarind seed are available from any local grocery store or farmers market in commercial tamarind producing countries including southern parts of Asia, mainly Andhra Pradesh, Karnataka, Kerala, Maharashtra, Madhya Pradesh, Orissa, Tamil Nadu and Utter Pradesh states in India.

Selection of pure seed: Seed viability is the most important trait indicating the quality of seed which was contributed by 1) year of the seed produced, 2) weight of the seed, 3) fruit maturity stage of the seed harvest and 4) seed storage conditions.

Source of grafted plants: An online source for acquiring tamarind planting material was available with pricing ($10 for a 1.5ft grafted plant) at https://exoticflora.in/products/sweet-tamarind-fruit-plants-tree (Accessed on July 9, 2018).

3.3 Cultivation Practices

3.3.1 Planting

Tamarind most commonly appears on farmland as an intercrop, on stream banks and commercially cultivated in hilly forest and tribal regions of Pandhirimamidi in Andhra Pradesh (AP), India. More than 50% orchards were self-propagated, supplying tamarind for the entire state of AP, national and international markets from periods of unknown time.

In Thailand, the cultivars grown are dwarf, vegetatively propagated, with early maturing sweet fruits. On plantations, seedlings were planted at a spacing of 13 m x 13 m. Intensive cropping systems use closer spacing (500 trees/ha) to achieve reduced tree size for easier harvests.

3.3.2 Vegetative (seedling) growth

Growth of seedlings is very slow with annual increase in height by 60 cm. Seedlings take 4-5 years or even longer to bear fruits. The grafted trees fruit within 3-4 years. In both young and matured trees, defoliation starts from February and continues until the first week of April. The tree starts producing new growth just before the completion of defoliation in April.

The moisture content of mature trees is very low during the dormant season, and increases during active growth stages, which include the rainy season. Increased trunk diameter was observed in non-bearing trees but not in bearing trees. Furthermore, the Carbohydrate:Nitrogen ratio was high (7.595) in flowering trees and was low (3.588) in non-flowering trees [3].

In perennial fruit trees, bud dormancy is induced during unfavorable climatic conditions (high temperature, low rainfall and low soil moisture), to restore internal nutrient status for better yields during cropping years. In tamarind, shoot tip abortion is an induced trait during unfavorable environmental conditions (drought evading mechanism). This supports sylleptic branching producing copious amount of vegetative growth by lateral or terminal bud sprouts first before the onset of rains, followed by the sprouting of pseudo-terminal buds leading to sympodial branching patterns during the rainy season [3].

Active shoot growth (first and second growth flush) during the wet season alternates with slow shoot growth (flowering to fruiting stage) during the dry season. Thus, tamarind has a well-established phenological system of leaf shedding after fruit ripening to avoid drought during the critical period of moisture stress (February-April in South Asia). The flowering stage coincides with the third growth flush. On average, there are five to six vegetative growth flushes per year. More are possible with high soil moisture or extension of the rainy season [3]. Information on the seedling, flowering and fruiting stages is shown in Fig. 2.

Management Practice: Tamarind responds well to coppicing and pollarding to regulate tree height for mechanical harvests. In the case of fruit crops, the amount of fruit set can be improved by de-blossoming and de-fruiting two and four months after fruit set, respectively in early flowering types. Root pruning is necessary once a year in fruiting orchards. If an increase is desired in the number of leaf cuttings, scheduled irrigations might be required at weekly intervals or as necessary.

3.3.3 Flowering stage

Flowering was observed from March to August in India on the previous season’s wood and about 36% of the new growth on bearing trees produced terminal inflorescences (panicles) [3]. There was a positive relationship among panicle length, number of flowers and fruits per panicle. On average, 5-6 months of heat units were required from flowering to maturity [3].

Distinct flowering durations were observed in seedling populations of tamarind. Flowering duration of 104, 93 and 69 days respectively, for late flowering (May-August), mid flowering (May-July) and early flowering (April-May) types [3].

A maximum number of heat units were required for fruit development in early flowering types (878) compared to mid and late flowering types (802). Early flowering types have less fruit due to self-incompatibility, and more flower and fruit drop due to moisture stress during fruit set. Mid and late flowering types have high fruit set resulting from higher number of fertilized ovules due to cross pollination and lack of moisture stress during fruit set. In the USA, the months from April to October (3-412^{o} F) with maximum number of heat units are the best for introducing late flowering genotypes of tamarind. These months have compatible climate with favorable heating degree days for active vegetative growth, flowering and fruit set.

Management Practice: Regular irrigation, de-blossoming and de-fruiting should be done each year to increase the flowering capacity of the shoots.

3.3.4 Fruit growth and development

Fruit growth has three distinct phases: pre-maturation, maturation and ripening. The fruit development phases I, II and III are characterized by the initial period of slow growth (increase in cell number in fruits), the period of exponential growth (cell enlargement, accumulation of resources in seeds and pericarp), and the period of declining growth (ripening) respectively (Table 2). Fruit showed a typical sigmoid growth curve with a slow increase in the contents of total titratable acidity, sugar, and fiber up to 29 weeks (phases I and II), followed by a rapid increase during ripening (phase III).

Management Practice: Timely pruning is necessary once in a year to accelerate fruiting in the following year.

3.3.5 Maturity stage

Tamarind starts producing economic fruit yields after 7 years in a seedling orchard, and after 3-4 years in grafted tree orchards, and will continue for more than 200 years. Leaf yield starts in six months from the time of planting an orchard and will continue throughout the year.

Maturity indices: The color change in shell from green to brown is an indication of maturation (Table 2). During the ripening process, an increase from 1.8 to 30.2% in total sugar content and reduced moisture content of fruit (from 66%) and pulp (from 86%) to 16% were observed indicating readiness to harvest.

The level of tartaric acid is one fruit maturity index. It shows a decline in maturing fruit (up to 6-7 months after fruit set) due to development of the seed, and then a steady increase during ripening (from 7-9 months after fruit set). Twenty-six weeks after anthesis, the pulp weight decreases, but the seed weight increases for 2-3 weeks. After 30 weeks, there was a decline in the weights of seed (until 34 weeks) and pulp (36 weeks).

Management Practice: Analysis of sample fruits prior to harvest is necessary because tamarind fruits will not ripe uniformly if harvested immature. Leaf harvests are recommended at monthly intervals following the skip row method during critical market demand for leaf vegetable. The skip row method extends the harvest season.

3.3.6 Harvesting stage

Tamarind fruits will be ready to harvest after 8-9 months after fruit set. Annual fruit harvest is 150 kg/tree or over 2 t/ha. In a year 12 leaf harvests at weekly intervals are possible during the peak season with the exact number of leaf harvests dependent on soil moisture availability, as new growth flushes depend on rains in unirrigated orchards.

Total sugars increased rapidly from 32-34 weeks, and titratable acidity was increased even after maturity until 36 weeks. At the time of harvest, the total acidity was 12.2%, total sugars were 30.2% and total soluble solids were 25oBrix. Well ripened fruit was similar to dry date fruit in having total sugar content of about 61% on a fresh weight basis and total acidity (tartaric acid) of 12.2 - 23.8% [3].

Management Practice: Regular root pruning for new root harvest, checking plantation for gaps, gap filling with grafted trees are recommended to aid in machine harvesting.

Table 2. Morphological changes during three major stages of fruit development

Developmental phase	Duration of phase (days)	Shell/Peel color	Pulp color	Seed color	Shell adherence	Other changes
Pre-maturation	154-158	Green	Greenish white	Light green	Shell differentiation visible between 78-84 days after anthesis	Volume of fruit reaches its maximum at the end of pre-maturation period
Maturation	50-60	Brown	Brown	Brown	Shell strongly adhered to pulp	Rapid increase in weight of fruit until the end of the maturation period
Ripening	60-70	Brown (increase in anthocyanin pigment)	Brown or red	Dark brown	Natural separation of shell from pulp	Drastic reduction in moisture content and increases in acidity and sugar contents

Source: [3]

Fig. 2. Morphological features of tamarind (*Tamarindus indica* L.) plant parts

Table 3. Common insect pests, and pathogens of tamarind tree and their control measures

S. No.	Name of the pest or pathogen observed and timing	Plant parts damaged, fed upon or attacked
A	**Insect pest (Family) / (scientific name)**	
1	Scale insects (Hemiptera: Diadpididae): October –November (Oriental yellow scale, *Aonidiella orientalis*, *Aspidiotus destructor*; black or olive scale, *Saisetia oleae*; tamarind scale, *Aspidiotus tamarindi*)	Suck the sap of buds, flowers, twigs, branches and feed on young fruits reducing crop yield
2	Larvae of tamarind weevil (*Caryedon serratus* Olivier)	Damage pods, seeds and fruits in field, and fruit and seeds in storage
3	Mealy-bugs (Hemiptera: Pseudococcidae): March (*Nipaecoccus viridis* and *Planococcus lilacinus*)	Feed on leaf petioles, tender and mature shoots causing of leaf fall and shedding of young fruit
4	Fruit borers (Lepidoptera: Pyralidae) during July-August (Stored nut moth or major fruit borer, *Paralipsa gularis* (*Aphomia gularis*); other fruit boring insects: *Dichocrosis punctiferalis, Phycita orthoclina*)	Damage pulp and seed causing 27-30% yield loss; caterpillars (18mm, stout, greyish with brown spots) infest the ripening pods on tree and persist with stored fruits continue the infestation to storage.
5	Stem borer	Stem, trunk
6	Tamarind seed beetle (Coleoptera: Bruchidae: Pachymerinae) (*Pachymerus gonagra* or *Caryedon sp*.)	Mostly storage pest, lays eggs on pods and seeds, larvae feed on pulp.
7	Tamarind seed borer [*Calandra (Sitophilus) linearis*]	Seed
8	Lesser grain borer, [*Rhyzopertha dominica*]	Infects stored seed
9	Larvae of *Achaea janata* Linn. (Lepidoptera: Noctuidae)	Feed on flowers (400-500 larvae per tree) resulting in reduced growth
10	Nematodes: *Xiphinema citri* and *Longidorus elongatus, Radopholus similis* (burrowing nematode); *Meloidogyne incognita*, (common root- knot nematode)	Affect roots of older tamarind trees in south India
11	White grubs of *Holotrichia insularis*	Feed on the roots of young seedlings
12	Insect adult feeders (Coleoptera: Curuculionidae) (*Myllocerus blandus, Myllocerus dicolor, M. viridis*)	Foliage feeders
13	Bagworm caterpillar (Lepidoptera: Psychidae) (*Chaliodes vitrea*; *Pteroma plagiophleps*)	Minor pests of tamarind foliage
14	Termites: (Isoptera: Kalotermitidae) (*Cryptotermus hainanensis*)	Fruits, flowers, bark, roots
15	Thrips:(Thysanoptera: Thripidae) - polypahgous (*Scirtothrips dorsalis*)	Flowers
16	*Cryptocrameri* spp. Westwood (Lepidoptera: Psychidae) and *Euproctis scintillans* (Lepidoptera: Lymantriidae) - polyphagous	Defoliator

S. No.	Name of the pest or pathogen observed and timing	Plant parts damaged, fed upon or attacked
17	Beetle larvae of *Lochmaeocles* spp. (Cerambycidae)	Damage to branches in Brazil
18	Butterfly, *Charax fablus* and *Taragama siva*	Foliage feeder
19	Aphids, *Toxoptera aurantii;* black citrus aphid, *Toxoptera aurantii*	Suck sap of leaf
20	Jassids, *Amrasca biggutula biggutula*	
21	Beetles of *Lasioderma serricorne* (Coleoptera:Anobiidae), *Calandra linearis* (Curculionidae), *Tribolim cataneum* (Tenebrionidae)	Fruit left for longer periods will be infested and carried over to storage
22	Rice weevil, *Sitophilus oryzae*	Infested pods and seeds in storage
23	Larvae of *Alphitobius laevigatus* and *Echocerus maxillosu*s and *Uloma* sp.	Minor pest on fruit
24	Cow bugs, *Oxyrhachis tarandus, Otinotus onerotus,* and *Laptoentrus obliquis*.	Leaves and Flowers
B	**Disease and pathogen (scientific name)**	**Plant Parts Damaged or Attacked**
1	Leaf spot-Fungal (*Bartalinia robilladoides*, *Exosporium tamarindi, Hendersonia tamarindi, Pestalotia poonensis, Stigmina tamarindii)*	Leaf
2	Leaf spot -Bacterial	Leaf
3	Powdery mildew (*Erysiphe polygoni, Oidium* sp.)	Mature, ripe fruit on trees and in storage
4	Sooty mold (*Meliola tamarindi*)	Tree, fruit
5	Stem disease (*Fracchiaea indica)*	Trunk
6	Rots: Stem rot (*Pholiota gollani*), collar rot (*Phytophthora nicotianae* var.*nicotianae*), root and wood rot (*Ganoderma lucidum*), Stem canker (*Hyoxylon nectrioides*), wood rot (*Lenzites palisoti*), trunk and root rot (*Stereum nitidulum*)	Stem, trunk and root
7	Bark parasite (*Myriangium tamarindii*)	Bark
8	Mold in refrigerated storage	On separated pulp
9	Saprot (*Xylaria euglossa*), brownish saprot, (*Polyporus calcuttensis*), and white rot (*Trametes floccosa*)	Tree

Source: [13,17] and https://www.infonet-biovision.org/PlantHealth/MedicinalPlants/Tamarind#simple-table-of-contents-3

3.4 Management Practices

3.4.1 Inter-cultural practices

Weeding is not necessary in tamarind orchards or when tamarind is used as an inter-crop in orchards with other fruits like mango, guava or sapota. Manual or mechanical weeding was recommended if annual vegetable, flower or fruit crops were planted in inter or intra-row spaces in tamarind. Inter-cultivation of weeds or machine hoeing or ploughing is recommended to control weeds, and to aerate the soil between trees.

3.4.2 Fertilizer or manure application

Manure may be added during summer in inter-row spaces, or a legume cover crop may be soil incorporated at 40 days of trees' vegetative growth to enrich the soil nutrient status. No other specific fertilizer application methods have been reported in literature. If tamarind is intercropped with wheat in temperate regions like the USA, fertilization should be done annually.

3.4.3 Pesticide application

There were a number of pests and diseases (>40) that may attack tamarind [13,17], (Table 3). Fruit borers damage maturing fruits, causing a great reduction in marketable yield, and ripe fruit in humid climates are attacked by beetles and fungi. Stored fruit and seed are commonly infested by weevils and larvae of the groundnut bruchid beetle in India. However, there are many reports on pest or disease-free tamarind trees and or its products in storage [5].

Season: Six major insect pest species were noticed causing initial damage at various growth stages of tamarind, namely fruit borer, mealy bug, hopper and scale, followed by hairy caterpillar and tree hopper which appeared from flowering to fruit maturity stage [17]. The author [17] also observed natural enemies of pests, e.g. dragon fly, damsel fly, red ant, black ant, spiders, ichneumonid wasp, orange wasp, praying mantid, lace wing and long horned grasshoppers.

Spiders were among the natural predators observed preying upon insects. Their population was noted as relatively high during September in India with 15 adults / tree [18].

Control measures: The insect pests and pathogens observed during the cropping season, were not considered serious in terms of economic losses, with the exception of the fruit borers. No chemical control measures were reported. Biological control measures were reported [17] that include use of natural enemies and larval parasites.

Key bio control agents included one larval parasite (*Cotesia* sp.) and three late larval parasitoids (*Charops* sp., *Brachymeria* sp. and *Xanthopimpla* sp.) that parasitized the larval and late larval stage of the stored nut moth, *P. gularis*. Stage specific mortality showed maximum mortality in early larval stage (22%) followed by the late larval stage (2-16%). Among the natural enemies, spiders (*Oxypes* sp., *Plexippus* sp., and *Olios* sp.) were observed as major biocontrol agents against scale insects and tree hoppers whereas, lace wing and praying mantid were the next major predators, preying upon scale insects and hoppers, respectively [17].

3.4.4 Pruning

Young trees are pruned to allow 3-5 well-spaced branches to develop into the main scaffold branches of the tree. Yearly pruning after trees reach a certain height maintains reduced tree size compatible with machine harvest [12]. Mainly pollarding, coppicing or less severe forms of pruning are required to maintain trees. Pruning is also required to remove dead or damaged wood.

3.4.5 Inter-cropping

Tamarind orchards are well suited for inter- and multi-storey cropping systems to include various crops of annual vegetable crops and seasonal fruit crops. These systems may benefit farmers by providing additional income through intense land utilization. A legume intercrop is recommended to enhance the orchard soil nutrient status. At different heights in a multi-storey cropping system, various fruit and vegetable crops can be planted that enable easy cultivation and harvesting.

Winter wheat should remain as a main component of any cropping system for the central great plains of the USA [19]. For arid and semi-arid regions receiving 300-500 mm rainfall per year in the USA where tamarind may be winter hardy, is a potential perennial vegetable crop that can be incorporated in a wheat-based cropping system rotating with forage legumes or annual leafy vegetables.

Crop's multi-storey intercropping system examples suggested by authors:

1) Tamarind - An annual cold tolerant vegetable (legume- beans/peas/fenugreek) or oil seed crops (canola/sesame/flax) - Seasonal fruit vegetable (papaya/moringa/tomato/brinjal) - shrubs (berries/cherries/vine crops/guava) - Tamarind.
2) Tamarind - An annual temperate oil seed crop (sesame/canola/flax) or annual flower crop (*Tagetus* / lilies) - Seasonal fruit vegetable (papaya/moringa/tomato/brinjal) - Sub tropical or temperate fruit tree shrubs (cherries/berries/cherimoya/*Atemoya*) - Tamarind
3) Tamarind - Forage legume – Wheat - Forage legume - Tamarind

3.4.6 Acclimatization, constraints and measures to overcome difficulties during introduction of tamarind

Acclimatization: Because of wide variation in seasonal climatic conditions, especially rainfall and temperature [11] in the USA, the screening and acclimatization of germplasm of tamarind and other new perennial leaf and fruit vegetable crops (e.g. tamarind, drumstick, curry leaf) is needed for research and commercial cultivation purposes. Selection of cold hardy genotypes and special care during acclimatization may enable increased production of these potentially profitable specialty crops in the future.

Constraints:

1) Orchard establishment costs, which may require additional, prior acclimatization in high tunnel greenhouses.
2) Costs for planting material and or germplasm screening.
3) Care and tools for cultivation and management.
4) Additional marketing costs for specialty crops.
5) Collaboration with other businesses or organizations that support research and production efforts related to introduction of new crops and intercropping with traditional crops.

Measures to overcome constraints: As mentioned, tamarind can be used in an intercropping system with traditional field crops. It can also be raised in nurseries specializing in propagation and sold as a crop for field production or as an ornamental plant in plant nurseries and garden centers. The sale of grafted plants can be profitable. Tamarind may enjoy wider marketing in the USA, as its population becomes more ethnically diverse and familiar with internationally known food crops. Selling tamarind fresh leaves or dried leaf powder to the international food stores may return $10 per pound, and is valued by Asian, American, and international communities due to its nutritional value and taste.

To overcome technical difficulties related to the procurement, care and management of tamarind, it is advisable to involve a horticulturist with experience in tropical crops. Such an individual can help in procurement of quality planting material, arboricultural practices, and technical aspects related to production of tamarind fruits and leaves for various food products. Involvement of educational organizations will help to create awareness about the crop, and to conduct agronomic, horticultural, genetic, taxonomic, marketing and economic studies while training future generations involving various technological innovations to enhance agricultural, food and industrial uses for tamarind.

3.5 Post-harvest Management

3.5.1 Processing

The pods are gathered when they are fully ripe. Fully ripened tamarind pods are composed of shell and fiber (11%), seeds (34%) and pulp or flesh (55%) [20]. The pods are shelled and separated either manually or mechanically to extract the flesh and seeds. The flesh or pulp is then separated from the seeds and dried in the sun for a few days to reduce moisture content.

Enzymatic oxidation of phenols is the common cause of naturally occurring tissue browning in tamarind, and the enzymes responsible are polyphenol oxidase (PPO), peroxidase and catalase. The processed flesh (pulp) is the richest source of tartaric acid (8-18%) and produces considerable income ($581,030,500 per year) from pulp export. A fruit to water ratio of 1:2 produces the highest yield of soluble and total solids. Pulp obtained with this method had about 13.2^{o}Brix and excellent fruit flavor with prolonged shelf life [20].

3.5.2 Storage and transport

The dried pulp or flesh is packed in leaf mats, polyethylene, jute bags, in aluminum foil or bamboo or wooden boxes and stored in cool dry places. Tamarind storage ability increased when salted (10%). The salted tamarind was then formed into thick massive mat [3] or balls and then sundried or steamed for a short time before long term storage [20].

The dried pulp or flesh is stored at room temperature for up to 4 months and at 39-41ºF (4-5ºC) for more than one year. It is shipped by refrigerated transport over long distances, and is shipped at room temperature for distances reached within 2 days without any loss in quality [21].

3.5.3 Marketing

Globally, tamarind pulp extract is marketed for food (as natural preservative, cooling and flavoring agent), pharmaceutical (antifungal, antiseptic, antimicrobial, antioxidant) and cosmetic (bleaching, skin hydrating agent) purposes, and as a fragrance oil for its sweet and sour essences (used in soaps, candles, air fresheners, bath oils, laundry products, etc.). The tamarind pulp extract markets for industries are divided into five global regions: North America, Latin America, Europe, Asia Pacific, Middle East and Africa [22].

4. CONCLUSION

In the USA, based on the mean climatic data provided, May-October was identified as the ideal season to begin cultivation, because of a relatively dry period in many regions with sufficient heating degree days for growth, flowering and fruiting of tamarind. Late flowering types (March to August) are best suited for the USA in drought prone areas, as soil moisture balance affects leaf shedding, sprouting of buds, fruit set, and fruit retention. Biological control measures ware useful to improve the yield and market quality of fruit.

Thus, a comprehensive review of the literature on tamarind makes future needs clear. Addressing these needs require the collaboration of educational and research institutions with private industry, by which both the public and private sectors will benefit. Collaborative research studies are needed on tamarind crop productivity, protected cultivation, genetics and genomic studies for crop improvement, and for industrial use traits (pod yield in terms of number, weight, length, pulp thickness, leaf yield). Because of the value of tamarind (trees, foliage, fruit, pulp and seed) in agriculture, food and nutrition, and medicine, it would be highly beneficial to collect a wide range of tamarind germplasm and conduct evaluations for useful traits. Selection of improved genotypes would enable tamarind to be grown more widely geographically and enhance its value and use globally.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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