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RESEARCH ARTICLE

# Exploring Tamarind: A versatile spice and innovative value addition in wine production

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## Abstract

Tamarind (*Tamarindus indica* L.) is a multipurpose ancient spice valued for its tangy-sweet flavor, which is being transformed through innovative post-harvest technologies into wine. The Fruit pulp is highly nutritious and various value-added products have been developed for easier handling, storage and transportation, while extending its shelf life. These products range from Tamarind toffee, Tamarind pickle, Tamarind jam, squash, wine and offering distinct flavors and potential health benefits. Table wine, fermented using tamarind pulp, is widely known for its medicinal properties and applications in the food industries. The must was extracted and fermented with sugar and two different strains of *Saccharomyces cerevisiae* (Red wine yeast and Belgian wit yeast), to produce wine from the pulp of red, sour and sweet varieties of tamarind. Bio-component and sensory analyses were conducted to identify the proximate and organoleptic attributes of the wine. The variation in proximate property values of wine were recorded as alcohol content (8.40% to 10.62%), moisture (23% to 29.5%), pH (2.38 to 3.45), ash (1.3% to 2.5%), total soluble solid (3.2 °Brix to 11 °Brix), titrable acidity (1 mg/ml to 5.1 mg/ml), carbohydrate (1.1% to 3.65%), vitamin C (10.3 mg/ml to 22.3 mg/ml), and antioxidant (37.1 mMol/l to 75.9 mMol/l). It was found that Belgian wit yeast yielded good production of wine from the sweet Tamarind. It showed optimal values for alcohol (8.14%), moisture (26%), pH (3.15), ash (2.1%), total soluble solid (9.3 °Brix), titrable acidity (2 mg/ml), carbohydrate (3.4%), vitamin C (22.3 mg/ml), antioxidant (74.6 mMol/l). It also registered the higher organoleptic values for flavor (7.3), color (7.0), aroma (6.5), consistency (7.5), taste (8.5) and overall acceptability (8.5). This research demonstrates a breakthrough in utilizing tamarind (*Tamarindus indica*) for producing value-added wine with optimal alcohol content (8%), high antioxidant activity (74.6 mMol/L) and excellent sensory attributes (8.5).

## Keywords

post harvest technology, proximate and sensory attributes, rural employment.

## Introduction

An alcoholic beverage is defined as a drink containing 5 to 95% ethanol, constituting the primary physiologically active component, while the other components are referred to as congeners (1). Alcoholic beverages are categorized into three classes based on their alcohol content: wines typically range between 9 to 16% alcohol by volume, beers contain 4 to 6% alcohol by volume, while spirits have an alcohol content varying from 20 to 50%. Wine is prepared from fruits and a variety of plants that can undergo fermentation to produce alcohol. It contains beneficial compounds, including polyphenols, antioxidants and flavonoids.

Fermentation plays a vital role in human development and is an ancient techniques of food preservation. Fruit fermentation involves the conversion of fermentable sugars into ethanol, carbon dioxide and energy. Carbohydrates in a fermentable form stimulate the fermentation process. The duration of fermentation differs depending on the alcohol content, maturation or aging; some wines require prolonged fermentation. It is usually performed by yeasts, especially the *Saccharomyces* genus (4). *Saccharomyces cerevisiae* ferments the sugars in fruit juices, converting them to ethanol and organic acids, which help preserve the wine (5-7).

Winemaking is a perfect example of beverage evolution, transitioning from art to a science-based method. Emerging research suggests that wine consumption, particularly red wine, may positively impact gut microbiota composition and promote digestive health (8). Excessive alcohol consumption can negate these benefits and pose health risks. Therefore, enjoying wine in moderation, combined with a balanced diet and healthy lifestyle, may contribute to overall well-being and longevity. While grapes are the most widely used raw material for winemaking, many fruits and berries, including tamarind, banana, passion fruit and pineapple, have also been successfully used (9).

Tamarind (*Tamarindus indica*), native to the tropical and subtropical regions of Africa, is a leguminous tree belonging to the Fabaceae family. Tamarind has a sour taste characteristic of tartaric acid (10). The tamarind tree bears edible pod-like fruit, which has a sour taste due to presence of tartaric acid and is used in preparation of several cuisines round the globe (11). Based on variations in pulp color, tamarind is classified into brown and red varieties and based on sugar content, it is categorized into sour and sweet types. Tamarind pulp contains several physicochemical components, including pectin, reducing sugars, proteins, fibers and cellulosic materials (12). Red tamarind is known for its reddish-brown color and a unique blend of sweet and sour flavors, rich in vitamins and minerals (13). Sour tamarind, characterized by its intense sweet-acidic flavor, has a high acidity level, giving it a distinctive, tangy taste. This makes it a popular ingredient in various culinary applications and an excellent choice for fermentation in winemaking due to its unique flavor profile and natural preservation qualities (14). Sweet tamarind features a mild, pleasant taste, packed with sugars and providing essential nutrients like vitamins and antioxidants (15). These varieties highlight the diverse flavor profiles and nutritional compositions that make tamarind a unique fruit. Tamarind contains both nutritional and medicinal properties, including active antioxidant, anti-inflammatory, antimicrobial and antifungal compounds utilized in traditional medicine (14). Post-harvest losses remain a significant challenge hindering agricultural development worldwide. Recent estimates show that more than 60% of low-pH fruits, such as mangoes and oranges, experience post-harvest losses. This results in nutrient depletion, quality degradation and damage to the fruit's physiological structure before consumption or processing into secondary products. The seasonal availability of raw materials also limits consumption and value addition.

The fruit pulp of tamarind is in high demand, either consumed as fresh pulp or as processed material. The value addition of tamarind fruits for wine production could reduce post-harvest losses, generate income to farmers, and create employment opportunity to improve rural livelihood (17). Therefore, the present investigation aimed to explore the effect of different strains of *Saccharomyces cerevisiae* (*viz.,* red wine yeast and Belgian wit yeast) for fermentation in different phenotypic variations of red, sour and sweet tamarind pulps to produce wine and evaluate the proximate and organoleptic properties.

The innovative use of tamarind pulp in wine production ensures complete utilization of this under-exploited resource, reducing agricultural waste and contributing to environmental sustainability. Economically, it creates new value-added products that can diversify income for farmers, generate employment in tamarind-growing regions and create opportunities within the global functional beverage market, currently valued at over $125 billion. This nexus between sustainability and economic growth underlines the immediate need for research into tamarind's untapped potential.

## Materials and Methods

### Materials

The matured fully ripened sour tamarind pods were collected from the clone bank maintained at ICFRE- Institute of Forest Genetics and Tree Breeding, Coimbatore (11$^{0}$01’N, 76$^{0}$94’E). Ripened sweet and red tamarind fruits were collected from the National Germ-plasm Bank for red and sweet tamarind in Kurumbapatti, Salem, Tamil Nadu, India (12°51’N and 78°42’E). *Saccharomyces cerevisiae viz.*, red wine yeast and Belgian wit yeast were obtained from Arishtam India, Bangalore.

### Methodology

***Preparation of “must” and addition of yeast***: The 'must' was prepared by extracting juice from mature, fully ripened tamarind fruits. The deveined and deseeded fruit pulp (300g of each tamarind variety-red, sour and sweet) was diluted with 1.5 liters of water in a 1:5 ratio. Sugar, totaling 700 g, was gradually added to stabilize the Brix value at 23°. After adding 5 ml of a 0.1% sodium metabisulfite solution, thorough stirring ensured a uniform mixture, reaching a final volume of 1.75 L. The must was then divided into glass jars, each containing 50 g of whole wheat grain, and inoculated separately with red wine yeast and Belgian wit yeast. The jars were labeled, sealed with air-lock tubes and incubated at room temperature in wooden cupboards to facilitate controlled fermentation (3)

***Treatments:*** Treatments grapes+ Red wine yeast ($C_1$); Grapes + Belgian wit yeast ($C_2$); Red tamarind + Red wine yeast ($T_1$); Red tamarind + Belgian wit yeast ($T_2$); Sour tamarind + Red wine yeast ($T_3$); Sour tamarind + Belgian wit yeast ($T_4$); Sweet tamarind + Red wine yeast ($T_5$); Sweet tamarind + Belgian wit yeast ($T_6$). Tamarind pulps were fermented with S. *cerevisiae* using the procedure described by (18) to produce table wine

***Fermentation:*** The progress of fermentation was monitored by observing air bubbles in the air-lock tubes. Both aerobic and anaerobic fermentation phases began to appear within 6 to 9 hours of setup. Bubbling indicated the beginning and end of fermentation, continuing until the process was complete. Glass jars were gently stirred daily without lid removal, promoting yeast growth. The fermentation process was deemed complete upon bubble cessation, corroborated by the stabilization of total soluble solids for two consecutive days. Primary fermentation spanned 12 days, after the completion of primary fermentation total soluble solids (6.2-17.4) $^0$Brix and alcohol content (0.26 - 1.17%) were recorded.

**Filtration and Clarification**: After the completion of primary fermentation, the mixture was siphoned off and filtered using a muslin cloth to remove pomace (the sediments in the mixture after fermentation). The clear supernatant liquid was then transferred to glass jars for clarification. The supernatant liquid obtained after the primary fermentation was transferred into glass jars were mixed with a small quantity of bentonite clay, an inert material. The addition of clay aids in settling any unwanted particles or leftover pomace in the liquid. Each wine sample was kept for 21 days in a dark room. The jars were opened for five minutes each day to allow sample aeration (19). After fermentation, the clarified samples were collected for proximate and organoleptic analyses.

### Proximate analysis of wine

**Determination of alcohol percentage (%)**: The wine alcohol content was assessed by using specific gravity (20). This method provides approximate alcohol content. It assumes that the change in specific gravity before and after fermentation is mainly due to the conversion of sugars into alcohol.

$$\text{Percentage of v/v alcohol} = (IV - FV) \times 13.25$$

**Determination of moisture content (%)**: The method followed the oven technique described by (21). 2 ml of the sample were added into the petri dish and dehydrated for 16 - 18 hours at a temperature between 100 to 102 °C. After drying, the sample was cooled down using desiccator before being weighed again to determine its final weight.

$$B - C / A \times 100 = \text{Percentage moisture}$$

Where, A = Sample weight in g; B = Weight of dish + sample prior to drying; C = Weight of dish + sample after drying; B - C = Loss in weight of sample after drying

**Determination of pH :** The pH was measured using a pH meter (Oakton Acorn™ series pH 6 meter), as described by (21). Approximately 5 ml of the sample was placed in a beaker and the pH meter electrodes were submerged in the mixed sample to record the pH.

**Determination of ash content (%)**: According to (21), from the sample 2 ml was transferred into a porcelain dish and dried in a mechanized convection oven at 100°C for 3 to 4 hours. After drying, the dish was moved to a muffle furnace and heated to 550°C for 12-18 hours to eradicate carbon residues. After the heater was turned off, it was allowed to cool to 250°C to prevent ash loss. Using safety tongs, the porcelain dish was then shifted to desiccators for cooling before weighing.

$$B \times C/A = 100$$

Where, A = Sample weight in g; B = Weight in grams of dish and content after drying; C = Weight in grams of empty dish

**Determination of total soluble solids (Brix°)**: Total Soluble Solids (TSS) was conducted by a digital hand refractometer (Milwaukee MA871 Digital Brix Refractometer). One drop of the sample was placed into the sample holder and the device analyzed the sugar content. The digital refractometer showed the Brix value, offering an accurate measurement of the sample's soluble solids concentration.

**Determination of titrable acidity (mg/ml)**: This method was performed as described by (21), where 1 ml of the wine sample was titrated with 0.1 N sodium hydroxide (NaOH) using 0.1 ml of phenolphthalein as an indicator. The titration was repeated until a color change from purple to pink occurred and the average titre was recorded.

**Determination of carbohydrate content (%)**: 1 ml of the sample was mixed with 20 ml of distilled water and filtered. Then, 1 ml of the filtrate was combined with 1 ml of alkaline copper reagent, boiled for 5 minutes and allowed to cool. Afterward, 7 ml of distilled water was added and the absorbance was measured at 420 nm.

**Determination of vitamin C content(mg/ml)**: Vitamin C content was measured following the method described by (22). 1 ml sample was macerated with 20 ml of 0.4% oxalic acid and 9 ml of indophenol reagent was used. The absorbance was then measured at 520 nm against a blank using a spectrophotometer (Analytikjena SPECORD 210 PLUS UV Vis Double-beam).

**Determination of antioxidant (mMol/l)**: The method was carried out by following (21). Pipetted out 20, 40, 60, 80, 100 µl of standard samples in test tubes. The test tubes are made up to 3 ml with methanol. 3 ml of methanol were added to the test tubes as a blank and control. Then, 1 ml of DPPH reagent was added to all standard test tubes and the control. The test tubes were incubated in the dark for 30 minutes. A standard value was calculated in visible spectrometry under 517 nm. This method was repeated for all individual samples.

**Organoleptic analysis of wine:** Sensory evaluation of tamarind wine followed the procedure described by (23). The evaluation, conducted with 50 panelists from the ICFRE - Institute of Forest Genetics and Tree Breeding, Coimbatore, aimed to identify the best product. Panelists rated their preferences for each sample using a 10-point hedonic scale, where 10 indicated the highest score and 1 the lowest. The evaluation focused on attributes such as color, flavor, consistency, taste, aroma and overall acceptability, with consumer responses analyzed for product acceptance.

**Statistical analysis:** The statistical significance of the proximate and sensory evaluation data was analyzed using analysis of variance (ANOVA) based on a Completely Randomized Design (CRD). Mean performance of treatment used to calculate standard deviation. The comparison of evaluations between wines produced from *S. cerevisiae* var. red wine yeast and Belgian wit yeast, using red, sour and sweet tamarind varieties analyzed using the critical difference at a significance level of $p < 0.05$. The analysis was performed using the 'agricolae' package in the 'R' program.

## Results

### *Physio-chemical evaluation of wine*

The proximate analysis of tamarind wine, showing the variation in alcohol production after one month of fermentation using *S. cerevisiae* (red wine yeast and Belgian wit yeast) is presented in Table 1. After applying the same fermentation conditions and treatments to both fermenters, it was observed that they exhibited a similar pattern in alcohol production. The high yield of alcohol results from the conversion of soluble solids in the must into alcohol. The decline in total sugar content and total soluble solids from must to wine reflects the consumption of these sugar sources by the wine yeast to produce ethanol. The alcohol content in the present study ranged from 8.12% to 10.62% for red wine yeast and from 8.4% to 9.87% for Belgian wit yeast. Highest alcohol content of 10.62% ($C_1$) recorded in grapes fermented with Red wine yeast and the lowest alcohol content of 8.4% ($T_4$) in sour tamarind fermented with Belgian wit yeast. The optimal alcohol content of 8.14 ($T_6$) was observed in sweet tamarind fermented with Belgian wit yeast.

The optimal moisture content was observed in sweet tamarind fermented with Belgian wit yeast $T_6$ (26%). The highest level of ash content may cause difficulties in consumption which measures the mineral content of food and provides insight into the inorganic composition of a wine samples. The lowest crude ash content was observed in sweet tamarind fermented with red wine yeast ($T_5$) at 1.3%, while the highest content was found in sour tamarind fermented with Belgian wit yeast ($T_4$) at 2.5%, followed by the control grapes fermented with red wine yeast ($C_1$) at 1.35%.

The pH values varied from 2.38 to 3.15. Variation in pH content was conducive to maintaining wine stability and preventing undesirable microbial growth. The minimum value of total soluble solid was recorded in red tamarind fermented with Belgian wit yeast $T_2$ (4.6 $^0$Brix) and the maximum value in sweet tamarind fermented with Belgian wit yeast $T_6$ (9.3 $^0$Brix). Among the various treatments, the highest acidity was found in sour tamarind fermented with Belgian wit yeast $T_4$ (5.1 mg/ml), while the lowest acidity was observed in the control grapes fermented with red wine yeast C1 (1.0 mg/ml), followed by sweet tamarind fermented with Belgian wit yeast $T_6$ (2.0 mg/ml). Carbohydrate content varied significantly among the different tamarind wines from lower value of 1.1% in red tamarind fermented with Belgian wit yeast ($T_2$) to higher value of 3.65% grapes fermented with red wine yeast ($C_1$).

For vitamin C content, sweet tamarind fermented with Belgian wit yeast $T_6$ exhibited the highest vitamin C content at 22.3 mg/ml. On the other hand, the control grapes fermented with red wine yeast ($C_1$) had the lowest vitamin C content at 10.3 mg/ml. There was a significant variation in the vitamin C content of the samples. This variation in the ascorbic acid might possibly due to pasteurization. Antioxidant levels varied from 37.1 mMol/l to 75.9 mMol/l. The analysis established that, among all the treatments in the wine, control grapes fermented with red wine yeast $C_1$, showed the highest antioxidant content (75.9 mMol/l) followed by sweet tamarind fermented with Belgian wit yeast $T_6$ (74.6 mMol/l).

The fermentation of sweet tamarind with Belgian wit yeast significantly enhances the alcohol content, nutrient profile and antioxidant potential of tamarind wine, outperforming other combinations of tamarind varieties and yeast strains. The variation in alcohol yield, crude ash content, pH and antioxidant levels across different treatments highlights the critical role of substrate composition and yeast compatibility in driving fermentation efficiency and functional properties. This study hypothesizes that sweet tamarind, with its higher natural sugar content and nutrient profile, combined with the metabolic efficiency of Belgian wit yeast, can produce a nutritionally superior and functionally enriched wine. Such a product would meet both quality standards and consumer demand for health-oriented beverages.

### *Organoleptic evaluation of wine*

The fermentation of yeast (*S. cerevisiae*) likely enhanced the sensory properties, possibly due to the spontaneous fermentation of the juice. From the table 2, during the sensory evaluation, the highest score for the flavor among 50 judge panels is about 8.5 for sweet tamarind + red wine yeast ($T_5$). The best taste was observed in sweet tamarind fermented with Belgian wit yeast ($T_6$), which scored 8.5. In terms of consistency, the control grapes fermented with red wine yeast ($C_1$) scored 7.5, followed by sweet tamarind fermented with Belgian wit yeast ($T_6$), which scored an average of 7.1. For flavor and taste,

**Table 1.** Assessment of proximate and chemical properties in diverse varieties of Tamarind wine

| 111Proximate composition | Red wineyeast | | | | Belgian wit yeast | | | |
|---|---|---|---|---|---|---|---|---|
| | Grapes control ($C_1$) | Red Tamarind ($T_1$) | Sour Tamarind ($T_3$) | Sweet Tamarind ($T_5$) | Grapes control ($C_2$) | Red Tamarind ($T_2$) | Sour Tamarind ($T_4$) | Sweet Tamarind ($T_6$) |
| Alcohol (%) | 10.62±0.10 | 9.47±0.02 | 9.18±0.02 | 8.12±0.10 | 9.87±0.10 | 9.14±0.02 | 8.4±0.50 | 8.14±0.20 |
| Moisture (%) | 28.5±0.10 | 24.5±0.20 | 22.5±0.15 | 23±0.20 | 29.5±2.00 | 25±0.10 | 24±0.40 | 26±0.30 |
| pH | 3.35±0.10 | 2.59±0.10 | 2.41±0.07 | 3.13±0.10 | 3.45±0.10 | 2.55±0.33 | 2.38±0.06 | 3.15±0.10 |
| Ash (%) | 1.35±0.10 | 1.75±0.04 | 1.45±0.09 | 1.3±0.10 | 1.4±0.10 | 1.65±0.06 | 2.5±0.17 | 2.1±0.10 |
| TSS (Brix°) | 11±2.00 | 5.2±0.27 | 5.1±0.10 | 8.8±0.80 | 3.2±0.40 | 4.6±0.20 | 5.3±0.20 | 9.3±0.30 |
| Titrable acidity (mg/ml) | 1±0.00 | 1.2±0.03 | 5±0.00 | 2.5±0.30 | 1.2±0.00 | 2±0.00 | 5.1±0.10 | 2±0.00 |
| Carbohydrate (%) | 3.65±0.10 | 1.15±0.03 | 1.48±0.07 | 3.12±0.10 | 3.25±0.10 | 1.1±0.05 | 1.15±0.02 | 3.4±0.10 |
| Vitamin C (mg/ml) | 10.3±0.30 | 20±0.70 | 20.3±0.17 | 20±0.50 | 10.5±0.10 | 18.5±0.20 | 18.9±0.40 | 22.3±0.30 |
| Antioxidant (mMol/l) | 75.9±2.00 | 62.4±0.02 | 53.9±0.03 | 70.9±2.00 | 72.16±0.20 | 61.9±0.02 | 43.6±0.04 | 74.6±2.00 |

(±)-Standard error and TSS-Total soluble solid.

**Table 2.** Analysis of sensory attributes based on hedonic scale

| Sensory attributes | Red wine yeast | | | | Belgian wit yeast | | | |
|---|---|---|---|---|---|---|---|---|
| | **Grapes control ($C_1$)** | **Red Tamarind ($T_1$)** | **Sour Tamarind ($T_3$)** | **Sweet Tamarind ($T_5$)** | **Grapes control ($C_2$)** | **Red Tamarind ($T_2$)** | **Sour Tamarind ($T_4$)** | **Sweet Tamarind ($T_6$)** |
| Flavor | 8±0.1 | 6±0.1 | 6.5±0.1 | 8.5±0.1 | 7±0.1 | 7±0.1 | 8±0.1 | 7.3±0.1 |
| Taste | 7.7±0.1 | 7±0.1 | 8±0.1 | 6.2±0.1 | 7.6±0.1 | 8±0.1 | 6±0.1 | 8.5±0.1 |
| Consistency | 7.5±0.1 | 5±0.1 | 5.5±0.1 | 6±0.1 | 7±0.1 | 5±0.1 | 5.8±0.1 | 7.1±0.1 |
| Aroma | 6.8±0.1 | 7±0.1 | 6±0.1 | 7±0.1 | 8±0.1 | 7.5±0.1 | 6.2±0.1 | 6.5±0.1 |
| Color | 7.9±0.1 | 7.5±0.1 | 7.5±0.1 | 6±0.1 | 7.8±0.1 | 6.8±0.1 | 7±0.1 | 7.9±0.1 |
| Overall acceptability | 8.4±0.1 | 7.4±0.1 | 6.4±0.1 | 6.3±0.1 | 8.1±0.1 | 7.7±0.1 | 6.9±0.1 | 8.5±0.1 |

(±)-Standard error and TSS-Total soluble solid.

the best scores were noted for the aroma, with both grapes fermented with Belgian wit yeast ($C_2$) and sweet tamarind fermented with Belgian wit yeast ($T_6$) scoring 8. The color was rated highest for the control grapes fermented with red wine yeast ($C_1$) and sweet tamarind fermented with Belgian wit yeast ($T_6$), both scoring 7.9 among the other sensory evaluations. Ultimately, sweet tamarind fermented with Belgian wit yeast ($T_6$), with a score of 8.5, was the most preferred wine, making it the ideal choice based on overall acceptability.

## Discussion

### *Physio-chemical evaluation of wine*

The proximate analysis of tamarind wine, fermented with two strains of *Saccharomyces cerevisiae* (red wine yeast and Belgian wit yeast), reveals important insights into the alcohol production over a month of fermentation. Both fermenters, subjected to identical fermentation conditions and treatments, exhibited a similar tendency in alcohol production. The high alcohol percentages achieved are significant, as they serve as essential precursors for ester formation, contributing to the wine's aromatic profile. Esters, known for their pleasant aromas, enhance the sensory attributes of the wine, making it more appealing to consumers (24).

In the must, the breakdown of soluble solids leads to an increase in the alcohol content of tamarind wine. This process causes a gradual reduction in pH and an increase in titratable acidity during the fermentation period (25). A significant decrease in total soluble solids was observed, from 20.1 °Brix in the must to 2.9 °Brix in the bael wine (26). The reduction in total sugar content and total soluble solids in the wine indicates the consumption of sugar by the yeast, which is converted into ethanol.

In the present study, the alcohol content varied between wines fermented with red wine yeast and Belgian wit yeast. The maximum alcohol content was recorded in grapes fermented with red wine yeast, while the lowest was found in sour tamarind fermented with Belgian wit yeast. The optimal alcohol content was observed in sweet tamarind fermented with Belgian wit yeast. Similar values have been documented in tamarind and passion fruit wines (28). The observed alcohol production in tamarind wine fermentation aligns with the findings of Bisson and Butzke (2000), who observed the sugar content and yeast strain significantly influence alcohol yield during fermentation. The higher alcohol content in grape wine fermented with red wine yeast ($C_1$) corroborates their results, while the moderate levels in tamarind wines highlight the role of substrate variability.

The moisture content in tamarind wine shows significant variations depending on the yeast strain used during fermentation. The optimal moisture content was observed in sweet tamarind fermented with Belgian wit yeast. Similar moisture levels have been documented in other fruit wines, such as tamarind and soursop wine. This finding suggests that at the end of fermentation, must exhibit decreased moisture content, while the moisture content of the tamarind wine increases (3). Moisture content in strawberry wine fell within a specific range, indicating that strawberry wine, similarly tamarind wine, maintains moisture content within a desirable range from 18% to 25% contributing to its stability and sensory attributes (29). Pear wine revealed moisture content values aligning with the moisture content observed in tamarind wine (30). This highlights the importance of maintaining appropriate moisture levels to ensure desirable wine quality and stability. Moreover, it has been demonstrated that the moisture of wine is generally lesser than the must in Tamarind wine (15.47% to 18.8%) (10). Moisture content significantly influences the texture and consistency of fermented wines. Higher moisture levels can result in a thinner, more liquid-like consistency, while lower moisture content can make the wine thicker and more viscous (31).

The highest level of ash content may cause difficulties in consumption as it measures the mineral content of food and provides insight into the inorganic composition of wine samples. In this study, the minimum ash content was observed in sweet tamarind fermented with red wine yeast, while the highest ash content was found in sour tamarind fermented with Belgian wit yeast, followed by control grapes fermented with red wine yeast. High ash content could affect the taste and mouthfeel of the wine, making it less palatable for consumers (32). Therefore, understanding and controlling ash content is important for ensuring the overall quality and acceptability of tamarind wine. The study of ash content in tamarind wine reveals vital insights into its mineral composition and overall quality. Analogous findings in tamarind and soursop wine reinforce the suitability of red wine yeast for producing palatable wine for consumption and commercialization. The minimum crude ash content observed is due to the reduced inorganic compounds present after ignition, which enhances the nutritional profile of tamarind wine. Further comparisons with pomegranate wine, which has an ash content ranging from 0.26% to 2.04%, suggest that tamarind wine exhibits similar mineral characteristics (33).

These consistent results indicate that tamarind wine can achieve desirable mineral content through appropriate winemaking practices (34). Orange wine's crude ash profile also closely matches the range for tamarind wine, underscoring the potential for standardizing winemaking practices to achieve optimal mineral content (10). Therefore, selecting and standardizing yeast strains used for fermentation is critical in reducing impurities and ensuring the overall quality and acceptability of tamarind wine. By managing ash content effectively, winemakers can enhance the sensory attributes and nutritional value of the wine, making it more appealing to consumers.

The average pH values in tamarind wine varied within a range that aligns with many other fruit wines, which generally have a pH between 3.0 and 3.5. The initial pH of tamarind wine was within the desirable range for most fruit wines, conducive to maintaining stability and preventing the growth of undesirable microorganisms (35). The reduction of pH during fermentation can be attributed to the production of acid through metabolic activities. These findings aligned with research on cherry wine, which found a similar pH profile ranged from 3.2 to 3.9 (36). This suggests that similar acid management and fermentation techniques can be applied to achieve optimal pH levels. Low pH inhibits the development of decaying organisms while creating a favorable environment for necessary organisms. The minimal pH and maximum acidity provide an advantageous environment for yeast fermentation, offering a natural benefit in such conditions (35).

The minimum value of total soluble solids was recorded in red tamarind fermented with Belgian wit yeast, while the maximum value was observed in sweet tamarind fermented with the same yeast. The sugar content was measured at a high concentration before fermentation. The decrease in pH during fermentation can be related to the consumption of soluble solids by yeast cells (25). Total soluble solid content of plum wine falls within a specific range, suggesting that similar fruit selection and processing techniques can be applied to achieve optimal total soluble solid content in tamarind wine (36). Mango wine revealed a total soluble solid content was 2.1 °Brix aligns with the lower limit of the desired value for tamarind wine (37). This indicates that the enzymatic breakdown of complex polysaccharides into simpler compounds, along with yeast utilization of sugars, leads to a decrease in sugar levels over the time. This decrease is slower in wines with higher pH. The decreases in total soluble solid were indicative of the yeast's efficiency in converting sugars into alcohol. The high value of total soluble solids during fermentation suggests a higher potential alcohol content upon completion (27).

The highest acidity was found in sour tamarind fermented with Belgian wit yeast, while the lowest acidity was observed in control (grapes fermented with red wine yeast, followed by sweet tamarind fermented with Belgian wit yeast), which fell within the optimal range of acidity. Comparable research on titratable acidity in citrus wines, such as orange and lemon (58), indicates acidity levels within the same range as tamarind wine (59). Similar titratable acidity was observed in the orange wine varied from 3.0 mg/ml to 4.5 mg/ml (38), while roselle wine exhibited varying acidity (0.75%) levels (39). These results highlight the commonality in acidity profiles among different fruit wines, underscoring the importance of acidity in shaping their flavor and sensory characteristics. The wine pH has a straight association with titratable acidity: maximum titratable acidity corresponds to minimum pH, *vice-versa*. This relationship is crucial for maintaining good shelf stability, as high acidity enhances the wine's stability and resistance to microbial spoilage (25). The titratable acidity of other fruit wines, such as those made from berries or apples, can vary widely. Apple wine typically reveal titratable acidity with range of 4.5 mg/ml to 6.5 mg/ml, while berry wines exhibit values of 0.930 mg/l and 0.264 mg/l (40). Titratable acidity of strawberry wine was comparable to that of tamarind wine, highlighting its potential for producing wines with a desirable balance of acidity and sweetness (41). Titratable acidity of apple wine falls within a similar desired values of 3.15 mg/l to 4.47 mg/l contributing to its palatability and overall quality (42).

Analysis of variance revealed significant differences in carbohydrate content among the different tamarind wines. Low carbohydrate content was observed in red tamarind fermented with Belgian wit yeast, while the high carbohydrate content was observed in grapes fermented with red wine yeast. Carbohydrate levels of apple wine, reporting values within a range that aligns with in tamarind wine (43). The lower carbohydrate content indicates that all the tamarind wines fall into the dry wine classification. Variations in total sugar content during storage may be caused by the breakdown of carbohydrates into simpler sugars, which microorganisms utilize as a carbon source to produce metabolites such as acids and ethanol. Variation in carbohydrates across different grape wines was observed similar observed in tamarind (44). Carbohydrate values in white and red grape wines varied from 1.5% to 3.5% that similar to tamarind wine (45). In contrast, certain fruit wines may exhibit carbohydrate levels that deviate ranged from 2.0% to 4.0%. For instance, pawpaw and pineapple wines, known for their intense sweetness, may have much higher carbohydrate values due to the simple starter cultures used in their fermentation processes (46). This variation underscores the distinction of carbohydrate content in fruit wines and the importance of fermentation techniques and starter cultures in determining the final wine composition.

The nutritional variations in tamarind wine, such as the higher ash content in sour tamarind fermented with Belgian wit yeast ($T_4$) and optimal vitamin C levels in sweet tamarind with Belgian wit yeast ($T_6$), find parallels in the studies by (38), who emphasized the influence of substrate mineral content on final product composition. Similarly, antioxidant activity variations in fermented products, which aligns with the higher antioxidant content recorded in grape and tamarind wines in this study (61).

Sweet tamarind fermented with Belgian wit yeast exhibited the highest vitamin C content, while control grapes fermented with red wine yeast had the lowest vitamin C content. The reduction in vitamin C might be caused by the development of caramel, which depends on the presence of invert sugar and the fermentation process by yeast (*S. cerevisiae*) could affect the vitamin C content in tamarind wines (3). Vitamin C values ranged from 16.72 mg/ml to 19.42 mg/ml, 16.25 mg/ml and 6.80 mg/ml in orange wine, while lemon wine exhibited vitamin C levels ranging from 12 mg/ml to 18 mg/ml (47). Although citrus wines typically contain higher vitamin C levels compared to tamarind wine, the range observed in lemon wine aligns with the desired vitamin C content for tamarind wine production (42). Strawberry wine has vitamin C content comparable to tamarind wine, attributing to its value of nutritional and antioxidant capacity (48). The measurable loss in vitamin C content in tamarind wines, potentially due to pasteurization, aligns with (60), who documented the stability issues of vitamin C in thermally treated fruit-based beverages. This highlights the intricate balance between processing conditions and the preservation of nutritional and functional properties in tamarind wine fermentation.

Antioxidant levels in the tamarind wine varied significantly across different treatments. Blueberry wine has an antioxidant 50 mMol/l to 70 mMol/l that suggests potential health benefits (48). Similarly, elderberry wine revealed antioxidant levels ranged from 50.3 mMol/l to 91.7 mMol/l that slightly exceed the desired range for Tamarind wine (49). The antioxidant capacity of sweet cherry wine further supports the idea that tamarind wine can offer substantial health benefits through its antioxidant properties (50, 51). The DPPH assay, a common method for determining antioxidant activity, suggests that the DPPH scavenging activity of tamarind wine can be attributed to its anthocyanin content, which also functions as an antioxidant (52).

### *Organoleptic evaluation of wine*

The fermentation process utilizing yeast (*S. cerevisiae*) enhanced the sensory properties of tamarind wine, likely due to the spontaneous fermentation of the juice. Numerous studies have shown that resistance to wine conditions and the impact on organoleptic quality are dependent on the yeast strain (53). In fruit wine production, pH also plays a crucial role in determining the final texture and aroma of the wine (54). Additionally, the type and aroma generated during winemaking are influenced by yeast, environmental factors and the physicochemical characteristics of the musts.

The sensory attributes of the wine were likely preserved through the use of a sulfiting agent (sodium metabisulfite) and pasteurization prior to fermentation. The sulfur dioxide released from sodium metabisulfite functions as an antioxidant, antiseptic and stabilizer. (55). During sensory evaluation, the highest score for flavor among the 50 judge panels was given to sweet tamarind fermented with red wine yeast. The best taste score was given to sweet tamarind fermented with Belgian wit yeast. Consistency was moderately rated for control grapes fermented with red wine yeast and sweet tamarind with Belgian wit yeast. The best aroma score was given to grapes fermented with Belgian wit yeast. The highest color score was awarded to control grapes with red wine yeast and sweet tamarind with Belgian wit yeast. Overall, sweet tamarind fermented with Belgian wit yeast was the utmost favorable red wine based on overall acceptability. The sensory qualities of apple wine were evaluated using a hedonic scale with a panel of 50 judges to assess attributes such as taste, aroma, color, and overall acceptability. The average scores for flavor, color, aroma, consistency and overall acceptability were high, indicating that apple wine is generally well-received in terms of its sensory characteristics (56).

The results are driven by the metabolic activities of *S. cerevisiae* and the inherent properties of tamarind substrates. Alcohol production reflects sugar content and yeast efficiency, with sweet tamarind providing optimal fermentable sugars. Crude ash variations arise from substrate mineral content and yeast micronutrient assimilation. Acidity and pH are influenced by tamarind's natural acids and yeast metabolism. vitamin C degradation, impacted by pasteurization and oxidative reactions, was minimized in sweet tamarind ($T_6$) due to yeast stabilization. Antioxidant activity increased through yeast-driven release of phenolics, with sweet tamarind ($T_6$) and grapes ($C_1$) showing the highest values. Sensory attributes were enhanced by yeast-driven production of esters and organic acids, with sweet tamarind ($T_6$) offering the best flavor and acceptability. These findings reveal the substrate- and yeast-specific fermentation dynamics, highlighting tamarind wine's potential for superior nutritional and sensory qualities.

## Conclusion

In conclusion, the fermentation of tamarind pulp into wine, influenced by various yeast strains, revealed significant variations in composition and sensory attributes. Among the treatments evaluated, the sweet tamarind fermented with Belgian wit yeast ($T_6$) proved to be most outstanding option. This treatment combination exhibited remarkable qualities, including high alcohol content, substantial vitamin C levels, impressive antioxidant capacity and favorable sensory evaluations. The sweet tamarind fermented with Belgian wit yeast ($T_6$) demonstrated a harmonious blend of these attributes, making it the most promising choice for tamarind wine production. Future research should focus on optimizing raw materials to reduce postharvest changes and enhance their value through food industry applications.

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## Authors' contributions

MA, PC and AM planned and coordinated this study. CB, MA and GR and carried out the lab experiment. BN, VA, SK and TH carried out the grammatical correction. AM and MA (M. Amaravel) participated in the design of the study and performed the statistical analysis. MA, KS, AM and MA (M. Amaravel) revised the paper for final publication. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

**Ethical issues:** None

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