Potato Res. (2026) 69:16
https://doi.org/10.1007/s11540-025-09989-0

Estimation of Poisson's Ratio of Potato Flesh: A Finite Element Analysis Approach

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Received: 4 April 2025 / Accepted: 2 October 2025

Abstract
Determining mechanical properties such as the modulus of elasticity and Poisson's ratio of agricultural products is a crucial initial step in designing optimal tools and machinery systems for mechanised harvesting and postharvest operations. However, this process presents measurement difficulties, particularly in calculating Poisson's ratio due to limitations in experimental approaches and the organic structure of some agricultural products. This study describes a finite element analysis (FEA) approach for estimating Poisson's ratio in potato flesh, a solid-like agricultural product sample. Analytical, experimental, and numerical methods were employed in the study. The results clearly demonstrate the success of the FEA approach compared to empirical calculations for determining Poisson's ratio (relative difference of 7.93%). This study contributes to advancing the understanding of complex deformation phenomena in solid-like agricultural products. Moreover, the application of the FEA approach has significant industrial and research implications for enhancing the critical mechanical properties of agricultural products.

Keywords Finite element analysis · Food processing · Mechanical properties · Poisson's ratio · Potato

Introduction

Understanding certain mechanical properties of agricultural products, such as the modulus of elasticity and Poisson's ratio, is crucial for the design and optimisation of mechanised harvesting and postharvest systems. These properties dictate how materials respond to mechanical forces during handling, processing, and storage, which in turn affects the efficiency of agricultural machinery. However, determining Poisson's ratio for agricultural products like potatoes presents significant challenges due to their organic nature and precise testing methodologies. Traditional

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Published online: 19 January 2026

experimental approaches often fall short in easily capturing these properties, leading to the exploration of advanced methodologies such as finite element analysis (FEA). Potatoes (*Solanum tuberosum*), as one of the major crops produced and consumed in the world, are integral to both diets and agricultural economies (Kumari et al. 2024; Mishra et al. 2024; Kumar et al. 2025). The accurate determination of their physical and mechanical properties is essential for minimising postharvest losses, enhancing storage conditions, and improving overall product quality from field to table. Prior research has employed various techniques, such as uniaxial compression tests, to measure these properties. These tests, typically conducted using devices such as the universal testing machine, provide valuable data on stress, strain, and elastic modulus. Despite their utility, these methods are often limited by their inability to fully account for the anisotropic and viscoelastic nature of potato tissues (Mohsenin 1986; Stroshine 1986; Peng et al. 2006; Altuntaş and Yıldız, 2007; Alzamora et al. 2008; Asnake et al. 2023; Xie et al. 2024). FEA has emerged as a robust computational tool to overcome these limitations. FEA enables the simulation of material behaviour under various conditions, offering a more comprehensive and accurate determination of mechanical properties such as Poisson's ratio. This approach enhances our understanding of the deformation characteristics of agricultural products and provides critical insights for the design and optimisation of agricultural machinery and postharvest processes (Krutz et al. 1984; Celik et al. 2013; Celik and Akinci 2016; Celik et al. 2019; Nikara et al., 2020a; Purlis et al. 2021; Fan et al., 2022a).

Previous studies have demonstrated the utility of FEA in agricultural applications. For instance, FEA has been employed to model the mechanical behaviour of fruit and vegetables under various loading conditions, providing insights into their stress–strain responses and potential failure modes. Additionally, FEA has been used to investigate the effects of mechanical impacts during harvesting and postharvest handling, contributing to the development of more effective and less damaging agricultural equipment. These studies highlight the ability of FEA to capture complex deformation phenomena and provide detailed analysis that traditional methods may overlook. Recent advancements in FEA techniques have further improved the accuracy and applicability of these methods (Silveira Velloso et al. 2018; Deng et al. 2021, 2024; Zulkifli et al. 2021; Poppa et al. 2023; Xie et al. 2023; Ping et al. 2023; Celik et al. 2023). The accurate determination of Poisson's ratio holds significance beyond its applications in agriculture. Related literature highlights that the historical evolution of Poisson's ratio over the last two centuries has tested various scientific theories and enhanced the comprehension of material properties across multiple disciplines. This historical context emphasizes the critical importance of precise measurement techniques and their extensive implications (Greaves 2013).

This study aims to estimate the Poisson's ratio of potato flesh using FEA, supported by analytical, experimental, and numerical methods. By comparing the FEA results with previous literature, the efficacy of this approach in accurately capturing the Poisson's ratio of potato flesh was demonstrated. This research holds significant implications for both academic and industrial applications, particularly in enhancing the mechanical handling and processing of potatoes and similar agricultural products.

Materials and Methods

Poisson's Ratio in the Context of Linear Deformation of Materials

The term Poisson's ratio can be fundamentally described as the ratio of lateral strain to axial strain in a material when subjected to loading, making it a dimensionless quantity. It is one of the key material parameters, alongside the modulus of elasticity, which helps to explain how a material deforms under specific loading conditions, particularly from the perspective of Hookean elasticity. As illustrated in Fig. 1, Poisson's ratio can be simply understood for certain materials; however, describing it universally for all materials is challenging due to the variability in the material's inner structure. In fact, Poisson's ratio is not a constant but varies from substance to substance and can even differ for the same material fabricated in different ways. Anisotropy in materials, along with assumptions and experimental data used during Poisson's ratio calculations, can lead to challenging results. There exists a universal relationship between Poisson's ratio and the ratio of bulk to shear modulus. All isotropic materials have Poisson's ratio values between −1 and 0.5. Materials with negative Poisson's ratio are termed auxetic. As Poisson's ratio values transition from negative to positive, the material's shape is compromised for incompressibility (Fig. 1).

In the context of deformation of solid agricultural products, most research employs elastic, homogeneous, isotropic linear material models to describe deformation issues through Hooke's law, which is only a first-order linear approximation of the real response of springs and other elastic bodies to applied forces. A common method to determine the modulus of elasticity and Poisson's ratio of solid agricultural products is through tensile or compression tests. Compression Test of Food Materials of Convex Shape is described in standard ASAE S368.4 DEC2000 (R2017) (ASABE Standard 2017). These types of material tests provide measured data of force against deformation (displacement), and subsequent calculations yield material parameters related to deformation and strength, such as directional deformation, stress, strain, modulus of elasticity, and Poisson's ratio.

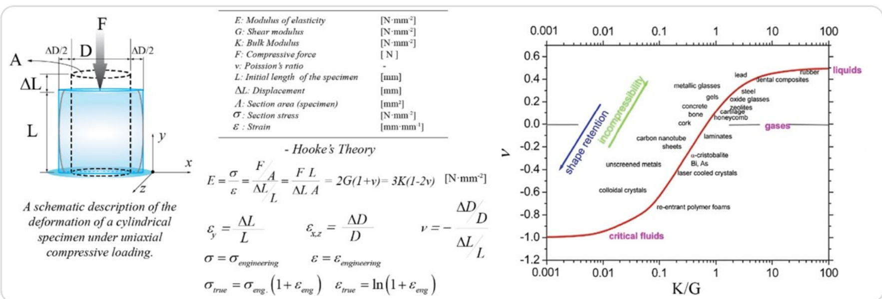


Fig. 1 A schematic overview of Hooke's calculations and the universal relationship between Poisson's ratio and the ratio of bulk modulus to shear modulus

Poisson's Ratio in the Context of Empirical Calculation Based on Product Moisture Content

The calculation of the Poisson's ratio can be performed using experimental data that provide longitudinal, radial, and tangential strain values. These experiments can be conducted using strain-gauge measurements, microscope measurement, indentation test, or image processing methods during destructive material testing (Lee et al. 2013; Zorzi and Perottoni 2013; Mizutani and Ando 2015; Fan et al. 2022a). Moreover, the literature also suggests an empirical approximation for calculating the Poisson's ratio of fruits and vegetables based on their moisture content. In this approximation, due to the challenges associated with measuring the Poisson's ratio of fruits and vegetables, primarily because of the variable water content depending on the product and time, the following formula, presented in Eq. 1, considers the Poisson's ratio of water in the product to be 0.5 and the Poisson's ratio of the flesh dry matter, which is similar to cork, to be 0.1 (Kojima 1983; Sirisomboon et al. 2012; Lammari et al. 2022). In this study, the constants in Eq. 1 (0.5 for water and 0.1 for cork-like dry matter) were adopted directly from the empirical model of Kojima (1983) without adjustment. The water value reflects the theoretical incompressibility limit for isotropic fluids, while the cork-like dry matter value is based on physical property data for plant-based cellular solids and has been applied in subsequent fruit and vegetable biomechanics studies. Retaining these constants allowed a direct comparison between the standard empirical method and the FEA-derived estimation in this work.

$$v = \frac{0.5M_w + 0.1(100 - M_w)}{100} \tag{1}$$

where v is the Poisson's ratio and Mw represents the average moisture content in percentage (%).

Poisson's Ratio Estimation in the Context of Finite Element Analysis

The literature on estimating Poisson's ratio for viscoelastic and rubber-like materials discusses various approaches, notably the finite element method (FEM), which has proven invaluable in engineering analyses across different fields (Lindley 1974; Sussman and Bathe 1987; Sim and Kim 1990; Williams and Gamonpilas 2008). This study proposes a simplified method to estimate Poisson's ratio parameter using experimental compressive test data within the framework of FEA, employing a technique known as design exploration analysis, which is the iterative process of investigating and evaluating different design alternatives and parameters to identify optimal or improved solutions. It can be considered in the design of experiments (DOE) approach. DOE, combined with FEA, facilitates design optimisation by identifying critical parameters and their interactions (Antony 2023). In this specific study focusing on estimating the Poisson's ratio parameter for potato flesh, design exploration through "What-if" analysis is employed when material parameters like elastic modulus, uniaxial stress, and strain data (including loading or deformation data) are available. The methodology relies on Hooke's law and operates within the linear deformation range of the material. This approach employs an elastic-perfectly plastic, homogeneous, isotropic material model under static loading or deformation conditions to mitigate the non-linear increase in data analysis. In short, the procedure involves assigning a range of Poisson's ratio values for a given modulus of elasticity, followed by analysing uniaxial strain data at the yield stress point under predefined linear static uniaxial deformation conditions derived from experimental tests. Estimation of Poisson's ratio is achieved by matching the FEA results to the specified axial deformation value.

Experimental Procedure

The procedures for physically measuring and testing the potato flesh specimens in this study were based on data from the author's previous research, as documented in the literature (Caglayan et al. 2018). Experimental studies were conducted at the Biological Material Test Laboratory, Department of Agricultural Machinery and Technology Engineering, Akdeniz University, Antalya, Türkiye. Compression tests followed the ASAE S368.4 W/Corr. 1 DEC2000 (R2017) standard for food materials (ASABE Standard 2017). Tuber samples (Agria variety) used in the tests were randomly collected from a local supermarket in Antalya, Türkiye. Cylindrical flesh specimens (dimensions: 27.5×20 mm) extracted from whole potato tubers underwent testing using a double-plate material compression test device (loading capacity: 2000 N). All specimens were tested at a room temperature of 20 °C and dried for 24 h at 105 °C to determine physical properties. The average moisture content of 10 specimens was 85.25% (wet basis). Compression tests on the tuber specimens were conducted at a uniform rate of 5 mm/min. Each test used 10 specimens, with physical measurements repeated three times. Data were acquired at a sampling rate of 10 Hz. Density of the potato flesh specimens was calculated from mass and volumetric measurements. Uniaxial deformation, compressive force, density, modulus of elasticity, and yield stress values were determined from experimental data. Experimental testing details and graphical outputs are presented in Fig. 2.

Finite Element Analysis Procedure

In the setup process for FEA, the structural analysis module of the ANSYS Workbench commercial FEM code was employed to simulate the compression of the cylindrical specimen model. The simulation included defining physical boundary conditions such as frictional contact and employing an idealised elastic-perfectly plastic, homogeneous, isotropic material model under static deformation conditions. Boundary conditions were applied as follows: the lower plate was fully constrained in all translational and rotational degrees of freedom, while the upper plate was prescribed a vertical displacement of 6.40 mm to achieve uniaxial compression. Tangential interaction between the specimen and the plates was defined as frictional contact with a coefficient of friction of 0.31 (Dalvand 2011), and normal contact behaviour was set to prevent penetration. Standard Earth gravity (9.81 m s^{-2}) was included. The specimen was unconstrained laterally to permit natural radial deformation during compression. All loading and constraints were implemented under static (quasi-static) analysis conditions to minimise inertial effects.

In detail, experimental material properties specific to the potato flesh specimen model were assigned; the potato flesh was represented by an idealised elastic–perfectly plastic material, assumed homogeneous and isotropic, and analysed under static (quasi-static) conditions. The idealised elastic–perfectly plastic description captures an initial linear-elastic response followed by plastic flow without hardening once the yield threshold is reached, providing a parsimonious but physically meaningful representation of the permanent deformation observed under uniaxial compression. The homogeneous–isotropic idealisation was adopted to minimise directional bias because the cores were prepared to average tissue orientation, the moisture content was high and uniform, and the loading was uniaxial compression. This modelling choice allows a focused parametric evaluation of Poisson's ratio against the measured deformation response while avoiding the proliferation of additional rheological parameters required by time-dependent or anisotropic models.

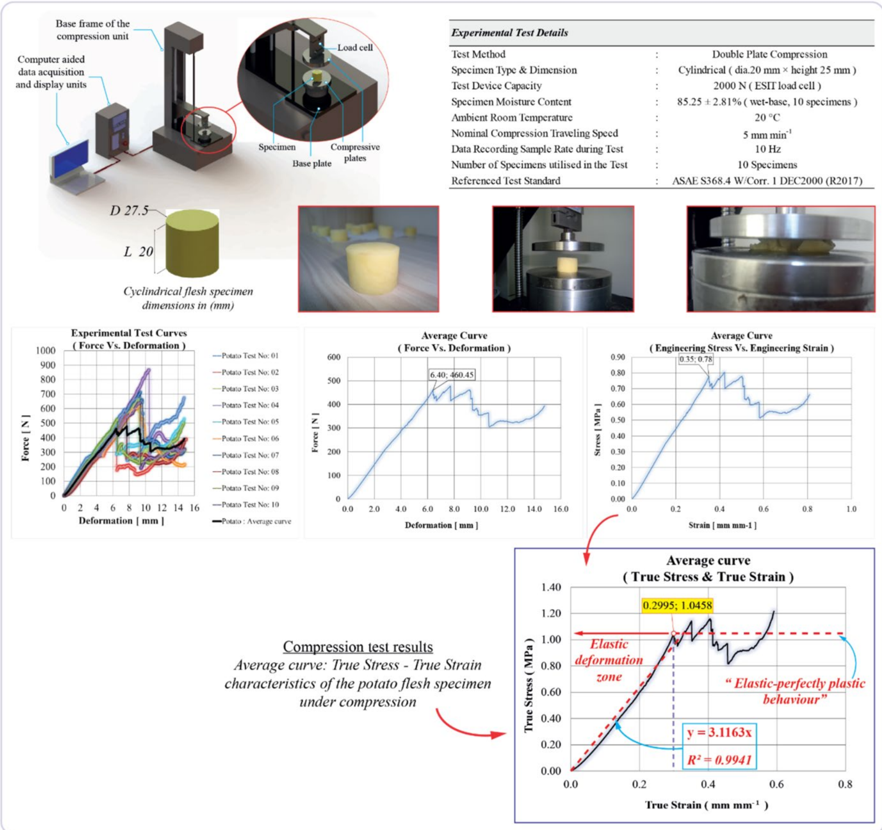


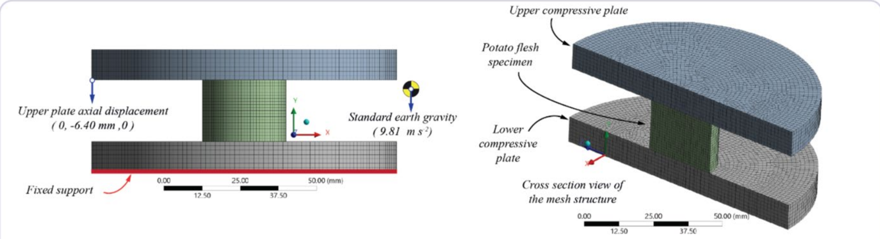
Fig. 2 Experimental procedure and graphical outputs

The meshing functions of the FEM code were used to generate the mesh structure. A uniform mesh approach with a minimum element size of 1 mm and 2 mm for the components of the flesh and the plates was assigned, respectively. For the internal verification, mesh quality was assessed using standard FEM code metrics. The average skewness was 0.130, indicating high-quality elements. The average aspect ratio was 1.274, well below the recommended limit of 5 for structural elements, and the average Jacobian ratio (Gauss points) was 0.883 (Jacobian ratio (Gauss points), which is bounded by −1 (worst) and 1 (best)), which is considered excellent. These metrics collectively confirm that the mesh was of high quality, providing numerical stability and reliable simulation results (Brys et al. 2004; ANSYS Product Doc. 2019).

The range varied from 0.20 to 0.50, with increments of 0.025 assigned to the Poisson's ratio data and a total of 13 parameters resolved for axial strain data. In detail, the design exploration in this study followed a structured DOE approach, focusing on a single-factor parametric variation. Poisson's ratio was treated as the primary factor, with 13 discrete levels (0.20–0.50, in increments of 0.025) investigated while holding all other parameters constant. This one-factor-at-a-time DOE framework enabled systematic quantification of the relationship between Poisson's ratio and simulated axial strain, facilitating correlation with experimental strain values to identify the most representative parameter. Although not a factorial or response surface design, this method applies DOE principles to ensure controlled, reproducible exploration of the parameter space (Myers H Raymond 2016); Antony 2023). The Poisson's ratio sweep from 0.20 to 0.50 was determined from a review of published data for potato tissue and comparable biological materials, which report values between approximately 0.30 and 0.49 under compression (Finney and Hall 1967; Kojima 1983; Bentini et al. 2009; Lammari et al. 2021; Fan et al. 2022b; Gai et al. 2024). The lower bound of 0.20 was selected to accommodate possible variability in tuber structure, moisture content, and testing uncertainty, whereas the upper bound reflects the incompressibility limit for isotropic solids. An increment of 0.025 was adopted to balance computational efficiency with adequate parameter resolution for the design exploration study. Figure 3 illustrates the simulation scenario, material properties, boundary conditions, and mesh details of the models.

Results and Discussion

The FEA of potato flesh specimen under compression provided detailed insights into its deformation behaviour and Poisson's ratio. The visual and numerical findings closely corroborated experimental results, indicating consistent deformation characteristics. Figure 4 illustrates the relationship among Poisson's ratio values obtained from 13 iterations, absolute axial strain data, and visual deformation outputs. The high R^2 value (0.9883) derived from the linear approximation of strain data further validates the accuracy of the FEA model in estimating Poisson's ratio. Upon conducting correlation analysis, a Poisson's ratio of 0.406 was determined using an experimental true strain value of 0.2995. This value was compared to an empirically calculated Poisson's ratio of 0.441, as per Eq. 1 (Kojima 1983), based on an average



Material properties assigned in the FEA

Material	Modulus of Elasticity (MPa)	Poisson's Ratio (-)	Yield Stress Point (MPa)	Axial Strain at Yield Stress Point (mm mm^{-1})	Axial Deformation at Yield Stress Point (mm)	Density (kg m^{-3})
Potato Flesh	3.1163 [1] *(R^2 : 0.9793)*	Ranged (from 0.20 to 0.50)	1.05 [1]	0.30 [1]	6.40 [1]	1089 [1]
Structural Steel [2]	200000	0.30	210	-	-	7850

1. Experimental data (True stress Vs. True Strain data) (Elastic-perfectly plastic, homogeneous, isotropic material model)
2. ANSYS - Material library (Linear elastic, homogeneous, isotropic material model)

Details of the Final FE Model (Mesh Structure)		
Job Title	:	Potato Flesh - PR Study
Meshing Approach	:	Uniform Meshing
Average Skewness Value / Quality Measure	:	0.13 / EXCELLENT
Element Types (ANSYS WB Code)	:	Hex20 / Wed15
Max. Element Size (mm)	:	2 (The Plates)
Min. Element Size (mm)	:	1 (The Specimen)
	:	
Total Number of Elements	:	67408
Total Number of Nodes	:	300991

Fig. 3 The FEA scenario, material properties, boundary conditions, and mesh details

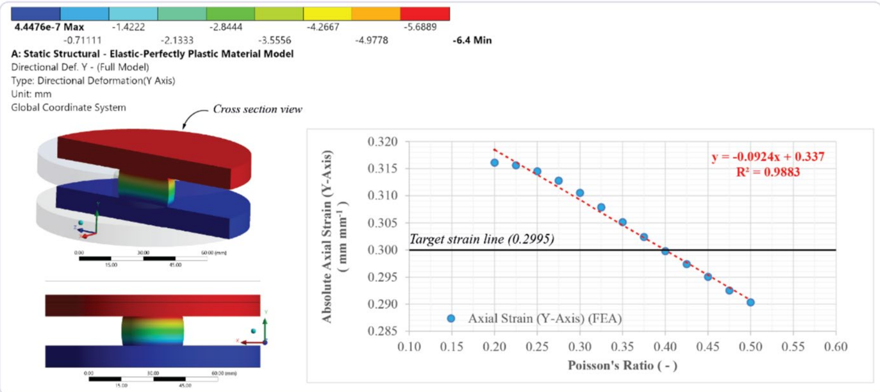


Fig. 4 FEA visual results and data estimation

moisture content of 85.25% (wet basis). The 7.93% relative difference between the FEA-derived and empirical values indicates satisfactory agreement between computational simulation and empirical observation. Comparison with relevant literature (Table 1) on potato material properties demonstrates that the Poisson's ratio values obtained in this study (0.406 from FEA and 0.441 from empirical calculation) fall within the reported range of 0.3 to 0.492 (Finney and Hall 1967; Kojima 1983; Mohsenin 1986; Bentini et al. 2009; Gulati and Datta 2015; Nikara et al. 2020b; Lammari et al. 2021; Jagessar 2022; Lammari et al. 2022; Fan et al. 2022a; Gai et al. 2024). This may be considered for the FEA model in predicting mechanical properties of potatoes under compression and emphasising its applicability in agricultural research. However, it is important to emphasise that the range reported in the literature may be considered extensive. This variation may be attributed to differences in experimental methods, moisture content, and the varieties of potatoes used in related studies (Hammad and Mondal 2023). Furthermore, the literature review highlights the limited availability of specific material properties, such as Poisson's ratio, particularly in the context of FEA studies. Additionally, it can be said that the empirical Poisson's ratio (mean = 0.441) had a 95% confidence interval of [0.431, 0.451], while the FEA-derived value (mean = 0.406) had a 95% confidence interval of [0.398, 0.414]. These intervals exhibit partial overlap, indicating statistical agreement within expected biological and modelling variability. The relative difference between the mean values remains 7.93%, relatively affirming the robustness of the FEA approach in estimating this parameter.

While the FEA-based estimation of Poisson's ratio in potato flesh aligns with empirical data and existing literature, some limitations should be noted: The idealised material assumptions in FEA (idealised elastic-perfectly plastic, homogeneous, isotropic material model) may not fully represent the viscoelastic behaviour of biological tissues (Sussman and Bathe 1987). Anisotropy effects due to the fibrous nature of potato flesh were not explicitly accounted for in the model, which could lead to minor deviations in strain distribution predictions. Similarly, the present idealised elastic-perfectly plastic, homogeneous–isotropic formulation does not capture viscoelastic creep or stress relaxation, potential orthotropy due to cellular alignment, strain-rate sensitivity, or damage/softening. More comprehensive frameworks, such as viscoelastic–plastic contact models or fractional-order viscoelastic formulations, have been applied to potato tissue and can recover time-dependent behaviour with greater fidelity (Guo and Campanella 2017; Gao et al. 2018; Liang et al. 2023). However, such models require additional testing (multi-step creep/relaxation or frequency sweeps) and introduce many parameters. Given that the present study aimed to identify an effective Poisson's ratio from quasi-static compression, the idealised elastic-perfectly plastic homogeneous–isotropic idealisation represents a pragmatic balance between physical realism and parameter parsimony. Future studies could incorporate viscoelastic and anisotropic material models to enhance the accuracy of potato mechanical property estimations. Additionally, investigating different potato varieties, storage conditions, and hydration levels would provide a more comprehensive dataset for optimising agricultural processing and machinery design. Consequently, further experimental investigations are necessary to establish comprehensive reference data for FEA analyses, especially regarding the deformation analysis of solid agricultural products like potatoes, as investigated in this study.

Conclusions

This study utilised FEA to examine how potato flesh deforms under compression and to estimate its Poisson's ratio. The visual results from FEA closely mirrored experimental observations, illustrating the effectiveness of computational simulations in capturing the intricate mechanical responses of agricultural products. The derived Poisson's ratio (FEA, 0.406; empirical, 0.441) aligns well with values reported in existing literature, affirming the reliability of the methodologies employed. The 7.93% relative difference between FEA and empirical calculations underscores the

Table 1 Comparison of the Poisson's ratio values collected from major literature sources with the FEA results obtained in this study

Reference source	Poisson's ratio	Moisture content (% wb)	Test method	Potato variety	Notes
FEA Estimation	0.406	85.25	FEA (compression test correlation)	Agria	Present work
(Kojima 1983) (Eq. 1)	0.441	85.25	Moisture-based empirical equation	Agria	Present work
(Fan et al. 2022)	0.300	91.88	Image-based axial strain under compression	Atlantic	Potato stems
(Bentini et al. 2008)	0.328	85.00 (storage environment)	Uniaxial compression test (Cold storage)	Solanum tuberosum L. cvs. Vivaldi and Primur	Value decreases over storage
(X. Gai et al. 2024)	0.350	51.70	Uniaxial compression test + DEM modelling	Furuite	Whole stem compression test, Model parameter fitting
(Lammari et al. 2021)	0.390	NR	Uniaxial tensile test+numerical modelling	Spunta	Creep test included into the study
(Jagessar 2022)	0.430	69.23	Compression test (flat disc indenter)	*Ipomoea batatas* L.	Viscoelastic Behaviour in Sweet Potato
(Lammari et al. 2022)	0.460	NR	Uniaxial compression test	Spunta and Daifla	Varietal difference noted
(Nikara et al., 2020b)	0.480	85.00	Uniaxial compression test	*Solanum tuberosum* L. cv. Sante	Flesh and peel tested, SEM was utilised
(Gulati and Datta 2015), (Mohsenin 1986)	0.490	≈81.82	Numerical model+compression test	*Solanum tuberosum*	Temperature and moisture content based study+conventional methods
(Finney and Hall 1967)	0.492	NR	Uniaxial compression	Russet rural	Early foundational study

NR not reported in the original publication robustness of FEA in estimating mechanical properties, considering variations in moisture content. This may also suggest that FEA can reliably predict mechanical properties in similar studies. These findings contribute significantly to our understanding of potato flesh mechanical behaviour and offer implications for optimising agricultural machinery and postharvest handling processes. Future research could explore additional factors such as moisture content and different potato varieties to further refine predictive models and enhance the precision of mechanical property assessments in agricultural contexts. Moreover, regarding the deformation analysis of solid agricultural products like potatoes, the literature review indicates a need for further detailed experimental research in future studies.

Author Contribution H. Kursat Celik: Project administration, investigation, visualisation, formal analysis, writing—original draft

Ibrahim Akinci: Investigation, data curation, methodology, resources, writing—original draft

Kubilay K. Vursavus: Project administration, conceptualisation, methodology

Jenny M. Roberts: Data curation, writing—review and editing

Allan E.W. Rennie: Supervision, writing—review and editing

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). This research was partially supported by the Scientific Research Projects Coordination Unit of Akdeniz University, Türkiye. The funding body had no involvement in the allocation of publication funds, the study's design, data collection, analysis, or interpretation, the preparation of the manuscript, or the decision to publish the findings. The dataset supporting this study is available upon request from the authors. The abstract of this paper was presented at the International Conference on Research of Agricultural and Food Technologies (I-CRAFT-2024), held in Tashkent, Uzbekistan, from 11 to 13 September 2024.

Data Availability The dataset supporting this study is available upon request from the authors.

Conflict of interest The authors declare no competing interests.

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