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RESEARCH ARTICLE

# Elasto-Mechanical Properties Assessment of Rice Grains: Integrating Macroscopic and Microscopic Approaches

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## ABSTRACT

This research focuses on the measurement of the modulus of elasticity as a key elasto-mechanical property for three Iranian rice varieties—Tarom Hashemi, Anbarbu, and Dom Siah—using macroscopic compression tests and Atomic Force Microscopy (AFM) at the microscopic scale. The results indicated that Anbarbu exhibited the highest modulus of elasticity, reaching 1656.940 MPa at the macroscopic level and 786.102 MPa at the microscopic level. These values represent measurements at different scales and should not be directly compared; instead, they reflect the structural resistance to deformation at each scale. Tarom Hashemi, in contrast, showed lower modulus values, with an average of 1466.263 MPa in macroscopic measurements and 697.630 MPa in microscopic measurements, indicating comparatively lower rigidity. The statistical *t*-test, conducted at a significance level of $p < 0.05$, confirmed significant differences between the macroscopic and microscopic measurements, emphasizing the importance of microscopic approaches for understanding detailed structural mechanics. These findings provide valuable insights for tailoring rice processing techniques by highlighting how the modulus of elasticity influences grain breakage and deformation, ultimately aiding in preserving grain quality during post-harvest handling and processing.

## 1 | Introduction

Rice (*Oryza sativa*) is one of the world's most essential staple crops, feeding over half of the global population. This cereal grain is a critical source of carbohydrates, providing nearly 20% of global calorie intake, especially in densely populated regions across Asia and Africa (FAOSTAT 2023). Additionally, rice offers valuable nutrients like fiber, vitamins (e.g., B vitamins), and essential minerals, including magnesium, zinc, and iron, which contribute to human health and development (Zafar and Jianlong 2023). Beyond its dietary importance, rice supports cultural practices and economic structures, particularly in countries where it is the primary crop and income source. However, the significance of rice is accompanied by its vulnerability to mechanical damage during post-harvest processing, which can adversely affect its nutritional and economic value. Studies indicate that post-harvest losses in rice production can range from 15% to 25%, with mechanical losses during handling, milling, and storage accounting for a significant portion of this total (Corrêa et al. 2007; Kruszelnicka et al. 2020; FAOSTAT 2023). These losses often result in decreased quality, broken grains, and reduced market value, underscoring the urgency for advanced technological approaches to mitigate these challenges and ensure better utilization of this essential crop.

To mitigate post-harvest losses, a deeper understanding of rice grains' mechanical behavior is essential, as it plays a critical role in developing efficient handling, processing, and

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storage equipment (Shen et al. 2024; Tang et al. 2024; Zhang, Li, et al. 2024). By assessing the elasto-mechanical properties of rice grains, engineers and scientists can design processing systems that minimize grain damage, thereby enhancing both quality and yield. For example, equipment used in milling or de-husking processes must be calibrated based on the grain's unique mechanical properties to prevent fractures and broken kernels (Wang et al. 2022; Zeng et al. 2022). Evaluating these properties is crucial for determining the resilience and durability of rice grains, which, in turn, directly influences machine performance and efficiency. Hence, comprehensive mechanical assessments provide valuable insights for reducing losses, extending shelf life, and achieving a more sustainable rice supply chain.

However, measuring the mechanical properties of rice and other agricultural products is inherently challenging due to several unique factors. Agricultural products often have irregular shapes, unlike standardized industrial materials, making precise mechanical testing difficult (Khodabakhshian and Emadi 2011; Zhang, Hu, et al. 2024). Furthermore, rice grains exhibit viscoelastic behavior, which means their response to mechanical stress is not immediate or purely elastic but changes over time, depending on factors such as moisture content, temperature, and variety (Kokawa et al. 2017; Gao et al. 2024). For example, at higher moisture levels, rice grains may deform more easily under stress, wheras at lower temperatures, they may become brittle and more prone to breakage. These characteristics demand customized testing procedures and equipment, complicating the assessment process. Traditionally, macroscopic mechanical testing has been conducted using devices like the Instron, which provides reliable but sometimes limited insights due to its broad testing mode (Vatani et al. 2025). Although effective, such macroscopic methods face limitations in capturing microstructural details that may influence grain behavior under stress, especially in light of rice's diverse morphological and varietal variations.

To address the limitations of macroscopic testing, new approaches, such as Atomic Force Microscopy (AFM), have emerged for evaluating agricultural products' mechanical properties at the microscopic mode (Zdunek and Kurenda 2013; Xi et al. 2015; Wen et al. 2020; Tinoco et al. 2022; Vatani et al. 2025). AFM provides high-resolution measurements of surface topography and nanomechanical characteristics, enabling detailed insights into the microstructural properties that influence rice grain strength and fracture tendencies. Recent research, including the study titled "Advances in food material nanomechanics by means of AFM," highlights the growing importance of AFM in food science, particularly for understanding the mechanical behavior of food materials at the nanoscale (Arredondo-Tamayo et al. 2023). This research showcases how AFM can be utilized to explore the elastic and viscoelastic properties of agricultural produce, revealing the intricate relationships between microstructural features and overall produce resilience.

Given these considerations, the present study aims to integrate macroscopic and microscopic approaches for a comprehensive elasto-mechanical assessment of rice grains. By combining traditional Instron-based macroscopic tests with advanced AFM analyzes, this research seeks to bridge the gap between large-scale mechanical properties and microstructural characteristics, providing a holistic understanding of rice grain behavior under stress. This dual-scale approach will enable the design of more precise, effective handling and processing equipment tailored to rice's specific mechanical profile. Ultimately, this study contributes to the ongoing effort to reduce post-harvest losses, improve grain quality, and support a sustainable agricultural framework.

## 2 | Materials and Methods

### 2.1 | Rice Samples Collection and Preparation

#### 2.1.1 | Sample Collection

In this study, three popular Iranian rice varieties—Tarom Hashemi, Anbarbu, and Dom Siah—were selected for elasto-mechanical behavior assessment (Figure 1). These varieties are widely cultivated and valued for their distinct characteristics, which may influence their mechanical properties under different loading conditions (Rahmani and Mani-Varnosfaderani 2022). A sample of 200 g of each variety was procured from rice distribution centers in Mashhad, Iran, in December 2023, ensuring the samples were of comparable age and stored under similar conditions before testing to control for post-harvest changes. Upon procurement, the rice samples were transported to the laboratory of the Department of Biosystems Engineering at Ferdowsi University of Mashhad for subsequent testing.

#### 2.1.2 | Sample Preparation

To maintain the integrity of the samples during storage, each variety was packed in double-layered polyethylene bags, specifically chosen to limit moisture transfer and prevent external contaminants from altering the physical or mechanical properties of the rice grains (Sheikh et al. 2021). All samples were stored at ambient laboratory conditions (approximately 20°C–25°C) to simulate typical handling environments and to ensure uniformity in pre-test conditions across varieties. Prior to testing, each sample was allowed to equilibrate within the laboratory for 24 h (Khodabakhshian et al. 2012). This equilibration period ensures that the samples reach a consistent ambient moisture level, which is critical for accurate and reproducible measurements of elasto-mechanical properties (Wang et al. 2022).


**FIGURE 1** | Rice samples used in this study.

## 2.2 | Physical Properties Measurement of Samples

### 2.2.1 | Measurement of Geometrical Properties

The geometric dimensions of the rice grains were measured in three mutually perpendicular directions, denoted as, and corresponding to the length, width, and thickness of each grain, respectively (Figure 2). These dimensions are critical for accurately determining the rice grain's structural and mechanical properties. For each variety, a random sample was selected, and the measurements were conducted using a digital caliper with a precision of 0.02 mm to ensure accuracy and consistency across samples (Yang et al. 2007; Khodabakhshian et al. 2012). Precision is especially crucial in elasto-mechanical studies, as minor variations in size can influence the outcomes of compressive tests and the grain's resistance to breakage. The measurements were repeated five times for grains from each variety to minimize potential errors due to irregular shapes or minor discrepancies in grain morphology. By adhering to these meticulous measurement protocols, the study ensures that the elasto-mechanical properties are directly comparable across different rice varieties, allowing for reliable assessment and analysis.

### 2.2.2 | Measurement of Gravimetrical Properties

The mass of rice samples was measured using a high-precision digital scale with an accuracy of 0.0001 g at the central laboratory of Ferdowsi University of Mashhad.

To determine bulk density, samples were poured into a graduated cylinder with a volume of 150 cm$^3$. A wooden plate was then drawn diagonally across the cylinder opening to remove any excess grains without applying pressure, ensuring that no force altered the bulk density. The mass of the remaining samples in the container was measured, and the bulk density ($\rho_b$) was calculated as the ratio of sample mass to container volume, as shown in Equation (1):

$$\rho_b = \frac{M_b}{V_b} \tag{1}$$

Where $\rho_b$ = bulk density (g/cm$^3$), $M_b$ = mass of the sample (g), $V_b$ = volume of the container (cm$^3$).

To determine true density, a liquid displacement method was employed. First, the mass of a portion of rice grains was measured.

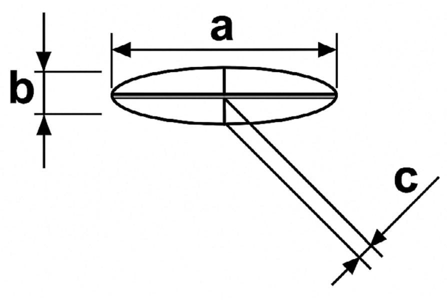


**FIGURE 2** | Geometric dimensions of rice.

These grains were then placed in a graduated cylinder containing toluene, which was chosen for its low absorbency, low solubility, and low surface tension, minimizing measurement error (Khodabakhshian et al. 2010). The true density ($\rho_t$) was calculated by dividing the mass of the grains by the volume of toluene displaced, as shown in Equation (2):

$$\rho_t = \frac{M_t}{V_t} \tag{2}$$

Where $\rho_t$ = true density (g/cm$^3$), $M_t$ = mass of the grains (g), $V_t$ = volume displaced by the grains (cm$^3$).

Porosity ($\varepsilon$) was calculated based on the measured bulk density and true density, using Equation (3) (Kruszelnicka 2021):

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \tag{3}$$

## 2.3 | Assessment of Elasto-Mechanical Properties at the Macroscopic Mode

### 2.3.1 | Tensile-Compression Test Equipment

To determine the macroscopic mechanical properties of rice grains, a compression test was conducted using a universal testing machine (Instron H5KS, Tinius Olsen, UK). This device is capable of assessing the mechanical properties of various materials under different loading conditions, including tensile, compressive, and shear loads. It also allows for the configuration of displacement and force units according to both SI and imperial systems. The testing machine consists of a fixed jaw and a movable jaw, between which the test sample is placed. Compressive loading is applied to each sample by moving the upper jaw, which is connected to a load cell. All operations and controls were managed through a computer system connected to the device. For this study, compressive force measurements were obtained using strain gage load cells. Prior to testing, the Instron device was calibrated using standardized calibration procedures. The calibration process included checking the force measurement accuracy with certified calibration weights and ensuring proper alignment of the load cell and moving parts. These calibration procedures were carried out to minimize experimental errors and ensure the precision of the force-deformation curves generated during the compression tests. During the compression tests, a force-deformation curve was generated for each sample. From the data obtained, the elasticity modulus—a key elasto-mechanical property—was calculated for each sample, as further detailed in the subsequent section. Previously, the authors have also utilized this device for measuring the mechanical properties of various agricultural products at a macroscopic mode and have published their research findings in reputable journals (Khodabakhshian et al. 2019; Khodabakhshian and Hassani 2021; Vatani et al. 2025).

### 2.3.2 | Evaluation of Rice Grain Behavior Under Compression Loading

To calculate the Young's modulus of each rice sample, grains were placed transversely between two steel plates, and the loading rate was set to 1.5 mm/min. The load was applied until the complete rupture of the grain, and the force-displacement curve was recorded by the material testing device and stored in the computer system. Based on the obtained curves, the Young's modulus for each sample was calculated using Hertz's theory, as follows (Khodabakhshian and Emadi 2011):

$$E = \frac{0.5P\left(1-\mu^2\right)}{\Delta L^{3/2}}\left(\frac{1}{R}+\frac{1}{R'}\right)^{1/2} \tag{4}$$

Where $E$ = Young's modulus (MPa), $P$ = applied force (N), $\Delta L$ = deformation of the grain (mm), $\mu$ = Poisson's ratio of the grain (set at 0.42 as per ASABE standards) (ASABE, 2000), $R$ and $R'$ = smallest and largest radii of curvature of the grain at the contact area with the plates (mm). The values of $R$ and $R'$ are determined using Equations (5) and (6) (ASABE 2000):

$$R = \frac{b^2 + c^2}{4c} \tag{5}$$

$$R' = \frac{a^2 + c^2}{4c} \tag{6}$$

Where $a$ = length, $b$ = width, $c$ = thickness, all in millimeters.

## 2.4 | Assessment of Elasto-Mechanical Properties at the Microscopic Mode

### 2.4.1 | AFM

The elasto-mechanical properties of rice grains at the microscopic mode were evaluated, focusing specifically on the elastic modulus as a key mechanical property. For this measurement, an atomic force microscope (AFM, model JPK, manufactured in Germany) was utilized. The AFM has broad applications, including surface topography analysis, cell and molecular studies at the nanometer mode, and surface force measurements. It enables imaging at atomic resolution and under physiological conditions, allowing detailed observation of living cell ultrastructure. Additionally, this device provides force spectroscopy data, which is essential for accurately determining the elastic modulus and other mechanical characteristics of microscopic samples. The authors of this article have previously utilized this AFM in microscopic research to measure the Young's modulus of agricultural products as a critical elastomechanical property. The results of these studies have been published in reputable research journals, providing valuable insights into the mechanical behavior of such materials at the microscopic level (Khodabakhshian and Baghbani 2021; Khodabakhshian and Hassani 2021; Khodabakhshian et al. 2021; Vatani et al. 2025).

### 2.4.2 | Elastic Modulus Measurement

Rice samples were prepared for elastic modulus measurement by first carefully selecting uniform, clean rice grains. The rice grains were thoroughly washed to remove any dirt or impurities and then dried at room temperature for 24 h to ensure the removal of any moisture. Once dried, the rice grains were mounted onto a flat glass substrate using double-sided tape, which provided a secure attachment without inducing any deformation or damage to the rice grains. The mounted samples were then placed into the AFM chamber, ensuring that the rice grain surface was properly aligned for precise measurements. The AFM was configured to operate in contact mode for force spectroscopy, with the tip brought into direct contact with the rice surface. A sharp silicon nitride tip was selected with a spring constant of 0.2 N/m, as this provided high sensitivity and minimal indentation force. The scanning area was set to a $5 \times 5\,\mu$m region, and the scan rate was adjusted to 1 Hz, ensuring high-resolution data collection without damaging the delicate rice surface. The AFM tip was moved towards the rice surface at a constant approach speed of $1\,\mu$m/s, and the tip was then retracted, recording the force response at each point. Force-displacement curves were captured during the approach and retraction cycles, with multiple force curves collected from different points on the rice grain surface to ensure representative data (Figure 3). The measured force was analyzed using the Hertzian contact model, which assumes elastic deformation for small indentations. The elastic modulus was derived by fitting the force-distance curves to the model, where the indentation force was related to the displacement of the AFM tip. The contact stiffness from the approach curve was used to calculate the modulus, and the data were processed using dedicated AFM software to extract the elastic modulus values. To ensure accuracy and consistency, multiple measurements were taken from different locations on the rice grain surface, and the average elastic modulus was calculated. The environmental conditions during the AFM measurements were carefully controlled, with a constant temperature of 22°C and relative humidity maintained at 45%, as these factors can significantly influence the mechanical properties of the rice grains. This protocol is adapted from previous studies in the field of microscopy using AFM for measuring the elastic modulus of agricultural products (Zdunek and Kurenda 2013; Xi et al. 2015; Wen et al. 2020; Khodabakhshian and Baghbani 2021; Khodabakhshian and Hassani 2021; Khodabakhshian et al. 2021; Tinoco et al. 2022; Vatani et al. 2025).

## 2.5 | Data Analysis

For the measurement of the elastic modulus of the samples at both macroscopic and microscopic modes, six repetitions were performed. Descriptive statistics of the data were analyzed using Excel 2019. The effect of different cultivars on the modulus of elasticity of rice grains was investigated using analysis of variance (ANOVA) and Duncan's multiple range test at a 95% and 99% confidence level. Additionally, a *t*-test for independent samples was applied to evaluate the difference between the mean elastic moduli obtained from the macroscopic compression tests and the mean modulus measured using AFM. Confidence intervals were included to further illustrate the results of the ANOVA.

# 3 | Results and Discussion

## 3.1 | Physical Properties

The dimensions, mass, bulk density, true density, and porosity of the rice samples are presented in Table 1. As shown in this table, the largest length measured was 7.43 mm, corresponding to the Dom

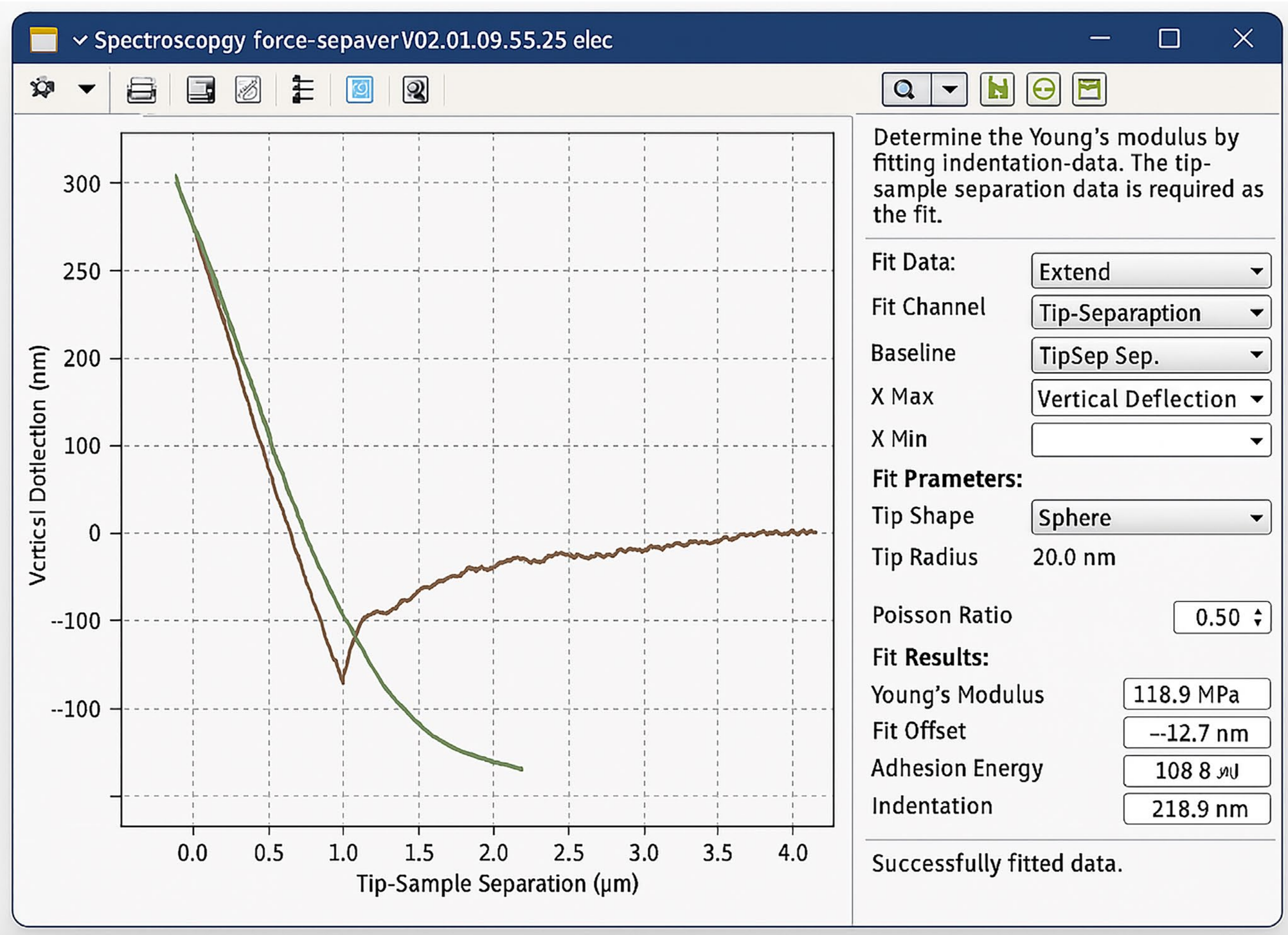


**FIGURE 3** | AFM force-displacement mapping of rice sample for elasto-mechanical property assessment.

Siah variety, whereas the smallest length (a) was 5.17 mm, corresponding to the Tarom Hashemi variety. According to Table 1, the largest width (b) was 2.24 mm, also associated with the Tarom Hashemi variety, and the smallest width (b) was 1.49 mm, again corresponding to the Tarom Hashemi variety. The maximum thickness (c) was 1.62 mm, corresponding to the Anbarbu variety, and the minimum thickness (c) was 1.16 mm, corresponding to the Dom Siah variety. The average dimensions of the rice samples for the Tarom Hashemi, Anbarbu, and Dom Siah varieties were 6.44, 6.45, and 6.28 mm for length, and 1.37, 1.43, and 1.35 mm for thickness, respectively.

As seen in Table 1, the maximum mass was found in the Anbarbu variety at 0.0228 g, whereas the minimum mass was found in the Dom Siah variety at 0.0164 g. The average mass for the rice samples of the Tarom Hashemi, Anbarbu, and Dom Siah varieties was 0.0194, 0.0202, and 0.0196 g, respectively. The highest bulk density recorded, according to Table 1, was 0.864 g/cm$^3$ for the Anbarbu variety, and the lowest bulk density was 0.716 g/cm$^3$ for the Tarom Hashemi variety. The average bulk densities for the rice samples of the Tarom Hashemi, Anbarbu, and Dom Siah varieties were 0.778, 0.794, and 0.791 g/cm$^3$, respectively. Additionally, the maximum and minimum true densities were 1.502 and 1.221 g/cm$^3$, respectively, for the Tarom Hashemi variety. The average true densities for the rice samples of the Tarom Hashemi, Anbarbu, and Dom Siah varieties were 1.371, 1.372, and 1.392 g/cm$^3$, respectively. The maximum and minimum porosity values were 47.00% and 40.50%, respectively, for the Tarom Hashemi variety. The average porosities for the rice samples of the Tarom Hashemi, Anbarbu, and Dom Siah varieties were 43.22%, 42.15%, and 43.15%, respectively.

### 3.2 | Exploring the Elastic Modulus of Rice Samples in Macroscopic Mode

The modulus of elasticity for the rice varieties under investigation in macroscopic mode, as depicted in Figure 4, reveals considerable variation among the different varieties. Tarom Hashemi, for instance, exhibited the lowest average modulus of elasticity at 1466.263 MPa, with a standard deviation of 272.863 MPa. This suggests that while Tarom Hashemi is known for its specific qualities such as aroma and texture, it shows lower resistance to deformation when subjected to compressive forces compared to the other varieties. This lower modulus of elasticity could be attributed to its unique cellular structure, which might not provide the same level of rigidity as other rice varieties like Anbarbu or Dom Siah.

Further investigation into the biochemical composition of Tarom Hashemi can provide insights into the observed mechanical behavior. For instance, rice varieties with a higher

**TABLE 1** | Physical properties of different rice varieties.

| Rice variety | Sample (replicate) | Dimensions (mm) *a* | *b* | *c* | Mass (g) | Bulk density ($g/cm^3$) | True density ($g/cm^3$) | Porosity (%) |
|---|---|---|---|---|---|---|---|---|
| Tarom Hashemi | 1 | 7.12 | 1.54 | 1.25 | 0.0184 | 0.725 | 1.284 | 43.52 |
| | 2 | 5.83 | 1.49 | 1.38 | 0.0178 | 0.716 | 1.351 | 47.00 |
| | 3 | 7.25 | 2.07 | 1.42 | 0.0213 | 0.840 | 1.412 | 40.50 |
| | 4 | 5.17 | 1.58 | 1.20 | 0.0165 | 0.718 | 1.221 | 41.18 |
| | 5 | 6.94 | 2.03 | 1.51 | 0.0213 | 0.840 | 1.457 | 42.37 |
| | 6 | 6.33 | 2.24 | 1.45 | 0.0211 | 0.830 | 1.502 | 44.73 |
| Average | | 6.44 | 1.83 | 1.37 | 0.0194 | 0.778 | 1.371 | 43.22 |
| Anbarbu | 7 | 6.80 | 2.23 | 1.53 | 0.0219 | 0.864 | 1.454 | 40.56 |
| | 8 | 5.83 | 1.92 | 1.37 | 0.0191 | 0.753 | 1.285 | 41.41 |
| | 9 | 6.25 | 2.14 | 1.62 | 0.0214 | 0.845 | 1.438 | 41.25 |
| | 10 | 7.05 | 2.31 | 1.60 | 0.0228 | 0.828 | 1.420 | 41.69 |
| | 11 | 6.82 | 1.67 | 1.22 | 0.0185 | 0.729 | 1.369 | 46.78 |
| | 12 | 5.93 | 1.50 | 1.24 | 0.0171 | 0.745 | 1.267 | 41.18 |
| Average | | 6.45 | 1.96 | 1.43 | 0.0202 | 0.794 | 1.372 | 42.15 |
| Dom Siah | 13 | 6.00 | 2.21 | 1.16 | 0.0191 | 0.754 | 1.304 | 42.21 |
| | 14 | 5.24 | 1.52 | 1.25 | 0.0164 | 0.752 | 1.408 | 46.59 |
| | 15 | 7. 43 | 2.01 | 1.32 | 0.0208 | 0.819 | 1.394 | 41.28 |
| | 16 | 5.87 | 2.18 | 1.49 | 0.0206 | 0.810 | 1.397 | 42.05 |
| | 17 | 7.01 | 1.82 | 1.53 | 0.0207 | 0.816 | 1.403 | 41.84 |
| | 18 | 6.14 | 2.17 | 1.36 | 0.0202 | 0.796 | 1.445 | 44.92 |
| Average | | 6.28 | 1.98 | 1.35 | 0.0196 | 0.791 | 1.392 | 43.15 |

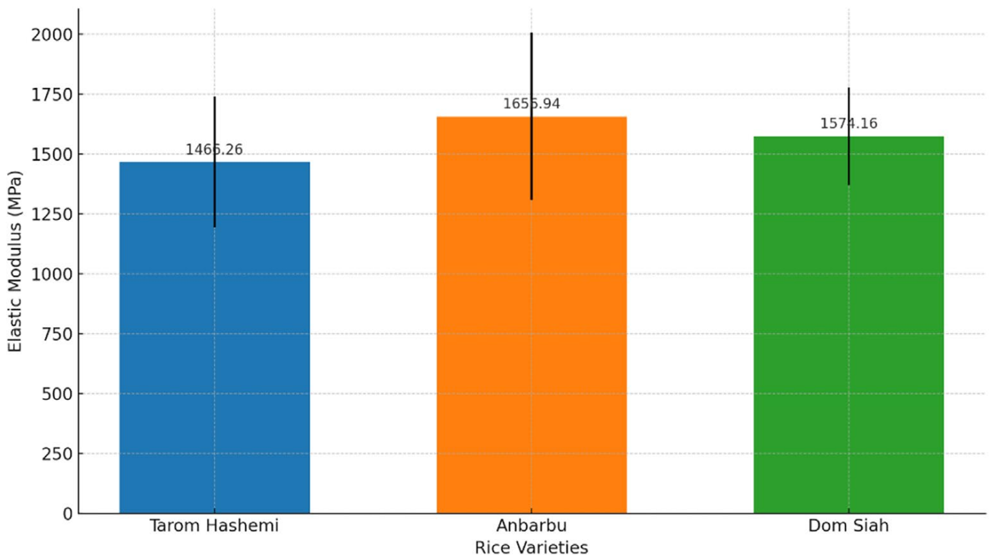


**FIGURE 4** | Average elastic modulus of rice varieties measured at the macroscopic mode using an Instron device.

amylose-to-amylopectin ratio typically exhibit lower elasticity due to the reduced structural integrity of starch granules. Additionally, the specific arrangement of starch granules within the endosperm, as well as the crystalline-to-amorphous regions of starch, can significantly influence mechanical stiffness. Cellulose and hemicellulose content in the cell walls also play a crucial role; a lower density or less organized arrangement of these polysaccharides may result in decreased mechanical rigidity. Furthermore, moisture content within the grains affects their plasticity and elastic response under compression, with higher moisture levels potentially contributing to lower modulus values.

The absence of significant statistical differences among the varieties, as demonstrated by the ANOVA results in Table 2, highlights the potential impact of environmental factors or experimental design on the measurements. Such factors could include variations in cultivation conditions (e.g., soil type, irrigation practices) or post-harvest handling, which may alter the biochemical composition and structural properties of the grains. This underlines the complexity of testing agricultural products like rice, where intrinsic and extrinsic factors interact to determine their mechanical properties. A deeper exploration of these variables, particularly in relation to biochemical markers such as protein content, lipid composition, and cell wall integrity, would provide a more comprehensive understanding of the mechanical behavior of Tarom Hashemi and other rice varieties.

In contrast to Tarom Hashemi, the Anbarbu variety exhibited the highest modulus of elasticity at 1656.940 MPa, indicating greater resistance to deformation under compression. This result aligns with expectations for a rice variety with a firmer texture and higher rigidity. The standard deviation for Anbarbu was 349.176 MPa, reflecting a moderate level of variation in its mechanical properties across the samples. This suggests that although Anbarbu demonstrates a higher modulus of elasticity on average, the variability among individual grains may be influenced by factors such as grain size, moisture content, and sample preparation. The observed differences in modulus of elasticity between Anbarbu and the other varieties could have practical implications for rice processing, where a higher modulus of elasticity might be advantageous for milling or cooking applications that require firmer rice.

**TABLE 2** | Analysis of variance for the elastic modulus of rice grains using compression tests.

| Source of variation | Sum of squares | Degrees of freedom | Mean square | *F*-calculated |
|---|---|---|---|---|
| Rice variety | 97,543 | 2 | 66,475 | 0.64 ns |
| Sample (repetition) | 440,582 | 5 | 69,118 | 0.79 ns |
| Error | 842,501 | 10 | 88,235 | |
| Total | 1,374,058 | 17 | | |

*Note:* ns denotes that the effect is not significant at the 1% and 5% levels.

The Dom Siah variety, with a modulus of elasticity of 1574.165 MPa, falls between Tarom Hashemi and Anbarbu, suggesting a more intermediate level of mechanical resistance. The standard deviation for Dom Siah (203.466 MPa) was slightly lower than that of Anbarbu, indicating that its modulus of elasticity measurements were somewhat more consistent across the sample set. Overall, these findings suggest that rice varieties with higher modulus values like Anbarbu might be preferred for specific processing applications where greater rigidity is desirable. However, the lack of significant statistical differences between the varieties, as revealed by the ANOVA, suggests that these differences may not be large enough to have a major impact on their practical use in the food industry. This highlights the importance of considering other factors, such as cooking behavior and texture, when evaluating rice quality for specific applications.

The comparison of the results from this study on the elastic modulus of Iranian rice varieties (Tarom Hashemi, Anbarbu, and Dom Siah) with previous research reveals both similarities and key differences, influenced by variety, testing methodology, and processing conditions. Sadeghi et al. (2010) found that the variety significantly affected the elastic modulus ($p < 0.01$) for two rice varieties, Sorkheh and Sazandegi, with values ranging from 555.6 MPa for Sazandegi to 996.1 MPa for Sorkheh. In contrast, this study shows higher elastic modulus values, reaching 1656.94 MPa for Anbarbu, suggesting that some Iranian varieties may exhibit stronger compressive resistance. These higher values could be attributed to genetic factors specific to the varieties or minor differences in testing methodology. Shitanda et al. (2002) analyzed the compressive strength of three rice varieties (Akitakomachi, Delta, and L201), obtaining a consistent Young's modulus around 543 MPa, with yield force being higher in long-grain compared to short-grain varieties. They reported minimal variety effect on Young's modulus, which differs from the findings in this study, where distinct elastic modulus values were observed across varieties. This discrepancy may be due to differences in grain morphology or variations in testing apparatus, as this study utilized an Instron device under controlled conditions, which may reveal varietal distinctions more clearly. Additionally, Corrêa et al. (2007) stated that processing, rather than variety, influenced the rupture force of rice grains. This study, which focuses on unprocessed grains, contrasts with that conclusion, emphasizing the inherent differences in elastic modulus among varieties, independent of post-harvest handling. These comparisons underline the need for standardized testing protocols, as both methodology and grain characteristics significantly impact the results. Moreover, they highlight that while factors like processing influence certain mechanical properties, the intrinsic elastic properties of rice are largely determined by variety, suggesting a need for further research on both the intrinsic and extrinsic factors that affect rice grain resilience.

### 3.3 | Exploring the Elastic Modulus of Rice Samples in Microscopic Mode

The elastic modulus measurements in Figure 5 reveal distinct differences in the mechanical properties of three rice varieties at the microscopic level, showcasing notable variability in their elasticity. The Anbarbu variety exhibits the highest average elastic modulus at 786.102 MPa, suggesting it possesses a firmer and more resilient structure in response to mechanical stress, which could be attributed to a denser or more robust cellular arrangement in its grain composition. This characteristic is potentially advantageous in scenarios where grain resilience to mechanical damage is desired, particularly during milling or other processing stages. In comparison, Dom Siah has a moderately high modulus, averaging at 736.872 MPa, placing it slightly below Anbarbu. This similarity in modulus suggests that Dom Siah may share some structural properties with Anbarbu, albeit with slightly less stiffness.

On the other hand, the Tarom Hashemi variety demonstrates a significantly lower modulus of elasticity, with an average of 697.630 MPa. This comparatively lower modulus suggests that Tarom Hashemi is less rigid and may exhibit greater flexibility or deformability under compressive forces, which may impact its suitability in processes requiring high structural integrity. The lower modulus could be due to inherent differences in cellular wall composition or variations in the microscopic structure, affecting its mechanical response. Across the varieties, the standard deviations observed, particularly 37.038 MPa for Anbarbu, indicate that while there are variances within each sample set, Anbarbu still demonstrates relatively consistent mechanical strength. The collective mean modulus of 740.201 MPa for all varieties provides a benchmark for the overall elastic behavior of rice grains at the microscopic mode, with Anbarbu and Dom Siah displaying relatively higher resilience compared to Tarom Hashemi. This variability among rice varieties highlights the importance of selecting specific types based on the desired mechanical properties, especially when aiming for applications that require high durability and resilience in rice grains during processing.

A review of previous research revealed that microscopic-level studies specifically investigating the mechanical properties of grains, particularly rice, remain scarce. Consequently, our comparative analysis of elastic modulus measurements draws on studies conducted on fruits and vegetables, where elasticity has been measured microscopically. In apple tissue, for instance, elastic modulus values range from 0.2 to 3.75 MPa, indicating a wide spectrum of internal stiffness depending on tissue density and type (Cárdenas-Pérez et al. 2016). In banana fruit, AFM measurements revealed that Young's modulus varied significantly with the probe shape, where a sharp needle yielded values between 0.060 and 0.014 MPa, whereas a bead-shaped needle produced a lower range of 0.006 to 0.031 MPa, reflecting the structural softness of banana cells (Khodabakhshian et al. 2021). Similarly, in studies on pomegranate fruit, elastic modulus values ranged from 0.70 to 0.160 MPa, suggesting a moderately higher stiffness in these cells compared to other softer fruits (Khodabakhshian and Hassani 2021). For tomato cells, the elastic modulus was found to be $0.010 \pm 0.035$ MPa with a sharp needle and $0.014 \pm 0.020$ MPa with a bead-shaped needle, again showing the influence of probe type on modulus results and further emphasizing the generally low stiffness of tomato tissues (Zdunek and Kurenda 2013).

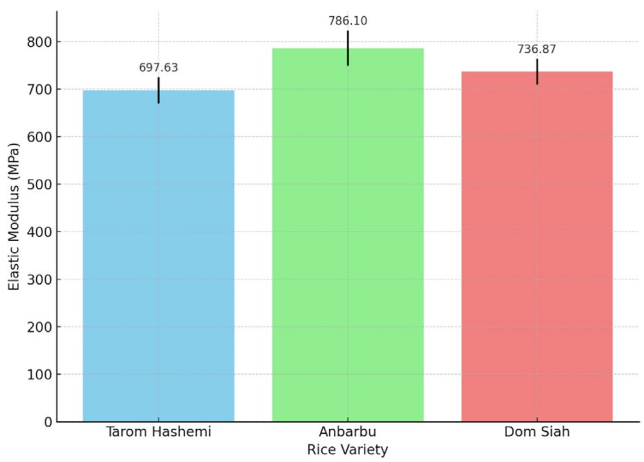


**FIGURE 5** | Average elastic modulus of rice varieties measured at the microscopic mode using an AFM.

In a recent study by Vatani et al. (2025), measurements on the modulus of elasticity for fruit tissues recorded values between 0.370 and 0.365 MPa, consistent with the lower range found in other studies, further affirming the diverse elasticity range across various fruit tissues. Additionally, Gawali et al. (2023) investigated the microscopic surface structure of an alba plant extract containing synthesized gold nanoparticles, reporting a mean roughness of 9.95 nm. Although this study focused on surface characteristics rather than direct elasticity measurements, it highlights the adaptability of AFM in agricultural material studies, capable of capturing both elastic and structural details at the micro and nano modes. Taken together, these studies on fruits and vegetables underscore the considerable range in elastic modulus across different agricultural tissues at the microscopic level, reflecting the diverse structural and mechanical characteristics inherent in these products.

### 3.4 | Elastic Modulus Variations in Rice Grains: A Comparative Approach Using Macro and Micro Mode Measurements

The results obtained from the macroscopic and microscopic measurements of the elastic modulus for rice grains reveal distinct differences. For the macroscopic measurements, the mean elastic modulus of the three rice varieties was found to be 1565.789 MPa, with standard deviations of 78.068 MPa. In contrast, the microscopic measurements, obtained via AFM, showed a mean elastic modulus of 740.201 MPa with a standard deviation of 36.195 MPa. A *t*-test comparison between these two methods yielded a calculated *t*-value (tc) of 16.285, which exceeded the critical value (tp) of 2.364 at the 95% confidence level, indicating a significant difference between the two methods. As shown in Figure 6, the *t*-test curve confirms this result, reinforcing the conclusion that the two methods measure mechanical properties at different modes. The larger values for the macroscopic measurements suggest that the methods are capturing different aspects of the material's mechanical behavior, with AFM providing a more localized insight into the microstructural properties of rice grains.

When comparing the results of this study with other research in the field, it is evident that the microscopic and macroscopic methods for measuring elastic modulus in agricultural products yield differing outcomes. In a study by Vatani et al. (2025), the elastic modulus for limequat fruit tissue was measured at both macroscopic and microscopic modes. The results showed a clear significant difference between the two methods, with the AFM method providing more reliable data. Similarly, Khodabakhshian and Hassani (2021) observed that microscopic

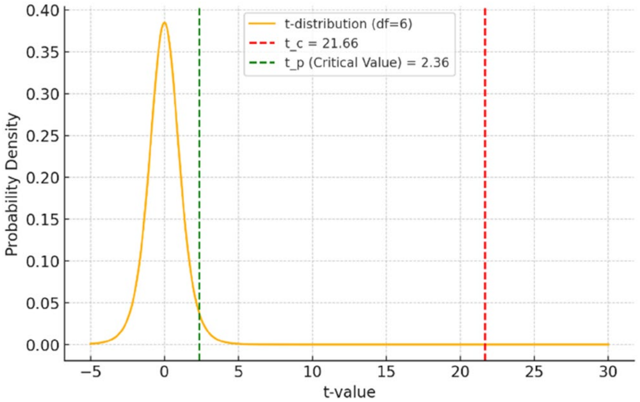


**FIGURE 6** | Average elastic modulus of rice varieties measured at the microscopic mode using an AFM.

techniques generally yield more accurate results compared to macroscopic methods, which are influenced by complex structures and nonlinear behaviors of agricultural products. These studies support the notion that while macroscopic methods can provide general estimates, microscopic approaches, such as AFM, offer enhanced precision in determining the elastic modulus of agricultural materials, especially when considering the intricacies of their microstructure. Thus, the significance of the t-test results and the enhanced accuracy provided by AFM can be seen as consistent with findings from other studies in the field.

In conclusion, the comparison between macroscopic and microscopic measurements of elastic modulus for rice grains and other agricultural products highlights the advantages of using microscopic techniques for more accurate and detailed mechanical property assessments. The results from this study, alongside those from other research, suggest that microscopic methods, particularly AFM, offer superior precision in characterizing the mechanical behavior of agricultural materials. Given these findings, it is reasonable to recommend incorporating microscopic measurements into standards for assessing the mechanical properties of agricultural products. This could be achieved by referencing these methods in revisions of existing standards, such as the "American Society of Agricultural and Biological Engineers (ASABE). (2000). Compression Test of Food Materials of Convex Shape," which may benefit from an update to include microscopic-mode measurements. These updates would enhance the accuracy of mechanical property assessments and contribute to more reliable evaluations in both research and industry applications.

## 4 | Conclusion

The study provides a comprehensive analysis of the modulus of elasticity as a fundamental elasto-mechanical property in three rice varieties, revealing significant differences in structural resilience across macroscopic and microscopic measurement scales. Anbarbu displayed the highest modulus of elasticity, with 1656.940 MPa in macroscopic tests and 786.102 MPa in microscopic assessments, highlighting its suitability for processes requiring greater rigidity. Tarom Hashemi, with lower modulus values—1466.263 MPa macroscopically and 697.630 MPa microscopically—was more flexible under compression, suggesting the need for gentle handling to prevent damage. The *t*-test results confirmed that macroscopic and microscopic testing methods measure distinct aspects of mechanical behavior, with microscopic analysis capturing localized properties critical for quality control in rice processing.

The application of AFM for measuring the modulus of elasticity at the microscopic scale offers detailed insights into rice grain structure, enabling precise characterization of mechanical resilience that conventional macroscopic methods may overlook. Given the enhanced accuracy and detail obtained from AFM, it is recommended that microscopic approaches be incorporated into relevant standards for agricultural product assessment. By updating standards, such as the ASABE's "Compression Test of Food Materials of Convex Shape," to include microscopic-mode measurements, researchers and industry professionals can achieve more reliable and nuanced evaluations of agricultural products, supporting improved processing practices and quality control across the food industry.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data used to support the findings of this study are available upon request from the corresponding author.

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