

Extraction and Characterization of Dietary Fiber from Tamarind (*Tamarindus indica* L.) and Its Byproducts: Physicochemical, Functional, and Corrosion-Inhibitory Properties

Tamarind (*Tamarindus indica* L.) ve Yan Ürünlerinden Diyet Lifi Ekstraksiyonu ve Karakterizasyonu: Fizikokimyasal, Fonksiyonel ve Korozyon Önleyici Özellikleri

Büşra Erdem¹ , Yakup Şirin¹ , Gülşah Gökçe¹ , Bahar Tan Özey² , Nurdane Yılmaz³ , Perihan Gürkan⁴ 

¹Semas Food Industry Tourism Trade Co. R&D Center, Ankara, Türkiye

²Kastamonu University, Graduate School of Natural and Applied Sciences, Department of Materials Science and Engineering, Kastamonu, Türkiye

³Kastamonu University, Faculty of Education, Department of Mathematics and Science Education, Division of Science Education, Kastamonu, Türkiye

⁴Gazi University, Faculty of Science, Department of Chemistry, Ankara, Türkiye

ABSTRACT

This study evaluates the functional and physicochemical properties of the fruit of tamarind (*Tamarindus indica* L.) and its isolated dietary fiber fraction. Some parameters of the fruits including dietary fiber content, swelling capacity, water and oil holding capacities, water activity, dry matter, protein, ash content, antioxidant activity (FRAP and DPPH), organic acids, sugar content, and corrosion-inhibitory properties were determined. The dietary fiber fraction exhibited significantly higher fiber content ($73.31 \pm 0.30\%$), swelling capacity ($9.21 \pm 0.01\%$), water holding capacity (6.17 ± 0.11 mL/g), and oil holding capacity (2.25 ± 0.09 g/g), indicating its potential for low-fat and digestive health-oriented food applications. Corrosion analyses indicated that the fiber fraction provided higher protective efficiency compared to the fruit, with values of 86.3% and 70.28%, respectively. In contrast, tamarind fruit displayed higher antioxidant activity (FRAP: 330.5 ± 1.57 μ mol Fe²⁺/mL; DPPH SC₅₀: 2.33 ± 0.11 mg/mL), protein content (96.34 ± 1.21 μ g/mL), and natural sugars (glucose: 1.52±0.09%; fructose: 1.93±0.07%), making it suitable for energy-dense formulations. Organic acids, primarily tartaric (3.80 ± 0.24 mg/g) and malic acids (0.60 ± 0.02 mg/g), were predominantly found in the fruit and negligible in the dietary fiber fraction. These results suggested that both tamarind pulp and its fiber-rich by-products can be valorized as functional ingredients, enhancing nutritional value and promoting sustainability in the food industry. Further *in vivo* studies are recommended to assess their effects on metabolic health and gut microbiota.

Keywords: Tamarind (*Tamarindus indica* L.), Dietary fiber, By-product, Green inhibitor, Corrosion

ÖZ

Bu çalışma, tamarind meyvesi (*Tamarindus indica* L.) ve izole edilmiş diyet lifi fraksiyonunun fonksiyonel ve fizikokimyasal özelliklerini değerlendirmektedir. Diyet lifi içeriği, şişme kapasitesi, su ve yağ tutma kapasitesi, su aktivitesi, kuru madde, protein, kül içeriği, antioksidan aktivite (FRAP ve DPPH), organik asitler, şeker içeriği ve korozyon analizi gibi temel parametreler incelenmiştir. Diyet lifi fraksiyonu, anlamlı derecede yüksek lif içeriği (%73,31±0,30), şişme kapasitesi (%9,21±0,01), su tutma kapasitesi (6,17±0,11 mL/g) ve yağ tutma kapasitesi (2,25±0,09 g/g) göstermiştir; bu da onun düşük yağlı ve sindirim sağlığına yönelik gıda uygulamaları için potansiyel taşıdığını göstermektedir. Korozyon analizi sonuçları, lif fraksiyonunun meyveye kıyasla daha yüksek koruma verimi sağladığını ortaya koymuştur; bu değerler sırasıyla %86,3 ve %70,28 olarak belirlenmiştir. Buna karşılık, tamarind meyvesi daha yüksek antioksidan aktivite (FRAP: $330,5 \pm 1,57$ μ mol Fe²⁺/mL; DPPH SC₅₀: $2,33 \pm 0,11$ mg/mL), protein içeriği (96,34±1,21 μ g/mL) ve doğal şekerler (glukoz: %1,52±0,09; fruktoz: %1,93±0,07) göstermiştir; bu da meyveyi enerji yoğun formülasyonlar için uygun kılmaktadır. Organik asitler arasında tartarik asit (3,80±0,24 mg/g) ve malik asit (0,60±0,02 mg/g) başlıca bileşenler olarak meyvede baskın şekilde bulunurken, diyet lifi fraksiyonunda ihmal edilebilir düzeydedir. Bu bulgular hem tamarind posasının hem de lif açısından zengin yan ürünlerin fonksiyonel bileşenler olarak değerlendirilebileceğini, besin değerini artırabileceğini ve gıda endüstrisinde sürdürülebilirliği destekleyebileceğini göstermektedir. Metabolik sağlık ve bağırsak mikrobiyotası üzerindeki etkilerinin değerlendirilmesi için ileri düzey *in vivo* çalışmalar önerilmektedir.

Anahtar kelimeler: Demirhindi (*Tamarindus indica* L.), Diyet lif, Atık, Yeşil inhibitör, Korozyon

Corresponding author (Yazışmalardan Sorumlu Yazar): Büşra Erdem

✉ busra@semas.com.tr

☎ +90 312 814 2025

☎ +90 312 819 0026

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INTRODUCTION

Tamarind (*Tamarindus indica* L.) is a perennial evergreen tree species belonging to the Leguminosae (Fabaceae) family [1]. The term "tamarind" originates from the Arabic phrase "temr-i hindi," which translates to "Indian date", with "temr" meaning date and "hindi" referring to India [2]. This tropical fruit tree is predominantly cultivated in warm climates such as those found in Egypt and India [3]. Tamarind trees typically reach a height of 10 to 25 m and bear dark chestnut-brown, pod-like fruits that resemble carob. The fruits, which are approximately 2.5 to 3.5 cm wide, are notable for their distinctive organoleptic properties, including a sweet-and-sour taste and a sticky pulp texture [2]. In particular, the tamarind plant has attracted attention for its health-promoting effects, as all of its parts, including the leaves, fruit, seeds, and bark, are widely used in both traditional medicine and industrial applications [4].

Tamarind fruit, which contains essential amino acids that cannot be synthesized by the human body and must therefore be obtained through diet, is considered a valuable source of plant-based protein [5]. In particular, tamarind seeds are rich in a variety of bioactive compounds, including phenolic and polyphenolic substances, fatty acids, and most notably xyloglucan, a biologically active polysaccharide [6-8].

Due to its high content of xyloglucan and other complex polysaccharides, tamarind seed has been associated with beneficial effects in combating obesity and inflammation-related metabolic disorders [9]. Additionally, *Tamarindus indica* L. is recognized as a potent source of antioxidants, contributing to its growing significance in the pharmacological and nutraceutical fields [10]. The extract of tamarind has demonstrated therapeutic potential in the treatment and management of various health conditions, including gastric ulcers, fever, diabetes, alcohol intoxication, constipation, bile duct disorders, inflammation, pharyngitis, jaundice, and even heatstroke [10-12].

Dietary fiber refers to plant-based compounds that cannot be digested by endogenous enzymes in the small intestine but are either completely or partially fermented by gut microbiota in the large intestine [13, 14]. The main dietary sources of fiber include fruits, vegetables, nuts, cereals, and legumes [15]. Dietary fiber is composed of carbohydrate polymers [16] and is generally categorized into two types: soluble and insoluble fiber [17].

Examples of soluble fibers include those found in apples, pears, and quinces, whereas insoluble fibers include cellulose, hemicellulose, and lignin [18]. Although the health benefits of soluble fibers have been extensively studied, the physiological effects of insoluble fibers remain relatively underexplored [19]. Among the components of the insoluble fiber fraction, cellulose is notable for its resistance to enzymatic degradation by mammalian enzymes [20]. Due to its insolubility in water, cellulose contributes to increased fecal bulk, water retention, and stimulation of peristaltic movements [16].

Soluble dietary fibers are often preferred over insoluble ones due to their advantageous physicochemical properties [21]. Studies have shown that soluble fiber may help reduce cholesterol levels, alleviate constipation, regulate blood glucose levels, and positively influence the gut microbiota [22].

In addition to their nutritional and functional roles, dietary fibers have gained attention for their environmental sustainability. As awareness of food waste and resource efficiency grows, by-products from the fruit processing industry, particularly solid residues, are being increasingly recognized as valuable sources of fiber [23]. These fibrous residues, once considered waste, are now being utilized in various applications such as functional ingredients, animal feed, and even renewable energy production [24-26]. Their integration into sustainable product development not only supports circular economy practices but also helps reduce the environmental burden associated with food processing [27].

The primary aim of this study is to comprehensively investigate the potential health and industrial applications of tamarind fruits. In particular, the study focuses on a detailed evaluation of the bioactive compounds in the plant's seeds, pulp, and by-products, including insoluble dietary fibers, polyphenols, and antioxidants. The physicochemical properties of these compounds, including water-holding capacity, bulking effect, and antioxidant activity, were systematically analyzed to assess the potential of tamarind as a functional, value-added ingredient in the food industry.

Furthermore, in subsequent phases, the potential of tamarind fruit and its isolated dietary fiber to form protective film layers on metal surfaces will be investigated. Within this context, the inhibitory effects of these natural compounds under acidic conditions (HCl medium) will be examined to evaluate the feasibility of tamarind derivatives as environmentally friendly, bio-based corrosion inhibitors. This approach aims to extend the study's scope beyond food applications, offering new research perspectives in material protection.

Additionally, the study aims to promote the valorization of agricultural by-products, contributing to environmental sustainability and economic development. By encouraging the reuse of waste materials, this approach seeks to generate added value while supporting a zero-waste vision. Accordingly, the study provides a scientific basis for the industrial utilization of tamarind by-products, fostering environmentally friendly, innovative, and sustainable applications in both food and material Technologies.

MATERIALS and METHODS

Materials

The tamarind fruit used in this study was procured in January 2024 from SEM-AS Food Industry Trade Ltd. Co., a company engaged in industrial fruit juice production. The tamarind fruit, imported from India, was obtained on September 7, 2024, with the batch

number “012024DMRH.” Both the residual fruit pulp generated during the production of tamarind juice and syrup and the fresh fruit samples were collected under appropriate conditions, transported to the laboratory for analysis, and stored at +4°C.

During the dietary fiber extraction process, both the fruit pulp and the directly obtained fiber samples were initially extracted with hot water at 85–90°C. Subsequently, the pH of the solution was adjusted to pH 12 by adding a 1 M NaOH solution (Merck, Darmstadt, Germany), and the process was continued. Following this step, the samples were treated with a 2% H₂O₂ (Sigma-Aldrich, Munich, Germany) solution to achieve decolorization and remove lignocellulosic impurities. The obtained dietary fibers were then filtered through a fine muslin cloth, dried at 55°C for 8 hours, and ground. [28].

The dried material was milled using a laboratory-scale ball mill (Testform, Laboratory Ball Mill Bond type, Türkiye; 6.3 L capacity, 200 mm diameter, 200 mm length) to achieve a fine particle size. The milled samples were subsequently separated into size fractions using a sieve shaker (Utest, Türkiye) with mesh sizes of 0.800 µm, 0.500 µm, 0.100 µm, and 0.050 µm.

All analyses were conducted in triplicate, and the water used in the experiments was deionized ultrapure water obtained from the Merck Millipore Synergy Ultra-Pure Water System.

All measurements were carried out in three independent replicates (n=3), and results are presented as mean values with standard deviation (mean±SD).

Methods

In this study, two sample groups were prepared simultaneously for comparative analysis: tamarind fruit powder and dietary fiber isolated from tamarind pulp. Both products were processed under standard laboratory conditions, following the same drying, grinding, and sieving procedures. This parallel approach ensured consistent processing, minimized variability, and enabled reliable comparison of the physicochemical and functional properties of the two materials.

Extraction of Tamarind Dietary Fiber

For tamarind sherbet production, a modified version of the AOAC 993.21 (non-enzymatic) total dietary fiber determination method was applied to the incoming tamarind fruit samples [29]. As a result of preliminary trials, the tamarind samples were prepared to achieve a 20% dry matter content. For this purpose, 100 g of tamarind fruit and 100 g of tamarind pulp were mixed with 500 mL of ultrapure water. The mixture was stirred at 300–350 rpm using a magnetic stirrer to remove starch and water-soluble components.

Subsequently, the samples were heat-treated at 85–90°C for 30 minutes. After cooling to 60°C, the pH of samples was adjusted to 12. For the bleaching process, 2% (v/v) hydrogen peroxide (H₂O₂) solution was used. Bleaching was carried out at 60–70°C, while

stirring at 300–350 rpm with a magnetic stirrer [30].

Water Holding Capacity and Swelling Capacity

In the determination of WHC, 500 mg of the dried insoluble dietary fiber (IDF) isolated from tamarind was weighed into a centrifuge tube, followed by the addition of 25 mL of distilled water. The mixture was allowed to stand for 2 hours at room temperature. Subsequently, the tube was centrifuged at 3,000×g for 10 minutes. The unabsorbed water remaining in the tube was carefully removed using Whatman No.1 filter paper, and the wet mass of the residue was recorded. WHC was calculated using Equation 1:

$$WHC \left(\frac{g}{g} \right) = \frac{W_w - W_s}{W_s} \quad (1)$$

where W_w is the weight of the hydrated sample, and W_s is the initial dry weight.

In the determination of swelling capacity (SWC), 200 mg of tamarind dietary fiber was accurately weighed and transferred into a 5 mL graduated measuring cylinder. The initial volume of the dry sample was recorded as V_1 . Then, 5 mL of distilled water was added, and the sample was allowed to hydrate at room temperature for 24 hours. After this period, the final volume, V_2 , was recorded as the swollen volume. SWC was calculated using Equation 2:

$$SWC \left(\frac{mL}{g} \right) = \frac{V_2 - V_1}{M} \quad (2)$$

where V_2 is the volume after hydration, V_1 is the initial volume of the dry fiber, and M is the mass of the dry sample [31].

Oil Holding Capacity

The oil holding capacity (OHC) of samples was determined with slight modifications. Fifty grams each of tamarind fruit and tamarind dietary fiber were weighed, and 10 mL of sunflower oil was added to each sample. The mixtures were shaken at 37°C for 1 hour and then centrifuged at 8,000×g for 30 minutes. The supernatant was discarded, and the remaining pellet was weighed. OHC was calculated using Equation 3:

$$OHC \left(\frac{g}{g} \right) = \frac{W_o - W_s}{(W_s)} (W_s) \quad (3)$$

Where W_o : Wet weight of the sample after oil absorption (g), and W_s : Initial dry weight of the sample (g) [32].

Antioxidant Activity by FRAP Method

The antioxidant capacity of the samples was determined using the Ferric Reducing Antioxidant Power (FRAP) method. This method is based on the reduction of the Fe(III)-TPTZ [2,4,6-tris(2-pyridyl)-S-triazine] (Sigma-Aldrich, Munich, Germany) complex to a blue-colored Fe(II)-TPTZ complex in the presence of antioxidants. The resulting complex exhibits a maximum absorbance at 593 nm, which was measured spectrophotometrically (SHIMADZU UV-1900I, Japan) [33].

The calibration curve was constructed using standard solutions of FeSO₄·7H₂O (Sigma-Aldrich, Munich, Germany) at varying con-

centrations (31.25, 62.5, 125, 250, 500, and 1000 μM). The FRAP reagent was prepared by mixing 300 mM acetate buffer (pH 3.6, Merck, Germany), 10 mM TPTZ, and 20 mM FeCl_3 (Sigma-Aldrich, Germany) in a ratio of 10:1:1. For the assay, 3 mL of the FRAP reagent was reacted with 100 μL of sample solution (Table 1).

The absorbance values obtained were compared to those of the $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ standard solutions measured under the same conditions, and the results were expressed as μM $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ equivalents. All pipetting procedures were carried out in accordance with the method described [34].

Table 1. Pipetting scheme used in the FRAP assay

Component	Blank MeOH	Test (Sample)	Color Blank MeOH*	$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$
FRAP Reagent	3 mL	3 mL	-	3 mL
Sample	-	100 μL	100 μL	-
$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (Variable Conc.)	-	-	-	100 μL
Methanol	100 μL	-	3 mL	-

In the 4th minute, absorbance is read at 593 nm
*Color blank for the sample dissolved in methanol.

DPPH• Radical Scavenging Activity

The DPPH• (2,2-diphenyl-1-picrylhydrazyl) assay is a widely used and reliable method for assessing the free radical scavenging potential of antioxidant compounds. DPPH• is a stable synthetic nitrogen-centered free radical that exhibits a deep violet color in solution, with a characteristic absorption maximum at 517 nm. When an antioxidant is present in the system, it donates an electron or a hydrogen atom to the DPPH• radical, thereby reducing it to a non-radical form and resulting in a measurable color change from purple to yellow. This decolorization is directly proportional to the scavenging capacity of the antioxidant being tested. In this study, the radical scavenging activity was evaluated by mixing a fixed volume of the DPPH• solution with various concentrations of the antioxidant-containing sample. The absorbance of the resulting mixtures was measured at 517 nm after a defined incubation period. The scavenging activity was then quantified as the percentage reduction in absorbance relative to a control [35].

The SC_{50} (Scavenging Concentration 50%) value, defined as the concentration of antioxidant required to scavenge 50% of the DPPH• radicals, was determined to express the antioxidant capacity [36]. A dose-response curve was generated by plotting sample concentration against the corresponding absorbance values. From this curve, the SC_{50} value (in mg/mL) was calculated by regression analysis, providing a quantitative measure of the sample's radical-scavenging efficiency.

Ash Content

Ash content was determined by placing 3 g of tamarind fruit residue and tamarind dietary fiber samples into crucibles and incinerating them at 550°C until no dark spots were observed. The per-

centage of weight loss was calculated to determine the ash content [37].

Protein Content

The protein content in tamarind fruit and tamarind dietary fiber extracts was determined using the Bradford colorimetric method. In this procedure, the samples obtained after extraction were treated with the dye Coomassie Brilliant Blue G-250 (Merck, Darmstadt, Germany), which binds to proteins, particularly to basic amino acid residues in an acidic environment. Upon binding, the dye shifts its absorption maximum from 465 nm to 595 nm. This spectral change is proportional to the intensity of the blue dye-protein complex and was measured spectrophotometrically [38, 39].

During the experimental procedure, 5 μL of each extract from both fruit and fiber fractions was mixed with 250 μL of Bradford reagent. After 5 minutes of incubation at room temperature, absorbance was measured at 595 nm. The obtained values were compared to a calibration curve constructed using bovine serum albumin (BSA) (Sigma-Aldrich, Munich, Germany), and the protein content was expressed accordingly.

Dietary Fiber Content

In this study, the dietary fiber content of raw material samples was determined in accordance with the official AOAC Method No. 991.43 [40]. For each analysis, 1.00 gram of the sample was weighed in duplicate. A buffer solution containing MES (2-(N-morpholino) ethanesulfonic acid) (Sigma-Aldrich, Munich, Germany) and TRIS (tris(hydroxymethyl)aminomethane) (Sigma-Aldrich, Munich, Germany), adjusted to pH 8.2, was added to each sample at a volume of 40 mL. After the addition of 50 μL of α -amylase (Sigma-Aldrich, Munich, Germany), enzyme to each tube, the tubes were sealed and incubated in a shaking water bath at 95–100°C for 30 minutes. Following this incubation, the samples were cooled to 60°C, and 100 μL of protease (Sigma-Aldrich, Munich, Germany) solution was added to each tube. The tubes were then incubated at 60°C for an additional 30 minutes. Next, the pH of each sample was adjusted to a range of 4.1–4.8 using 0.561 N HCl. Subsequently, 200 μL of amyloglucosidase (Sigma-Aldrich, Munich, Germany), an enzyme was added to each sample, followed by incubation at 60°C for 30 minutes. After enzymatic digestion, the samples were filtered by vacuum filtration (CLS Vacuum Pump, Türkiye). The obtained residues were sequentially washed with 78% ethanol (Merck, Darmstadt, Germany), 95% ethanol (Merck, Darmstadt, Germany), and acetone (Merck, Darmstadt, Germany). The washed residues were dried overnight in an oven at 105°C and then cooled in a desiccator. Following the drying process, ash and protein analyses were performed on the residues. Based on the data obtained, the percentage of dietary fiber was calculated using Equation 4:

$$\text{Dietary Fiber (\%)} = \frac{(R_1 - A_1 - P_1) + (R_2 - A_2 - P_2)}{m_1 + m_2} \times 100 \quad (4)$$

where R_1 : Residue weight obtained from the first sample (g), R_2 :

Residue weight obtained from the second sample (g), A_1 : Ash content of the first sample (g), A_2 : Ash content of the second sample (g), P_1 : Protein content of the first sample (g), P_2 : Protein content of the second sample (g), m_1 : Initial weight of the first sample (g) and m_2 : Initial weight of the second sample (g).

Organic Acid and Sugar Analyses

For the analyses, 1 gram of tamarind extract was mixed with 20 mL of distilled water until a homogeneous mixture was obtained. The resulting mixture was vigorously shaken for 2 minutes, then subjected to ultrasonic extraction in an ultrasonic bath (Selecta SA, Barcelona, Spain) for 1 hour without temperature control. Following this, the sample was centrifuged at 15,000 rpm for 15 minutes at 4°C using a Nucleo centrifuge (400 NF, Ankara, Türkiye). From the supernatant, 2 mL was collected and filtered through a Millipore filter (pore size 0.45 µm; Millipore Corp., Bedford, USA) for HPLC analysis (Shimadzu, Reservoir Tray, Japan). Quantitative determination of major sugars, including glucose, fructose, and sucrose, was performed using calibration curves generated with pure standards from Sigma (Table 2).

Table 2. Chromatographic conditions used for sugar determination by HPLC

Device	HPLC SHIMADZU brand, Reservoir Tray model
Mobile Phase	Water/Methanol Merck, Darmstadt, Germany), / Acetonitrile Merck, Darmstadt, Germany), (550/300/200)
Detector	Fluorescence Detector (360 nm- 440 nm)
Column Length	ODS-2 (C18 -250 mm-5µm- 4.6 mm)
Flow Rate	1 mL/min
Column Temperature	25°C
Injection Volume	100

For the determination of organic acids, the same HPLC instrument was used, but with a different column and flow rate. For quantitative analysis, pure standards of malic, citric, and tartaric acids (Sigma, Poole, UK) were used (Table 3) [34].

Table 3. Chromatographic conditions used for organic acid determination by HPLC

Device	HPLC SHIMADZU brand, Reservoir Tray model
Mobile Phase	NaH ₂ PO ₄ (Merck, Darmstadt, Germany), /Water (50mM)
Detector	Fluorescence Detector (210 nm)
Column Length	5µm, 150 * 4.6 mm I.D
Flow Rate	1 mL/min
Column Temperature	40°C
Injection Volume	10

Corrosion-Inhibition Efficiency

In this study, the corrosion behavior of tamarind fruit and tamarind dietary fiber extracts on mild steel in 1 M HCl solution (Merck, Darmstadt, Germany) was investigated using electrochemical methods. Measurements were performed with a Gamry Reference 3000 Potentiostat/Galvanostat/ZRA (Gamry Instruments Inc.,

USA). Both potentiodynamic polarization (Tafel) and electrochemical impedance spectroscopy (EIS) techniques were applied [41].

Electrode surfaces were prepared using an automatic mechanical polisher (Metkon, Türkiye) and sequentially polished with 800, 1000, and 1200 grit papers, rinsed with distilled water and ethanol, and then dried. A C20 mild steel working electrode, Ag/AgCl reference electrode, and graphite counter electrode were employed. The working electrode was embedded in epoxy resin, leaving an exposed active area of 0.3846 cm². The composition of the mild steel was: 0.20% C, 0.3% Ni, 0.6% Mn, 0.01% P, 0.2% Si, 0.023% S, 0.3% Cr, 0.2% Mo, balance Fe. All experiments were conducted at 25±1°C under ambient temperature and aerated conditions.

The corrosive medium was prepared by diluting 37% hydrochloric acid with deionized water. Tamarind fruit and tamarind dietary fiber were dried under ambient conditions and ground into a fine powder. For extract preparation, 100 g of tamarind sample was mixed with 200 mL of ethanol and 800 mL of distilled water for 24 hours, then filtered and the solvent removed by rotary evaporation. The obtained dried extract was dissolved in the HCl solution at concentrations of 100, 125, 150, 175, and 200 ppm. This procedure was applied in accordance with reported methods for plant-based corrosion inhibitors [42].

EIS measurements were carried out at open circuit potential, in the frequency range of $2 \times 10^{-1} - 1 \times 10^5$ Hz with a 10 mV AC sinusoidal perturbation, and the polarization resistance (R_p) was determined from Nyquist plots. The inhibition efficiency obtained from EIS (η_{EIS}) was calculated using Equation 5:

$$\eta_{EIS} = \left[1 - \frac{R_{p,i}}{R_{p,o}} \right] \times 100 \quad (5)$$

where, $R_{(p,0)}$ represents the polarization resistance measured in the absence of inhibitor, while $R_{(p,i)}$ corresponds to the polarization resistance measured in the presence of inhibitor.

Potentiodynamic polarization (Tafel) curves were recorded over a potential range of ±250 mV around the open circuit potential at a scan rate of 1 mV/s. The logarithm of the current density (i_{corr}) was plotted against the electrode potential (E), and the corrosion potential (E_{corr}) and corrosion current density (i_{corr}) were determined using the Tafel extrapolation method. The inhibition efficiency (%IE) was calculated using Equation 6 and surface coverage (θ) was calculated using Equation 7 were calculated using the following equations:

$$\%IE = \left[1 - \frac{i_{corr}}{i_{corr}^*} \right] \times 100 \quad (6)$$

$$\theta = 1 - \frac{I_{corr}}{I_{corr}^*} \quad (7)$$

Here, i_{corr}^* and i_{corr} represent the corrosion current densities measured in the presence and absence of inhibitor, respectively. This method enables quantitative evaluation of the effectiveness of tamarind fruit and dietary fiber extracts in reducing the corrosion rate of mild steel in an acidic environment.

Water Activity

Water activity (aw) values of tamarind fruit and tamarind dietary fiber samples were determined at room temperature using a water activity meter (Novasina Labmaster, 1119971, Switzerland). To ensure the accuracy and reproducibility of the measurements, each sample was analyzed in triplicate. This approach enabled a comparative evaluation of the water retention characteristics and stability between the fruit and fiber fractions [43].

RESULTS and DISCUSSION

In this study, the dietary fiber contents of tamarind fruit and the fiber fraction isolated from tamarind were determined to be $28.2 \pm 0.04\%$ and $73.31 \pm 0.30\%$, respectively (Table 4). These results indicate that while tamarind fruit naturally contains dietary fiber, the isolated fiber fraction provides a significantly higher concentration. This highlights the potential of fruit-derived fibers as functional ingredients in the food industry.

Table 4. Physicochemical and functional properties of tamarind fruit and tamarind dietary fiber

Parameter	Tamarind Fruit	Tamarind Dietary Fiber
Dietary Fiber Content (%)	28.2 ± 0.04	73.31 ± 0.30
Swelling Capacity (%)	2.30 ± 0.01	9.21 ± 0.01
Water Holding Capacity (mL/g)	1.96 ± 0.17	6.17 ± 0.11
Water Activity (aw)	0.945 ± 0.23	0.459 ± 0.17
Dry Matter (%)	45.23 ± 2.13	94.44 ± 1.18
Oil Holding Capacity (g/g)	1.74 ± 0.12	2.25 ± 0.09
Antioxidant Activity (FRAP) ($\mu\text{mol Fe}^{2+}$ eq.)	330.5 ± 1.57	77.07 ± 1.04
Antioxidant – DPPH SC50 (mg/mL)	2.33 ± 0.11	0.54 ± 0.07
Ash Content (%)	3.24 ± 0.09	4.31 ± 0.1
Protein ($\mu\text{g/mL}$)	96.34 ± 1.21	4.27 ± 0.58
Organic Acids (mg/g)		
Citric Acid	0.22 ± 0.04	N.D
Tartaric Acid	3.80 ± 0.24	N.D
Malic Acid	0.60 ± 0.02	N.D
Sugar Content (%)		
Glucose	1.52 ± 0.09	0.17 ± 0.01
Fructose	1.93 ± 0.07	0.21 ± 0.01

N.D: Not detected

The swelling capacity of dietary fiber is defined as the increase in volume that occurs when the fiber absorbs water or draws water into its matrix. This property increases the fiber's mechanical bulk in the gastrointestinal tract, allowing it to remain in the stomach and intestines longer, thereby contributing to prolonged satiety and reduced energy intake. In this study, the swelling capacities of tamarind fruit and isolated tamarind dietary fiber samples were $2.30 \pm 0.01\%$ and $9.21 \pm 0.01\%$, respectively (Table 4).

Water holding capacity, one of the functional properties of dietary fibers, refers to the amount of water that a fiber can retain relative to its own weight. This property has significant effects on food consistency, texture stability, shelf life, and gastrointestinal functions [44]. The WHC of a fiber varies depending on its structural char-

acteristics, particle size, surface area, and the content of hydrophilic components [45]. In this study, the water holding capacities of tamarind fruit and the dietary fiber extracted from the fruit were compared. According to the results, the WHC of tamarind fruit was determined as 1.96 ± 0.17 mL/g, while that of dietary fiber was 6.17 ± 0.11 mL/g (Table 4). These results indicate that the interaction capacity of the soluble and insoluble components present in tamarind fruit with water is higher than that of the purified fiber fraction. The water holding capacity of tamarind shows similarity to that of certain vegetables and fruits reported in the literature. It is comparable to orange peel (1.8 – 2.0 mL/g; [46]) and coconut fiber (2.0 – 4.0 mL/g; [47]), whereas it is lower than spinach fiber (6.4 mL/g; [48]), and tropical fruit fibers (2.5 – 5.0 mL/g; [49]). These findings suggest that tamarind can be considered a potential functional food component in terms of water holding capacity.

Water activity is an important parameter that reflects the amount of free water in a food and its availability for microbial growth. In this study [34], the water activity of tamarind fruit was found to be 0.945 ± 0.23 , indicating a relatively high level. High water activity suggests that the fruit may be more susceptible to microbial growth and chemical changes. On the other hand, the water activity of the isolated tamarind dietary fiber was measured as 0.459 ± 0.17 , which is significantly lower than that of the fruit. This low value indicates that the fiber has a dry structure with low moisture content, making it more stable against microbial activity. These results suggest that tamarind fiber could serve as a functional food ingredient, particularly in applications that require moisture control and extended shelf life.

Dry matter content is an important parameter that reflects the solid composition of food materials and their potential stability. In this study, tamarind fruit had a dry matter content of $45.23 \pm 2.13\%$, whereas the isolated tamarind dietary fiber had a significantly higher dry matter content of $94.44 \pm 1.18\%$. The higher dry matter content in the dietary fiber indicates that most of the water was removed during the isolation process, yielding a concentrated, stable fiber fraction. In contrast, the lower dry matter content of the whole fruit reflects its higher moisture content, which may influence its texture, shelf life, and susceptibility to microbial growth.

The oil-holding capacity of dietary fibers is a noteworthy property for maintaining and improving the quality of food products. This characteristic particularly helps reduce oil losses that may occur during cooking. Additionally, the oil-binding ability of fibers can help regulate plasma cholesterol levels by limiting fat absorption. Therefore, it plays an important role from both technological and health perspectives [50]. In this study, the oil-holding capacity of tamarind dietary fiber (2.25 ± 0.09 g/g) was found to be higher than that of the tamarind fruit sample (1.74 ± 0.12 g/g) (Table 4). This result may be attributed to the dietary fiber being richer in fiber, free from soluble components, and having a more porous structure. In contrast, the fruit sample contains soluble sugars, acids, and water—components that do not contribute to oil binding and may dilute the overall binding capacity. These findings are consis-

tent with similar studies reported in the literature [51, 52].

In this study, the antioxidant activities of tamarind fruit and the dietary fiber fraction isolated from the fruit were evaluated using the FRAP assay. According to the results, the antioxidant capacity of the tamarind fruit was determined to be $330.5 \pm 1.57 \mu\text{mol Fe}^{2+}/\text{mL}$, while the corresponding value for the dietary fiber fraction was found to be $77.07 \pm 1.04 \mu\text{mol Fe}^{2+}/\text{mL}$ (Table 4). These findings indicate that tamarind fruit exhibits a significantly greater reducing power than its isolated dietary fiber.

This difference may be attributed to the higher levels of bioactive compounds present in the fruit, such as phenolic compounds, ascorbic acid, and flavonoids, which are known for their antioxidant properties. In contrast, the dietary fiber fraction, derived from the fibrous residue of the fruit, may display lower antioxidant capacity due to the partial removal of polyphenols and water-soluble components during the extraction process. Similarly, several studies in the literature support the high antioxidant potential of tamarind fruit. For instance, in a study [52], the FRAP value of tamarind pulp was reported as $216.17 \pm 14.06 \mu\text{mol Fe}^{2+}/\text{g}$, while the seed fraction exhibited a significantly higher value of $659.74 \pm 16.40 \mu\text{mol Fe}^{2+}/\text{g}$ [53]. These results demonstrate considerable variation in antioxidant activity among different fruit components, with seeds and pulp being richer in phenolic compounds. In another study [54], it was shown that the addition of phenolic extracts obtained from tamarind waste to tamarind nectars significantly enhanced their antioxidant capacity measured by FRAP, ABTS, and ORAC assays, resulting in an approximately 1900% increase in total antioxidant activity.

In light of these findings, the FRAP values obtained in the present study, particularly for tamarind fruit, are consistent with those reported in the literature and further confirm the fruit's richness in phenolic and flavonoid compounds. Although the dietary fiber fraction exhibited relatively lower antioxidant capacity compared to the whole fruit, the FRAP value of $77.07 \pm 1.04 \mu\text{mol Fe}^{2+}/\text{mL}$ indicates that it still possesses a notable reducing potential. This suggests that tamarind dietary fiber could serve not only as a functional food ingredient but also as a promising candidate for use in health-promoting products, pharmaceutical applications, and natural antioxidant formulations.

In this study, the free radical scavenging capacities of tamarind fruit and its derived dietary fiber fraction were evaluated using the DPPH assay. According to the results, the SC_{50} value for the fruit extract was determined as $2.33 \pm 0.11 \text{ mg/mL}$, while the Trolox® equivalent (TE) antioxidant capacity (TEAC) of the dietary fiber fraction was measured as $0.54 \pm 0.07 \text{ mg/mL}$ (Table 4). These findings indicate that the dietary fiber fraction exhibits a markedly lower antioxidant capacity compared to the whole fruit. Similar results have been reported in previous studies. For instance [55], reported that the methanolic extract of tamarind fruit exhibited strong DPPH radical scavenging activity, primarily attributed to its phenolic constituents. In another study, an SC_{50} value of approx-

imately 1.9 mg/mL was reported for extracts obtained from tamarind pulp [7]. Although this value is close to the $2.33 \pm 0.11 \text{ mg/mL}$ observed in the present study, it falls outside the given error range, indicating that the two values do not fully overlap statistically; nonetheless, both values are of the same order of magnitude, suggesting a high degree of consistency between the findings. Furthermore [31], demonstrated that phenolic extracts derived from tamarind by-products significantly enhanced the DPPH radical scavenging capacity of fruit-based formulations.

Taken together, the SC_{50} and TEAC values obtained in the present study highlight the notable antioxidant potential of tamarind fruit, establishing it as a promising natural source of free radical scavengers. Although the dietary fiber fraction exhibited comparatively lower antioxidant activity, likely due to the partial removal of phenolic compounds during extraction, it still demonstrated measurable radical scavenging capacity. The observed TEAC value of $0.54 \pm 0.07 \mu\text{mol TE/mL}$ indicates that this fraction may have practical applications not only as a functional food ingredient but also in nutraceuticals, health-promoting products, and formulations incorporating natural antioxidants.

Ash determination is one of the fundamental analyses used to assess the mineral content of a food product. This analysis reflects the proportion of inorganic residue remaining after the combustion of organic components at high temperatures. Ash content not only indicates the total mineral composition of the food but also reveals changes in mineral concentration during the purification process of components such as dietary fiber [40]. In this study, the ash contents of tamarind fruit and its dietary fiber were determined as $3.24 \pm 0.09\%$ and $4.31 \pm 0.1\%$, respectively (Table 4). The higher ash content observed in the dietary fiber compared to the fruit may be attributed to the removal of water, sugars, and soluble proteins during fiber isolation, as well as the potential concentration of minerals within the fiber matrix due to solubilization during NaOH treatment [44, 47].

Similarly, studies on fibers obtained from coconut residue have reported ash contents in the range of 4.1-4.5% [45], whereas in orange peel, this value varies between 2.6-3.2% [51]. In another study, the ash content of tamarind pulp was determined to be $2.96 \pm 0.004\%$, and the ash content of shell flour was determined to be $3.76 \pm 0.000\%$ [56]. These findings suggest that tamarind dietary fiber can be utilized not only as a functional fiber source in food products but also as a potential mineral supplement.

In this study, the total protein content of tamarind fruit and isolated dietary fiber samples was determined using the Bradford method. According to the analysis results, the protein content of the tamarind fruit was measured as $96.34 \pm 1.21 \mu\text{g/mL}$, whereas this value decreased to $4.27 \pm 0.58 \mu\text{g/mL}$ in the dietary fiber sample. This decrease is thought to be associated with the loss of soluble proteins resulting from the extraction and purification processes used during dietary fiber isolation (Table 4).

Organic acids are important components that directly influence the flavor and microbial safety of fruits and vegetables [57]. In this study, citric acid, tartaric acid, and malic acid were identified. According to the obtained data, the fruit sample contained 0.22 ± 0.04 mg/g of citric acid, 3.80 ± 0.24 mg/g of tartaric acid, and 0.60 ± 0.02 mg/g of malic acid, whereas these organic acids were not detected in the dietary fiber sample (Table 4). The absence of organic acids in the dietary fiber sample can be attributed to the removal of water-soluble components during fiber isolation, which substantially reduces the acid content of the fiber fraction.

In tamarind fruit, the contents of fructose and glucose were determined to be $1.93 \pm 0.07\%$ and $1.52 \pm 0.09\%$, respectively. Following dietary fiber extraction, these values decreased significantly to $0.21 \pm 0.01\%$ for fructose and $0.17 \pm 0.01\%$ for glucose. This indicates that a substantial portion of mono- and disaccharides was removed during the extraction processes used to prepare the fiber fraction, resulting in a fiber product that is largely free of sugars. In a study conducted by [58], the glucose content in ripe tamarind fruits collected from different regions of Nigeria was reported to range from 1.1–4.4% (11–44 mg/g), while the fructose content ranged from 0.7–3.2% (7–32 mg/g). These values are considerably higher than those obtained in the fruit sample analyzed in the present study. The observed differences may be attributed to factors such as cultivation conditions, geographical origin, fruit maturity, and variations in analytical methods.

The corrosion behavior of mild steel in 1 M HCl in the presence of tamarind fruit and tamarind dietary fiber was evaluated using potentiodynamic polarization analysis. It is presumed that the tamarind dietary fiber extract reduces the corrosion rate by forming a protective layer on the steel surface, likely due to the presence of insoluble dietary fibers and polyphenolic constituents originally contained in the fruit.

The electrochemical behavior of mild steel in 1 M HCl solution in the presence of tamarind fruit, under aerated conditions, is presented by the Nyquist plots in Figure 1. As can be seen, the diameter of the depressed capacitive semicircle systematically increases with the increasing concentration of tamarind fruit extract (from 100 ppm to 200 ppm). This clearly indicates that the corrosion inhibition efficiency increases with higher concentrations of tamarind fruit extract. The increase in the radius of the curves signifies a substantial rise in charge transfer resistance, which is inversely proportional to the corrosion rate.

Potentiodynamic polarization curves were examined to evaluate the effect of tamarind fruit on mild steel. The Tafel plots exhibited a pronounced downward shift in both the anodic and cathodic branches, stabilizing around 0.5 V (Figure 2). This indicates that the extract suppresses both oxidation (anodic) and reduction (cathodic) reactions on the metal surface, thereby reducing the corrosion rate.

Furthermore, the polarization results revealed that the inhibitory effect became most pronounced at an inhibitor concentration

of 200 ppm. These findings support that tamarind fruit acts as a mixed-type inhibitor and forms an effective protective layer on the metal surface.

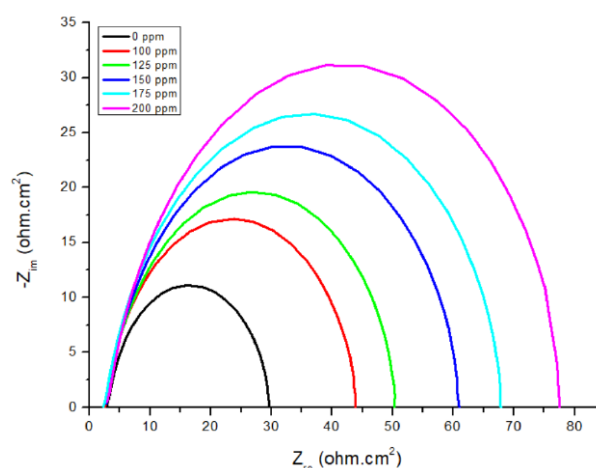


Figure 1. Nyquist plots of the mild steel electrode in 1 M HCl solution containing different concentrations of tamarind fruit extract inhibitor

According to the data presented in Figure 2 and Table 5, increasing the inhibitor concentration up to 200 ppm resulted in a decrease in cathodic current density and a shift of the corrosion potential (E_{corr}) towards more negative values, indicating a reduction in the corrosion rate. The inhibitor derived from tamarind fruit reduced the corrosion rate by 70.28% at the highest concentration tested. The simultaneous decrease in both anodic and cathodic reaction rates with increasing concentration supports the formation of a protective layer on the metal surface.

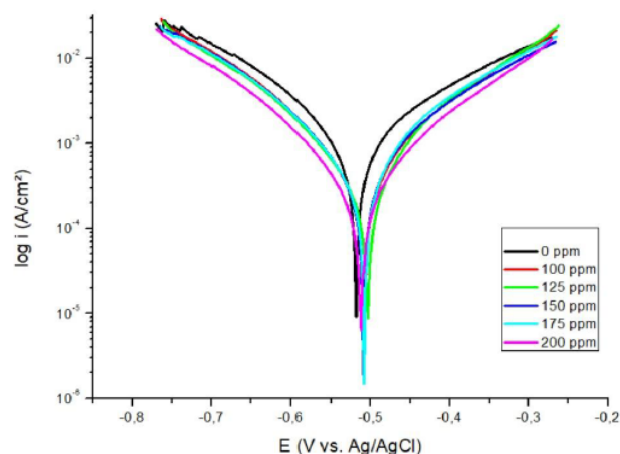


Figure 2. Tafel polarization curves at different inhibitor concentrations (tamarind fruit)

In the absence of the inhibitor, E_{corr} was approximately -519 mV, whereas in its presence, it stabilized between -508 and -513 mV. The corrosion current density (i_{corr}) decreased significantly from $737 \mu\text{A}$ when the inhibitor was introduced. Likewise, the corrosion rate decreased from 874.3 mpy to substantially lower values. The inhibition efficiency (%IE) and surface coverage (θ) increased with inhibitor concentration, reaching %IE = 70.28 and $\theta = 0.7028$ at 200 ppm. These findings confirm that tamarind fruit extract can serve as an effective corrosion inhibitor.

The electrochemical behavior of mild steel in 1 M HCl solution containing tamarind dietary fiber, under aerated conditions, is shown in the Nyquist plots in Figure 3. As observed, the diameter of the depressed capacitive semicircle increases systematically with the increasing concentration of tamarind dietary fiber (from 100 ppm to 200 ppm). This clearly demonstrates that the corrosion inhibition efficiency rises with higher concentrations of tamarind dietary fiber. The increase in the radius of the curves indicates a significant enhancement in charge transfer resistance, which is inversely proportional to the corrosion rate.

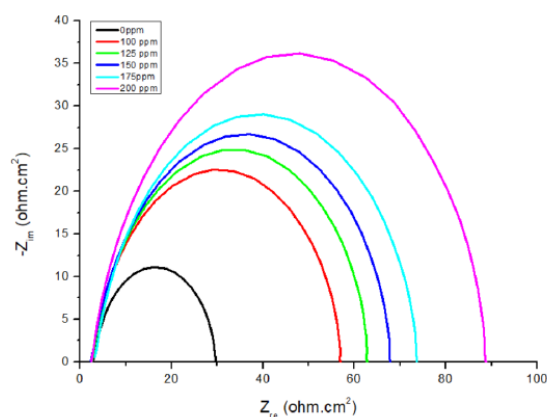


Figure 3. Nyquist plots of the mild steel electrode in 1 M HCl solution containing different concentrations of tamarind dietary fiber inhibitor

Potentiodynamic polarization analysis demonstrated that tamarind dietary fiber reduces the corrosion of mild steel. The decrease observed in both the anodic and cathodic branches of the Tafel curves indicates that the extract suppresses oxidation and reduction reactions (Figure 4). The protective effect increased with inhibitor concentration and approached its maximum at 200 ppm. These findings suggest that tamarind dietary fiber acts as a mixed-type inhibitor and forms a protective layer on the metal surface.

According to the data presented in Figure 4 and Table 6, increasing the inhibitor concentration up to 200 ppm resulted in a decrease in cathodic current density, a shift of the corrosion potential (E_{corr}) towards more negative values, and a corresponding reduction in the corrosion rate. The inhibitor exhibited a maximum corrosion inhibition efficiency of 86.3%.

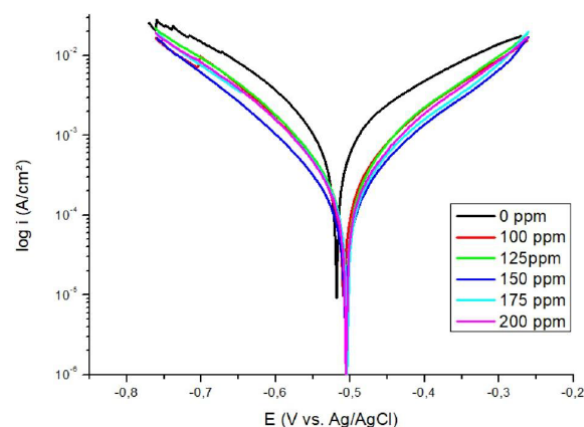


Figure 4. Tafel polarization curves at different inhibitor concentrations (tamarind dietary fiber)

Examination of Figure 4 shows that the inhibitor derived from tamarind fruit effectively reduces the corrosion rate. As the inhibitor concentration increases, both anodic and cathodic reactions are suppressed, and the corrosion current density (i_{corr}) decreases, indicating enhanced inhibitory performance and the formation of a protective layer on the metal surface. E_{corr} represents the corrosion potential, which was approximately -519 mV in the absence of an inhibitor. With increasing inhibitor concentration, E_{corr} remained relatively stable between -508 and -506 mV.

The corrosion current density, i_{corr} , was $737 \mu\text{A}$ in the uninhibited solution and decreased significantly as the inhibitor concentration increased. Similarly, the corrosion rate dropped from 874.3 mpy to considerably lower values. The inhibition efficiency (%IE), which indicates the extent to which the inhibitor reduces the corrosion rate, increased with concentration. In the absence of an inhibitor, %IE was naturally 0%. At 100 ppm, %IE was 67.57%, and at 200 ppm, it reached 86.3%. θ represents the surface coverage or the fraction of the metal surface protected by the inhibitor. In the absence of an inhibitor, θ is naturally 0. As the inhibitor concentration increases, θ rises, reaching 0.6757 at 100 ppm and 0.8863 at 200 ppm.

In summary, increasing the inhibitor concentration leads to a decrease in corrosion current density, corrosion rate, and Tafel slopes, while the inhibition efficiency (%IE) and surface coverage (θ) increase. These results indicate that the inhibitor derived from

Table 5. Electrochemical parameters obtained from Tafel extrapolation for the inhibitor derived from tamarind fruit

Inhibitor	C (ppm)	$-E_{corr}$ (mV)	i_{corr} (μA)	β_a (mV/dec)	β_c (mV/dec)	Corrosion rate (mpy)	% IE	θ
HCl	-	519	737	112.40	110.3	874.3		
	100	508	549	149.2	145.6	652.1	25.510	0.2551
	125	504	473	137.1	145.6	561.5	35.82	0.3582
	150	509	299	84.2	95.9	354.6	59.43	0.5943
	175	508	276	74.3	94.3	327.6	62.55	0.6255
	200	513	219	96.9	97.7	259.4	70.280	0.7028

Table 6. Electrochemical parameters obtained from Tafel extrapolation for the inhibitor derived from tamarind dietary fiber

Inhibitor	C (ppm)	$-E_{\text{corr}}$ (mV)	i_{corr} (μA)	β_a (mV/dec)	β_c (mV/dec)	Corrosion rate (mpy)	% IE	θ
HCl	-	519	737	112.40	110.3	874.3		
	100	509	239	102.50	107.2	283.5	67.570	0.6757
	125	506	224	94.1	102.4	265.6	69.61	0.6961
	150	507	152	100.6	112	180.8	79.38	0.7938
	175	504	107	67.5	65.3	126.6	85.48	0.8548
	200	506	101	62.8	62.9	119.7	86.300	0.8630

tamarind seed is effective in controlling corrosion. While tamarind fruit extract reduced corrosion by 70.28%, tamarind dietary fiber increased this effect to 86.30%, indicating that the fiber fraction forms a denser, more stable protective layer on the metal surface and exhibits higher inhibitory efficiency than the fruit extract.

The corrosion inhibition performance obtained in the present study is in good agreement with previous reports on tamarind-based green inhibitors. Jayakumar et al. [41] investigated the corrosion inhibition of mild steel in 1 M HCl using a tamarind fruit pulp aqueous extract and, by weight-loss measurements, reported inhibition efficiencies ranging from 74% to 88% over a concentration range of 100–600 ppm, with the reduction in Tafel slopes indicating that the extract behaved as a mixed-type inhibitor. The present study shares several key features with that work: the same metal/electrolyte system (mild steel in 1 M HCl), the same electrochemical techniques (potentiodynamic polarization and EIS), the same concentration-dependent increase in protective efficiency, and the same mixed-type inhibition behaviour, in which both the anodic and cathodic branches of the Tafel curves are suppressed. The maximum inhibition efficiency obtained here for the tamarind fruit extract (70.28% at 200 ppm) is of the same order of magnitude as the values reported by Jayakumar et al., the differences being reasonably attributable to the narrower concentration range studied here (100–200 ppm vs. 100–600 ppm), the ethanol-water extraction solvent, and differences in steel composition and immersion conditions.

The principal difference and the novelty of the present work lie in the comparative evaluation of the tamarind fruit extract against the dietary-fiber fraction isolated from tamarind processing by-products. Whereas Jayakumar et al. [41] examined only the aqueous fruit pulp extract, the present study demonstrates that the isolated dietary-fiber fraction provides a markedly higher protective efficiency (86.3% at 200 ppm) than the fruit extract (70.28%). The valorization of a fibrous by-product as a corrosion inhibitor rather than the use of the edible fruit itself has not previously been reported for *Tamarindus indica* and is fully consistent with the circular-economy and zero-waste objectives of this study.

The corrosion-inhibiting action of the tamarind derivatives can be explained by the adsorption of their bioactive constituents onto the mild steel surface. Both the fruit and the fiber fraction are rich in oxygen-containing organic compounds - polyphenols and fla-

vonoids, organic acids (mainly tartaric and malic acid), proteins/ amino acids and, in the fiber fraction, hydroxyl-rich polysaccharides such as cellulose, hemicellulose and xyloglucan. These molecules possess heteroatoms (mainly oxygen) bearing lone electron pairs, together with aromatic rings and conjugated π -electron systems, which can coordinate to the vacant d-orbitals of surface iron atoms. In the acidic 1 M HCl medium, chloride ions first adsorb on the positively charged steel surface, after which the protonated inhibitor molecules adsorb electrostatically (physisorption), while the lone electron pairs of the functional groups simultaneously form coordinate bonds with iron (chemisorption). The resulting adsorbed film acts as a barrier that isolates the metal from the corrosive electrolyte and suppresses both the anodic dissolution of iron and the cathodic hydrogen-evolution reaction, which accounts for the mixed-type behaviour observed in the Tafel curves. As the inhibitor concentration increases, the surface coverage (θ) rises and a more compact, continuous protective layer is formed, leading to higher charge-transfer resistance and lower corrosion current density, as reflected in the increasing diameter of the Nyquist semicircles. The superior performance of the dietary-fiber fraction is attributed to its higher content of hydroxyl-bearing insoluble polysaccharides and its more porous, film-forming structure, which enable a denser and more uniform protective layer than that formed by the fruit extract. This interpretation is consistent with the findings of Jayakumar et al. [41], who reported, on the basis of AFM measurements, that adsorption of the tamarind extract reduced the surface roughness of mild steel from 299 ± 12 to 154 ± 6.6 nm with increasing inhibitor concentration owing to uniform coverage of the metal surface, and that the adsorption obeyed the Langmuir isotherm with a free energy of adsorption of about -40 kJ/mol, indicative of chemisorption through coordinate bonding.

CONCLUSIONS

This study investigated the compositional and functional properties of tamarind fruit and its isolated dietary fiber fraction, highlighting the potential applications of both fractions in different contexts. The dietary fiber fraction, with its high total dietary fiber content and oil-holding capacity, demonstrates potential as a fat replacer or for developing low-fat functional food formulations. On the other hand, the fruit fraction, due to its sugar content, can be used in flavor-enhancing, energy-dense products.

The study emphasizes that both fractions can serve as multifunctional ingredients in food- and health-oriented products. Furthermore, future studies are recommended to optimize processing conditions to preserve the bioactive and techno-functional properties of both fractions and to investigate their in vivo effects, particularly on gut microbiota modulation and metabolic health.

Corrosion tests conducted in this study confirmed the protective effect of the applied inhibitors on metal surfaces, showing a significant reduction in corrosion rates at optimal concentrations. In future studies, the corrosion-inhibiting effects of different plant-based inhibitors can be explored and their performance compared across various metal surfaces. This approach could enable the development of eco-friendly and cost-effective corrosion inhibitors, extending the lifespan of metals in industrial applications, reducing maintenance costs, and minimizing the use of toxic chemicals.

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REFERENCES

- [1] Baser, K.H.C. (2021). Tamarind (*Tamarindus indica* L.). *Bağbahçe Bilim Dergisi*, 95, 24–26.
- [2] Sezgin, A.C., Durmaz, P. (2019). The role and consumption of sherbets in ottoman culinary culture. *Journal of Tourism and Gastronomy Studies*, 7(2), 1499–1518.
- [3] Özkurt, Ö. (2020). Determination of fatty acid composition of *Tamarindus indica* L. seeds by ultrasound-assisted microwave extraction. Master's thesis, Graduate School of Natural and Applied Sciences, Niğde Ömer Halisdemir University, Niğde, Türkiye. (Thesis No.635323)
- [4] Yañez, E., Zacarias, I., Aguayo, M., Vasquez, M., Guzman, E. (1995). Nutritive value evaluated on rats of new cultivars of common beans (*Phaseolus vulgaris*). *Plant Foods for Human Nutrition*, 47, 301–307.
- [5] Özaltın, B. (2016). Determination of bioactivities of *Tamarindus indica* L. (tamarind) sorbet, concentrated with different methods. (Master's thesis, Graduate School of Natural and Applied Sciences, Department of Food Engineering, Erciyes University, Kayseri, Türkiye). (Thesis No.430016)
- [6] Soni, N., Singh, V.K. (2019). Traditional, nutraceutical and pharmacological approaches of *Tamarindus indica* L. (imli). Malacology Laboratory, Department of Zoology, DDU Gorakhpur University, Gorakhpur, India.
- [7] Kumar, A., Sharma, S. (2011). Effect of tamarind (*Tamarindus indica* L.) seed powder on the antioxidant properties of cookies and mango juice. *International Journal of Food Science and Technology*, 46(1), 104–110.
- [8] Zhu, C.H., Li, Y.X., Xu, Y.C., Wang, N.N., Yan, Q.J., Jiang, Z.Q. (2023). Tamarind xyloglucan oligosaccharides attenuate metabolic disorders via the gut-liver axis in mice with high-fat-diet-induced obesity. *Foods*, 12(7), 1382.
- [9] Li, X., Guo, R., Wu, X., Liu, X., Ai, L., Sheng, Y., Zhang, Z., Wu, Y. (2020). Dynamic digestion of bitter melon seed polysaccharides: Indigestibility and in vitro gut microbiota changes in gastrointestinal simulations. *Carbohydrate Polymers*, 239, 116194.
- [10] Eren, R. (2023). Effects of *Tamarindus indica* L. extracts enclosed in PLA by electrospray method on the vitality of breast cancer cells. (Master's thesis, Graduate School of Natural and Applied Sciences, Department of Molecular Biology and Genetics, Marmara University, İstanbul, Türkiye).
- [11] Ahmad, N.I., Mustar, S., Abdul Rahman, S., Mohd Salim, R.J.M. (2024). *Tamarindus indica* L. Its Phytochemicals and Health Related Issues. In Science of Spices and Culinary Herbs-Latest Laboratory, Pre-clinical, and Clinical Studies: Volume 6 (pp. 93-146). Bentham Science Publishers.
- [12] Hamuel, J.D. (2007). Antimicrobial activity of *Tamarindus indica* Linn. *Tropical Journal of Pharmaceutical Research*, 5(2), 597–603.
- [13] Carlsen, H., Pajari, A.-M. (2023). Dietary fiber – a scoping review for Nordic Nutrition Recommendations 2023. *Food and Nutrition Research*, 67, 9979.
- [14] Salçın, N., Ercoşkun, H. (2021). Dietary fiber and its importance for health. *Academic Food Journal*, 19(2), 234–243.
- [15] Gill, S.K., Rossi, M., Bajka, B., Whelan, K. (2021). Diet and fiber in gastrointestinal health and disease. *Nature Reviews Gastroenterology and Hepatology*, 18(2), 101–116.
- [16] Mudgil, D., Barak, S. (2013). Composition, properties and health benefits of indigestible carbohydrate polymers as dietary fiber: A review. *International Journal of Biological Macromolecules*, 61, 1–6.
- [17] Khorasaniha, R., Olof, H., Voisin, A., Armstrong, K., Wine, E., Vasanthan, T., Armstrong, H. (2023). Diversity of fibers in common foods: Key to advancing dietary research. *Food Hydrocolloids*, 139, 108495.
- [18] Feng, L., Luo, Z., Wang, J., Wu, K., Wang, W., Liu, Z., Wen, J., Wang, Z., Duns, G.J., Ma, X., Tan, B. (2024). Effects of different ratios of soluble to insoluble dietary fiber on growth performance and intestinal health of piglets. *Animal Nutrition*, 13(5), 257–271.
- [19] Kim, Y., Hwang, S.W., Kim, S., Lee, Y.S., Kim, T.Y., Lee, S.H., Kweon, M.N. (2020). Dietary cellulose prevents gut inflammation by modulating lipid metabolism and gut microbiota. *Gut Microbes*, 11(4), 944–961.
- [20] Wolin, M.J. (1981). Fermentation in the rumen and human large intestine. *Science*, 213(4515), 1463–1468.
- [21] Song, Y., Li, Q., Liu, Y., Ma, Y., Lin, C., Bai, X., Nie, N., Liu, Y., Yi, Z., Zheng, H., Yu, S. (2025). Inconsistency in quality characteristics of soluble dietary fiber in wild *Rosa roxburghii* Tratt fruits from different regions. *Scientific Reports*, 15, 8289.
- [22] Zhang, S., Xu, X., Cao, X., Liu, T. (2023). The structural characteristics of dietary fibers from *Tremella fuciformis* and their hypolipidemic effects in mice. *Food Science and Human Wellness*, 12(2), 503–511.
- [23] Argun, M.E., Argun, M.Ş., Ateş, H. (2025). Zero waste principle in the fruit processing industry: recovery, upcycling, and revalorization approaches. *Journal of Water Process Engineering*, 100, 107.
- [24] Llanaza Coalla, H., Blanco Fernández, J.M., Moris Morán, M.A., López Bobo, M.R. (2009). Biogas generation from apple pulp. *Bioresource Technology*, 100(17), 3843–3847.
- [25] Tejada-Ortigoza, V., García-Amezquita, L.E., Kazem, A.E., Campanella, O.H., Cano, M.P. (2019). In vitro fecal fermentation of high pressure-treated fruit peels used as dietary fiber sources. *Molecules*, 24(4), 697.
- [26] Liu, Y., Tang, Y., Mei, H., Liu, Z., Li, Z., Ma, X., Luo, Z., Huang, W., Li, Y., Yu, M. (2024). Feeding combined probiotics fermented citrus pulp improves growth performance, meat quality, fatty acid profile, and antioxidant capacity in yellow-feathered chickens. *Veterinary Sciences*, 11, 1469947.
- [27] Binoj, J.S., Raj, R.E., Daniel, B.S.S. (2017). Comprehensive characterization of industrially discarded fruit fiber *Tamarindus indica* L. as a potential environmentally friendly bio-reinforcement for polymer composites. *Journal of Cleaner Production*, 141, 1326–1337.
- [28] Luo, M., Wang, C., Wang, C., Xie, C., Hang, F., Li, K., Shi, C. (2023). Effect of alkaline hydrogen peroxide assisted with two modification methods on the physicochemical, structural and functional properties of bagasse insoluble dietary fiber. *Frontiers in Nutrition*, 9:110706.
- [29] Brunt, K., Sanders, P. (2013). Improvement of the AOAC 2009.01 total dietary fibre method. *Food Chemistry*, 140(3), 710–716.
- [30] Horzum, M. (2018). Optimization of dietary fiber production from industrial apple pomace waste and the effect of particle size on technological properties. (Master's thesis, Erciyes University, Graduate School of Natural and Applied Sciences, Department of Food Engineering, Kayseri, Türkiye). (Thesis No. 517129)
- [31] Yang, X., Dai, J., Zhong, Y., Wei, X., Zhang, Y., Wu, M., Huang, A., Wang, L., Huang, Y., Zhang, C., Chen, X., Xiao, H. (2021). Characterization of insoluble dietary fiber from three food sources and their potential hypoglycemic and hypolipidemic effects. *Food and Function*, 12, 5005–5016.
- [32] Zhai, X., Ao, H., Liu, W., Zheng, J., Li, X., Ren, D. (2022). Physicochemical and structural properties of dietary fiber from *Rosa roxburghii* pomace by steam explosion. *Journal of Food Science and Technology*, 59(6), 2381–2391.
- [33] Benzie, I.F., Strain, J.J. (1996). The ferric reducing ability of plasma (FRAP) as a measure of "antioxidant power": The FRAP assay. *Analytical Biochemistry*, 239(1), 70–76.
- [34] Erdem, B., Cengiz, S., Şirin, Y., Gürkan, P., Artık, N. (2024). Food supplement production from propolis, honey, and mulberry molasses and its optimization. *Journal of Apitherapy and Nature*, 7(1), 28–52.
- [35] Gulcin, İ., Alwasel, S. H. (2023). DPPH Radical Scavenging Assay. *Processes*, 11(8), 2248.
- [36] Cuendet, M., Hostettmann, K., Potterat, O., Dyatmiko, W. (1997). Iridoid glucosides with free radical scavenging properties from *Fagraea blumei*.

- Helvetica Chimica Acta*, 80(1), 1–10.
- [37] Turkish Accreditation Agency (TURKAK). (2024). Accreditation certificate annex – Accreditation scope: Gıda ve Yem Kontrol Merkez Araştırma Enstitüsü (Accreditation No: AB-0030-T, Revision No: 26). Ankara: TURKAK.
- [38] Kruger, N.J. (2009). The Bradford method for protein quantitation. In J.M. Walker (Ed.), *The Protein Protocols Handbook* (3rd ed., pp. 17–24). Humana Press.
- [39] Bradford, M.M. (1976). A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Analytical Biochemistry*, 72(1–2), 248–254.
- [40] AOAC. (2000). *Official Methods of Analysis of AOAC International* (17th ed.). Gaithersburg, MD: Association of Official Analytical Chemists.
- [41] Jayakumar, S., Nandakumar, T., Vadivel, M., Thinaharan, C., George, R.P., and Philip, J. (2020). Corrosion inhibition of mild steel in 1 M HCl using *Tamarindus indica* extract: electrochemical, surface, and spectroscopic studies. *Journal of Adhesion Science and Technology*, 34(7), 713–743.
- [42] Umoren, S.A., Solomon, M.M. (2018). Plant extracts as green corrosion inhibitors for ferrous metals in acidic media. *Journal of Industrial and Engineering Chemistry*, 62, 1–18.
- [43] Şirin, Y., Erdem, B., Cengiz, S., Gürkan, S., Gürkan, P. (2024). Determination of biochemical composition and adulteration of black mulberry extracts. *Gıda*, 49(6), 1038–1061.
- [44] Elleuch, M., Bedigian, D., Roiseux, O., Besbes, S., Blecker, C., Attia, H. (2011). Dietary fibre and fibre-rich by-products of food processing: Characterisation, technological functionality and commercial applications: A review. *Food Chemistry*, 124(2), 411–421.
- [45] Thebaudin, J.Y., Lefebvre, A.C., Harrington, M., Bourgeois, C.M. (1997). Dietary fibres: Nutritional and technological interest. *Trends in Food Science and Technology*, 8(2), 41–48.
- [46] Marlett, J.A., McBurney, M.I., Slavin, J.L. (2002). Position of the American Dietetic Association: health implications of dietary fiber. *Journal of the American Dietetic Association*, 102(7), 993–1000.
- [47] Raghavendra, S.N., Rastogi, N.K., Raghavarao, K.S.M.S., Tharanathan, R.N. (2004). Dietary fiber from coconut residue: effects of different treatments and particle size on the hydration properties. *European Food Research and Technology*, 218(6), 563–567.
- [48] Saraç, G., Doğan, M. (2016). Investigation of some functional properties of plant-derived dietary fibers. *Gıda*, 41(3), 152–159.
- [49] John, I.P., Gurumurthy, K. (2023). Physicochemical characterization and functional properties of fruit dietary fibers. *Current Research in Nutrition and Food Science*, 11(3), 1300–1307.
- [50] Sert, D. (2019). Investigation of alternative dietary fiber sources and dietary fiber production. (Master's thesis, Ege University, Graduate School of Natural and Applied Sciences, Department of Food Engineering, İzmir, Türkiye). (Thesis No. 556988)
- [51] Grigelmo-Miguel, N., Martín-Belloso, O. (1999). Comparison of dietary fibre from by-products of processing fruits and greens and from cereals. *LWT - Food Science and Technology*, 32(10), 503–508.
- [52] Ajayi, S.A., Nwosu, C.O., Ogbunugafor, H.A. (2006). *Tamarindus indica* L.: A review of traditional uses, phytochemistry and pharmacology. *Africa Focus*, 23(1), 53–67.
- [53] Khairunnuur, F.A. Jr, Zulkhairi, A., Azrina, A., Moklas, M.M., Khairullizam, S., Zamree, M.S., Shahidan, M.A. (2009). Nutritional composition, in vitro antioxidant activity and *Artemia salina* L. lethality of pulp and seed of *Tamarindus indica* L. extracts. *Malaysian Journal of Nutrition*, 15(1), 65–75.
- [54] Lima, M.A., Souza, D.S., Coutinho, J.P., Silveira, T.F., Ballus, C.A., Filho, J.T., Godoy, H.T. (2020). Application of tamarind waste extracts to improve the antioxidant properties of tamarind nectars. *Food Research International*, 137, 109370.
- [55] Sudjaroen, Y., Haubner, R., Würtele, G., Hull, W.E., Erben, G., Spraul, M. (2005). Isolation and structure elucidation of phenolic antioxidants from tamarind (*Tamarindus indica* L.) seeds and pericarp. *Food and Chemical Toxicology*, 43(11), 1673–1682.
- [56] Ferreira, A.R., Ribeiro, H.L., Zandonadi, R.P. (2019). Functional and nutritional properties of tamarind (*Tamarindus indica* L.) pulp. *Carpathian Journal of Food Science and Technology*, 11(3), 82–89.
- [57] Kim, Y.H., Lim, J.Y., Yoon, K.S. (2019). Effect of Yuza (*Citrus junos* Sieb. ex Tanaka) powder and a mixture of sodium lactate and sodium acetate on water activity, quality, and safety of beef jerky. *Food and Nutrition Sciences*, 10(6), 588–605.
- [58] Adeola, A.A., Aworh, O.C. (2010). Sugar and dietary fibre components of tamarind (*Tamarindus indica* L.) fruits from Nigeria. *Nigerian Food Journal*, 28(2), 13–21.