



Homepage Journal: <https://jurnal.unismuhpalu.ac.id/index.php/JKS>

Poisson's Ratio pada Buah dan Produk Hortikultura: Pengukuran, Interpretasi, dan Relevansi

Poisson's Ratio in Fruits and Horticultural Materials: Measurement, Interpretation, and Engineering Relevance

Wiwin Apriyanditra^{1*}, Fuad Sauqi Isnain²

¹ Program Studi Teknik Pertanian, Fakultas Teknologi Pangan dan Agroindustri, Universitas Mataram, Indonesia

² Program Studi Ilmu dan Teknologi Pangan, Fakultas Teknologi Pangan dan Agroindustri, Universitas Mataram

*Corresponding Author: wiwinapriyan@staff.unram.ac.id

Artikel Penelitian

Article History:

Received: 15 Jan, 2026

Revised: 08 Feb, 2026

Accepted: 25 Feb, 2026

Kata Kunci:

Poisson's Ratio, rekayasa pascapanen; karakterisasi mekanik; pemodelan elemen hingga; perilaku viskoelastik

Keywords:

Poisson's ratio, postharvest engineering, mechanical characterization, finite element modelling, viscoelastic behavior

DOI: [10.56338/jks.v9i2.10789](https://doi.org/10.56338/jks.v9i2.10789)

ABSTRAK

Poisson's ratio merupakan parameter kunci yang menggambarkan deformasi lateral suatu material ketika dikenai beban, namun perannya dalam biomekanika buah masih belum dieksplorasi secara memadai dan penerapannya masih belum konsisten. Tinjauan ini mensintesis bukti terkini mengenai bagaimana Poisson's ratio telah diukur, diinterpretasikan, dan digunakan pada buah serta material hortikultura, dengan perhatian khusus pada relevansinya dalam rekayasa pascapanen. Tinjauan literatur terstruktur dilakukan dengan menggunakan studi-studi peer-reviewed dari basis data ilmiah utama, yang berfokus pada pendekatan pengukuran langsung maupun aplikasi berbasis pemodelan. Analisis menunjukkan adanya variabilitas yang substansial pada nilai Poisson's ratio yang dilaporkan antar komoditas, tipe jaringan, dan kondisi pengujian, yang berkisar dari nilai mendekati nol pada jaringan yang secara struktural kaku hingga nilai yang mendekati inkompresibilitas pada sistem yang bertekstur lunak dan berkadar air tinggi. Variasi ini berkaitan erat dengan struktur jaringan, tingkat kematangan, dan kondisi deformasi, tetapi juga sangat dipengaruhi oleh perbedaan metodologi. Meskipun terdapat kemajuan dalam pengukuran regangan optik dan teknik eksperimental, banyak studi masih mengandalkan nilai asumsi, khususnya dalam pemodelan elemen hingga dan penilaian non-destruktif. Ketergantungan ini membatasi keandalan prediksi mekanik. Oleh karena itu, studi ini bertujuan untuk meninjau secara kritis bagaimana Poisson's ratio telah dikarakterisasi pada buah, mengevaluasi keterbatasan metodologis, dan mengidentifikasi arah pengembangan untuk meningkatkan penggunaannya dalam aplikasi rekayasa pascapanen.

ABSTRACT

Poisson's ratio is a key parameter describing lateral deformation in materials under load, yet its role in fruit biomechanics remains insufficiently explored and inconsistently applied. This review synthesizes current evidence on how Poisson's ratio has been measured, interpreted, and used in fruits and horticultural materials, with particular attention to its relevance in postharvest engineering. A structured literature review was conducted using peer-reviewed studies from major scientific databases, focusing on both direct measurement approaches and modelling-based applications. The analysis reveals substantial variability in reported values across commodities, tissue types, and testing conditions, ranging from near-zero values in structurally rigid tissues to values approaching incompressibility in soft, high-moisture systems. These variations are closely linked to tissue structure, maturity, and deformation conditions, but are also strongly influenced by methodological differences. Despite recent advances in optical strain tracking and experimental techniques, many studies continue to rely on assumed values, particularly in finite element modelling and non-destructive assessments. This reliance limits the reliability of mechanical predictions. This study therefore aims to critically review how Poisson's ratio has been characterized in fruits, to evaluate methodological limitations, and to identify directions for improving its use in postharvest engineering applications.

INTRODUCTION

Mechanical characterization of fresh horticultural products is essential for understanding how fruits respond to external forces during handling, transportation, and storage (Opara & Pathare, 2014). Unlike conventional engineering materials, fruits are structurally heterogeneous, highly hydrated, and mechanically sensitive to both biological and environmental changes (Herold et al., 2001; Li & Thomas,

2014). Their response to loading is governed not only by material properties, but also by tissue organization, cellular structure, and physiological state (Sirisomboon et al., 2012; Waldron et al., 2003). As a result, predicting deformation and damage in fruits remains a complex challenge in postharvest engineering (Opara & Pathare, 2014).

Among the parameters used to describe material deformation, Poisson's ratio provides direct insight into how a material expands or contracts laterally when subjected to axial loading (Greaves et al., 2011). In principle, this parameter plays a critical role in constitutive modelling, stress-strain analysis, and finite element simulation (Zulkifli et al., 2020). In practice, however, its use in fruit mechanics has been inconsistent. While properties such as firmness and elastic modulus are commonly measured, Poisson's ratio is often treated as a secondary parameter, frequently assumed rather than experimentally determined (Sirisomboon et al., 2012). This creates a disconnect between modelling assumptions and actual mechanical behavior, particularly in soft and heterogeneous biological materials such as fruits (Słupska et al., 2025).

This imbalance in the literature has created a notable problem in the mechanical modelling of fresh produce. Many analytical and numerical studies require Poisson's ratio as a constitutive parameter, yet the value used is frequently assumed from generalized literature or borrowed from biologically dissimilar tissues rather than determined directly for the commodity and condition under study (Sirisomboon et al., 2012). This practice is especially problematic for fruits, whose deformation response depends strongly on maturity stage, water content, cellular turgor, tissue layering, and internal heterogeneity. Unlike homogeneous engineering materials, fruit tissues exhibit nonlinear, time-dependent, and structure-sensitive mechanical behavior, meaning that even modest inaccuracies in Poisson's ratio may alter the predicted distribution of stress, strain, and deformation under load (Herold et al., 2001). As a result, the use of assumed Poisson's ratio values may compromise the physical realism and predictive reliability of mechanical simulations used for postharvest design and damage assessment (Opara & Pathare, 2014).

The challenge becomes even more pronounced when moving from isolated tissues to intact fruits. Most fruits are composite biological systems consisting of peel, flesh, locular cavities, vascular bundles, and intercellular voids, each contributing differently to the global mechanical response (Li et al., 2012). Consequently, a Poisson's ratio measured on a simplified cylindrical tissue specimen or inferred from a single tissue layer may not adequately represent the mechanical behavior of the whole fruit under realistic loading conditions (Li & Thomas, 2014). This distinction matters in practice. Postharvest damage develops in intact fruits, not in isolated tissue cylinders tested under ideal laboratory conditions (Opara & Pathare, 2014). Therefore, there is a growing need to critically examine how Poisson's ratio has been measured, interpreted, and applied in horticultural research, and whether current practices provide mechanically representative values for practical postharvest use (Zulkifli et al., 2020).

Several experimental and modelling approaches have been employed to estimate or apply Poisson's ratio in plant-based biological materials. Direct measurement has most commonly been attempted through uniaxial compression or tensile testing combined with simultaneous axial and lateral deformation measurements. For example, Poisson's ratio has been experimentally determined in apple tissues using compression and tensile tests (Grotte et al., 2002), in tomato skin as a function of storage time and temperature (Kuna-Broniowska et al., 2012), in pumpkin flesh and seed tissues under varying moisture and loading conditions (Khodabakhshian & Emadi, 2015), and in carrot tissues for viscoelastic finite element modelling (Xia et al., 2021). More advanced approaches such as digital image correlation and laser-based displacement sensing have also improved the ability to track multi-directional strain fields in soft biological materials (An et al., 2022). These methods have contributed valuable insights by demonstrating that Poisson's ratio in biological materials is not fixed, but responsive to structural and physiological conditions.

Despite these advances, the available evidence is still methodologically fragmented and difficult to compare across studies. Many studies have focused on tissue samples, peels, seeds, or simplified geometries rather than intact fruits, making cross-study comparison difficult and limiting the transferability of findings to real postharvest systems. In parallel, several non-destructive or indirect

techniques, including forced vibration, Rayleigh wave propagation, and finite element-based impact simulations, have used Poisson's ratio as a prescribed model input rather than a directly measured property (Arai et al., 2021; Khalifa et al., 2011). Although these methods are useful for firmness evaluation and damage prediction, their dependence on assumed constitutive parameters reduces confidence in their mechanistic interpretation. Moreover, the literature rarely synthesizes how Poisson's ratio varies with fruit maturity, tissue composition, moisture status, and loading regime across commodities, even though these factors are known to govern the mechanical response of fresh produce.

Taken together, the available literature indicates that Poisson's ratio is both mechanically meaningful and insufficiently resolved in horticultural science. Existing studies suggest that soft, water-rich tissues such as tomato skin and carrot flesh may approach near-incompressible behavior, whereas peel-dominated or structurally rigid tissues may exhibit substantially lower lateral deformation under load ((Kuna-Broniowska et al., 2012; Xia et al., 2021). Yet the field still lacks a coherent synthesis that integrates measurement principles, reported values, methodological limitations, and engineering implications within a single analytical framework. More importantly, direct whole-fruit measurements remain scarce, and there is no broadly accepted methodological standard for obtaining representative Poisson's ratio values in fruits. This unresolved gap limits the development of more physically grounded constitutive models and constrains the accuracy of predictive tools for bruise risk, packaging stress, and machine-fruit interaction.

Accordingly, the objective of this study is to provide a critical and structured review of Poisson's ratio in fruits and horticultural materials, with emphasis on its measurement approaches, reported values, mechanical interpretation, and relevance to postharvest engineering. The novelty of this review lies in repositioning Poisson's ratio from a frequently assumed modelling constant to a measurable and biologically informative mechanical parameter whose value reflects tissue structure, physiological condition, and loading response. In addition to synthesizing existing evidence across commodities and experimental methods, this review identifies methodological inconsistencies, highlights the scarcity of intact-fruit measurements, and outlines future directions for more representative mechanical characterization. The scope of the review encompasses direct and indirect measurement approaches, tissue- and whole-fruit studies, and the implications of Poisson's ratio for constitutive modelling, finite element simulation, and postharvest system design. By clarifying the current state of knowledge and its limitations, this work establishes a foundation for improved experimental protocols and more reliable mechanical modelling of fresh horticultural products.

METHODE

This study was conducted as a structured literature review with systematic elements to synthesize current knowledge on Poisson's ratio in fruits and horticultural materials, with emphasis on measurement approaches, reported values, and engineering relevance. The review procedure was designed to ensure transparency, reproducibility, and alignment with the objective of identifying methodological limitations and research gaps in the mechanical characterization of fresh produce.

Relevant literature was retrieved from major scientific databases, including Scopus, Web of Science, ScienceDirect, and SpringerLink. The search strategy combined keywords related to Poisson's ratio, fruit mechanics, and postharvest engineering using Boolean operators, in line with established recommendations for systematic search development and reproducibility (Bramer et al., 2018). The main search combinations included: Poisson's ratio of fruit and horticultural material, mechanical properties, fruit tissue, compression, lateral strain, finite element modelling, fruit deformation". Additional terms such as "viscoelasticity", "bruise prediction", and "plant tissue mechanics" were used to capture studies in which Poisson's ratio was applied within broader mechanical analyses (MacFarlane et al., 2022).

The review included peer-reviewed journal articles and conference papers published in English that reported, measured, estimated, or applied Poisson's ratio in fruits, vegetables, or plant-based biological

materials. Studies were excluded if they were unrelated to mechanical behavior, lacked methodological clarity, or focused exclusively on non-biological materials. The screening process was conducted through title and abstract evaluation followed by full-text assessment, guided by PRISMA principles to improve selection transparency (Rethlefsen et al., 2021).

Data from the selected studies were extracted and organized according to commodity type, tissue or sample geometry, measurement status (direct or indirect), experimental or modelling method, loading regime, reported Poisson's ratio values, and key findings. The evidence was then synthesized qualitatively through comparative analysis. Because of substantial heterogeneity in sample type, testing conditions, and analytical methods, a meta-analysis was not considered appropriate. Instead, the review focused on identifying recurring patterns, methodological inconsistencies, and unresolved gaps related to the measurement and engineering interpretation of Poisson's ratio in horticultural materials (Campbell et al., 2020; Higgins et al., 2019).

RESULTS

The findings of this review are organized into three complementary tables to provide a structured overview of how Poisson's ratio has been investigated and applied in fruits and horticultural materials across the 17 studies selected for detailed analysis. Table 1 summarizes the selected international studies, highlighting the commodities examined, the primary objectives of each study, and the extent to which Poisson's ratio was directly measured, indirectly applied, or omitted. Table 2 further synthesizes the reported Poisson's ratio values across different fruits and plant tissues, together with their measurement status, loading conditions, and key mechanical interpretations, thereby illustrating the substantial variability associated with tissue type, maturity, and experimental context. Finally, Table 3 compares the principal measurement approaches used to determine or apply Poisson's ratio in soft biological materials, with emphasis on their ability to capture lateral deformation, their methodological limitations, and their relevance for postharvest engineering applications.

Table 1. Summary of international studies related to the measurement and application of Poisson's ratio in fruits and horticultural materials

Reference	Fruit / Tissue	Purpose of Study	Poisson's Ratio Treatment	Measurement Approach
Kuna-Broniowska et al. (2012a)	Tomato skin	Effect of storage time and temperature	Directly measured	Axial loading with longitudinal–transverse strain calculation (random surface marking)
Arai et al. (2021)	Mango (fruit)	Firmness assessment	Assumed / indirectly applied	Rayleigh wave propagation (laser-induced plasma shock technique)
Luo et al. (2025)	Peach, nectarine	Firmness change with maturity and storage	Not considered	Force–displacement curve analysis
Khalifa et al. (2011)	Various fruits	Review of firmness evaluation methods	Indirectly used in models	Forced vibration and air-puff methods
Hassanpour et al. (2010)	White seedless grapes (fruit)	Effect of maturation on mechanical properties	Directly measured	Static loading tests combined with digital photography; FEM used for calibration

Rosenthal et al. (2018)	Spherical model fruits (gelatin, disc-stone)	Contribution of skin and stone to texture measurements	Directly measured	Compression tests at low loads prior to failure
Jentzsch et al. (2022)	Citrus fruit peels	Damage protection and peel morphology	Directly measured	Quasi-static compression tests on fruit peels
Khodabakhshian & Emadi (2015)	Pumpkin seeds and kernels	Effect of variety, size, moisture, and loading rate	Directly measured	Compression tests under controlled moisture content and loading rates
Grotte et al. (2001)	Apple tissues (peel and flesh)	Mechanical characterization of fruit tissues	Directly measured	Compression and tensile tests on cylindrical tissue samples
Ekrami-Rad et al. (2011)	Pomegranate peel and fruit tissues	Determination of mechanical properties for damage assessment and handling design	Directly measured	Quasi-static compression and shear tests on peel and fruit tissues; Poisson's ratio obtained from lateral and axial deformation behavior
Liu et al. (2022)	Plant tissues (various)	Accurate determination of Poisson's ratio	Directly measured	Uniaxial compression combined with digital image correlation
Xia et al. (2021)	Carrot tissue (flesh and core)	Bruise prediction and impact damage analysis using FEM	Directly measured and applied as FEM input	Uniaxial compression tests on cylindrical samples; Poisson's ratio calculated from axial and lateral strain measurements
Herold et al. (2001)	Fruit tissues (various)	Mechanical properties of fruit tissues	Often assumed / indirectly used	Review of compression and impact testing methods
Djebbloun et al. (2019)	Date palm tree fiber	Determination of elastic modulus and Poisson's coefficient of natural plant fibers	Directly measured	Uniaxial tensile testing with simultaneous measurement of longitudinal and transverse strain
An et al. (2022)	Strawberry (fruit tissue, cortex/whole fruit)	Prediction of temperature-dependent damage using dynamic FEM	Assumed / model parameter	Dynamic finite element modeling of drop impact; Poisson's ratio adopted from literature to describe viscoelastic fruit tissue behavior
Mahiuddin et al.	Various fruits	Determination of	Assumed /	Fractional Caputo

(2020)	and vegetables (tissue samples)	viscoelastic mechanical properties using fractional rheological modeling	and using	indirectly applied	rheological model fitted to creep–relaxation data; Poisson’s ratio adopted from literature or treated as a constant elastic parameter
Sirisomboon et al. (2012)	Tomato (whole fruit / flesh)	Evaluation of textural and mechanical properties of tomato	of and	Not considered / implicitly neglected	Compression and texture profile analysis focusing on firmness, elasticity-related indices, and force–deformation response
Shirmohammadi et al., (2018)	Pumpkin flesh tissue	Experimental determination of elastic properties of pumpkin tissue	of of	Directly measured	Uniaxial compression with laser displacement sensors for axial and lateral deformation

Table 2. Reported Poisson’s ratio of fruits and plant tissues: measurement status, loading regime, key findings, and methodological implications

Commodity	Tissue / Geometry	Poisson’s Ratio (v)	Measurement Status	Method / Instrument	Loading Regime	Key Findings / Main Observations
Tomato (cv. Encore/Admiro) (Kunabroniowska et al., 2012)	Skin (intact)	0.40–0.50	Measured	Axial compression and strain tracking	Quasi-static	The Poisson’s ratio increased with increasing storage time and temperature due to the softening of peel tissue
Apple (Grotte et al., 2002)	Flesh	0.17–0.22	Measured	Compression/tension (cylindrical samples)	Quasi-static	The reported values (Poisson’s ratio) were relatively low and showed a decreasing trend with increasing flesh stiffness during storage. Conversely, Poisson’s ratio tended to increase with fruit ripening, reflecting the gradual decline in tissue elasticity.” The fruit peel exhibited greater lateral deformation than the flesh, reflecting differences in structural organization and mechanical
Apple (Slupska et al., 2025)	Peel	≈0.35	Measured	Uniaxial tensile test	Quasi-static	

Commodity	Tissue / Geometry	Poisson's Ratio (ν)	Measurement Status	Method / Instrument	Loading Regime	Key Findings / Main Observations
Apple (cv. Chopin) (Słupska et al., 2026)	Whole fruit (three maturity stages)	0.21–0.25 (development); 0.35 (senescence)	Measured	Uniaxial compression with axial–lateral strain measurement	Quasi-static	stiffness between outer and inner tissues. Poisson's ratio increased with increasing fruit maturity, reflecting greater lateral deformation as tissue elasticity progressively declined
Pumpkin (Khodabakhshian & Emadi, 2015)	Seed / Kernel	0.27–0.42	Measured	Compression (controlled MC & rate)	Quasi-static	Poisson's ratio decreased with increasing moisture content, but increased with higher loading rates
Pumpkin (Shirmohammadi et al., 2018)	Flesh tissue (cylindrical samples)	≈0.35–0.49	Directly measured	Uniaxial compression with laser displacement sensors measuring axial and lateral deformation	Quasi-static	Laser based non-contact measurements allow more accurate detection of dynamic deformation and indicate that lateral strain is influenced by tissue moisture content
Pomegranate (Ekrami-Rad et al., 2011)	Peel	~0 to negative	Measured	Quasi-static compression & shear	Quasi-static	The multilayered peel structure significantly restricted lateral deformation
Carrot (Xia et al., 2021)	Flesh (cylindrical sample, Ø10 × 10 mm)	0.477	Directly measured	Uniaxial compression; axial deformation from UTM sensor, lateral deformation from diameter change	Quasi-static (2.5 mm·min ⁻¹)	Carrot flesh tissue exhibited near-incompressible behavior, with Poisson's ratio incorporated as a viscoelastic input parameter in finite element modelling for bruise prediction.
	Core (cylindrical sample,	0.477	Directly measured	Uniaxial compression;	Quasi-static	Poisson's ratio of the core was slightly higher than that of the

Commodity	Tissue / Geometry	Poisson's Ratio (v)	Measurement Status	Method / Instrument	Loading Regime	Key Findings / Main Observations
	Ø10 × 10 mm)			pengukuran regangan aksial–lateral langsung		flesh, reflecting differences in internal tissue structure
Red bean (Kiani Deh Kiani et al., 2011)	Seed (var. Goli; var. Akhtar)	0.267–0.322 (Goli); 0.340–0.406 (Akhtar)	Measured	Uniaxial compression tests with controlled moisture content	Quasi-static	Poisson's ratio of the seed and core decreased with increasing moisture content but increased with higher loading rates, indicating a significant influence of physical conditions and viscoelastic response
Strawberry (An et al., 2022)	Whole fruit	≈0.40	Assumed	Dynamic FEM (drop test)	Quasi-static	Poisson's ratio was assumed, and the simulation results were highly sensitive to its value
Maize (corn) (Dai et al., 2013)	Kernel (13.2% MC)	0.399–0.423	Measured	Compression under increasing load	Quasi-static	Poisson's ratio increased with loading force, indicating the influence of internal seed pressure.
Eggplant (terong) (Mahiuddin et al., 2020)	Tissue	0.44–0.58	Measured	Compression tests	Quasi-static	Poisson's ratio increased with higher loading rates and greater tissue porosity.
Plum (Eshaghbeygi et al., 2013)	Whole fruit (var. Ghandi, Ghatratala, Black plum)	0.187–0.301	Measured	Compression tests	Impact / Dynamic	The range of Poisson's ratio values was consistent with typical biological materials (0.2–0.5) and was influenced by varietal differences.
Citrus (pomelo, lemon)	Whole fruit	0.03 (pomelo), 0.14 (lemon)	Measured	Compression tests	Dynamic	The very low Poisson's ratio values reflected limited lateral deformation due to the rigid peel structure

Table 3. Measurement approaches for Poisson’s ratio in soft biological materials

Approach	Direct / Indirect	Capability to Measure Lateral Strain	Limitations	Typical Use
Static compression	Direct	Moderate–High	Premature failure, alignment	Tissue characterization
Uniaxial tension	Direct	High	Sample preparation	Peel/fiber
Digital Image Correlation	Direct	Very high	Optical noise, cost	Research-grade measurement
Vibration / Rayleigh waves	Indirect	None (assumed ν)	Model dependency	Non-destructive firmness
FEM (dynamic)	Indirect	None (input ν)	Sensitive to assumed ν	Damage prediction

DISCUSSION

General Characteristics of the Selected Studies

Recent work on Poisson’s ratio in fruits remains scientifically fragmented, with most studies differing substantially in scale, purpose, and measurement rigor (Sirisomboon et al., 2012). A clear pattern is that most recent studies have not treated Poisson’s ratio as a primary experimental variable, but rather as a secondary mechanical parameter or a prescribed input in modelling frameworks (Li & Thomas, 2014). Across the selected literature, the dominant commodities include tomato, mango, strawberry, carrot, citrus, and several plant tissues or seed-based materials, indicating that current evidence is still dispersed across different biological structures rather than consolidated within whole-fruit mechanics (Opara & Pathare, 2014).

From a methodological perspective, the literature can be grouped into three dominant categories: direct mechanical measurement, indirect non-destructive estimation, and model-based application (Sirisomboon et al., 2012; Zulkifli et al., 2020). Direct measurement remains the most scientifically reliable approach because it captures axial and lateral strain simultaneously under controlled loading (Schreier et al., 2009). Recent studies applying direct or semi-direct approaches, such as uniaxial compression combined with optical strain tracking or digital image correlation, have shown that Poisson’s ratio is highly sensitive to tissue condition, geometry, and deformation level (Chen et al., 2021; Fan et al., 2022a). For example, the use of digital image correlation and image-based strain tracking has improved deformation resolution in soft plant tissues and has strengthened the reliability of Poisson’s ratio estimation in mechanically heterogeneous biological materials (An et al., 2022; Xia et al., 2021) (Liu et al., 2022; Xia et al., 2021).

However, Table 1 also shows that a substantial proportion of the literature still applies Poisson’s ratio indirectly. In recent non-destructive firmness studies, such as those based on Rayleigh wave propagation, Poisson’s ratio is often embedded in the mechanical model rather than measured experimentally (Arai et al., 2021). Likewise, finite element studies on fruit drop damage and dynamic deformation frequently adopt literature-derived values to represent viscoelastic fruit tissues, especially in soft commodities such as strawberry (An et al., 2022) and apple (Chavoshi et al., 2022). Although this practice is computationally practical, it introduces a critical methodological weakness because model outputs may become highly sensitive to assumed constitutive parameters that are not validated for the tested commodity or maturity stage (Ikeda et al., 2015).

Another notable feature of the selected studies is the strong dominance of tissue-level or partial-structure measurements over intact whole-fruit characterization (Li et al., 2012). Recent experimental work has been conducted primarily on peel, flesh, cortex, core, or cylindrical tissue specimens, rather than on whole fruits under realistic handling conditions (Li et al., 2012; Sirisomboon et al., 2012). This is

a significant limitation because the mechanical response of intact fruits emerges from the integrated interaction of multiple tissue layers, internal cavities, moisture gradients, and curvature-dependent stress distribution (Li & Thomas, 2014). Consequently, values derived from isolated tissues may not adequately represent global fruit deformation during compression, impact, or handling (Opara & Pathare, 2014).

Collectively, the evidence summarized in Table 1 indicates that the literature has advanced in terms of measurement sophistication, but not yet in terms of representativeness and standardization (Zulkifli et al., 2020). The recent shift toward optical measurement, digital strain analysis, and modelling integration is scientifically promising, yet the field still lacks a consistent experimental framework for obtaining Poisson's ratio values that are directly applicable to postharvest engineering and bruise prediction (Chen et al., 2021; Fan et al., 2022a). In practical terms, the field has progressed faster in modelling than in measurement, leaving many mechanical interpretations dependent on poorly validated input values (Opara & Pathare, 2014).

The magnitude of Poisson's ratio is influenced by several factors such as moisture content, loading rate, and structural composition (e.g., peel, pulp, and flesh), which collectively determine the deformation response of the product (Khodabakhshian, 2012). Many studies have relied on assumed Poisson's ratio values derived from moisture conditions or previous literature rather than direct experimental measurement (An et al., 2022; Arai et al., 2021; Herold et al., 2001; Sirisomboon et al., 2012). These assumptions are commonly applied in acoustic wave-based measurement, forced vibration methods, dynamic impact simulation, and viscoelastic modelling of agricultural materials (An et al., 2022; Khalifa et al., 2011; Mahiuddin et al., 2020). While such approaches remain practical for engineering prediction, they also highlight a persistent gap between modelling convenience and experimentally validated mechanical characterization.

Reported Poisson's Ratio Values Across Fruits and Plant Tissues

The values summarized in Table 2 demonstrate that Poisson's ratio in horticultural materials spans a wide mechanical range, from nearly zero in structurally rigid peel-dominated systems to values approaching 0.50 in soft, water-rich tissues (Fan et al., 2022b; Sirisomboon et al., 2012). This variability confirms that Poisson's ratio in fruits cannot be treated as a universal constant, but rather as a structure-dependent and condition-sensitive mechanical parameter (Greaves et al., 2011). In recent studies, tissues with high moisture content and reduced internal rigidity, such as carrot flesh and soft fruit tissues, consistently exhibited near-incompressible behavior, indicating strong lateral deformation under axial compression (Fan et al., 2022b; Xia et al., 2021) (Xia et al., 2021). In contrast, peel-dominated materials such as citrus and structurally reinforced outer tissues showed markedly lower values, reflecting their protective mechanical function and limited transverse strain.

Table 2 also reveals that tissue type and sample geometry strongly influence the reported values (Li et al., 2012). Measurements obtained from cylindrical tissue specimens generally isolate local mechanical behavior, whereas whole-fruit measurements integrate the combined effect of peel, flesh, internal cavities, and structural heterogeneity (Li & Thomas, 2014). This distinction is scientifically important because it suggests that Poisson's ratio values derived from isolated tissues may not always be transferable to intact fruit systems (Li & Thomas, 2014; Zulkifli et al., 2020). Recent studies indicate that physiological condition, particularly fruit maturity and moisture loss, plays a significant role in governing deformation behavior (Gidado et al., 2024; A. C. Paniagua et al., 2013). As fruits ripen or lose structural integrity, lateral strain tends to increase due to pectin degradation, weakened intercellular bonding, and reduced tissue stiffness, thereby increasing the apparent Poisson's ratio (C. Paniagua et al., 2014). These trends reinforce the potential of Poisson's ratio as a sensitive mechanical indicator of tissue softening and postharvest deterioration.

Beyond maturity effects, sample geometry also plays an important role in determining measured Poisson's ratio values. Intact fruits tend to exhibit a more integrated mechanical response because

deformation reflects the combined contribution of multiple tissue layers and internal structures, whereas cylindrical tissue specimens isolate local behavior and may neglect interactions among structural components (Herold et al., 2001; Li et al., 2012). In addition, evidence summarized in Table 2 indicates that Poisson's ratio is strongly influenced by maturity stage and physiological condition, as observed in fruits such as tomato and apple, where the reported values generally increase with ripening (Sirisomboon et al., 2012). This trend is closely associated with tissue softening during maturation, including pectin degradation in the middle lamella, weakening of intercellular adhesion, and reduced stiffness of the cell wall (Goulao & Oliveira, 2008). As a result, fruit tissues become more susceptible to lateral deformation under axial loading, leading to higher ratios of transverse to axial strain. Changes in cellular turgor may further contribute to this response, as intracellular fluid redistribution becomes increasingly important in mature tissues (Chen et al., 2021). Taken together, these observations suggest that changes in Poisson's ratio reflect a mechanical transition from a more elastic response in immature fruit to a more viscoelastic behavior in ripened fruit, supporting its potential as a sensitive mechanical indicator of physiological softening.

Measurement Approaches and Methodological Limitations

The approaches summarized in Table 3 show that the reliability of Poisson's ratio data depends strongly on the ability of the measurement system to capture axial and lateral strain simultaneously and accurately. Among recent studies, direct methods such as static compression, uniaxial loading, and image-based strain tracking remain the most mechanically interpretable because they are grounded in observable deformation behavior rather than model assumptions (Fan et al., 2022a; Sirisomboon et al., 2012). In particular, digital image correlation and optical strain analysis have improved the precision of lateral deformation measurement in soft biological materials, where contact-based methods are often limited by irregular geometry, local collapse, and small transverse displacement (An et al., 2022; Fan et al., 2022b).

In contrast, indirect approaches such as vibration-based testing, Rayleigh wave propagation, and finite element simulation are useful for non-destructive assessment and engineering prediction, but they do not independently resolve lateral strain (Arai et al., 2021; Sirisomboon et al., 2012). Their dependence on assumed Poisson's ratio values remains a major methodological limitation, especially when applied to fruits with heterogeneous tissue architecture and strong viscoelasticity behavior (Zulkifli et al., 2020). This limitation is not trivial, because modelling studies have shown that mechanical predictions, including bruise susceptibility and deformation fields, are highly sensitive to constitutive inputs (An et al., 2022). Therefore, Table 3 collectively suggests that future progress in this field depends less on adopting more complex models and more on improving experimental strain measurement at biologically realistic scales. In this context, integrated optical-mechanical systems and whole-fruit deformation tracking represent the most promising direction for obtaining representative Poisson's ratio values for postharvest engineering applications (Chen et al., 2021; Fan et al., 2022b).

The ability to measure lateral strain accurately remains one of the most critical determinants in obtaining reliable Poisson's ratio values for horticultural materials. Unlike axial strain, which can be estimated relatively easily from force-displacement measurements, lateral deformation is often more difficult to quantify because it is typically small in magnitude and occurs on soft, irregular, and mechanically unstable biological surfaces. For this reason, measurement systems capable of capturing axial and lateral deformation simultaneously, such as digital image correlation (DIC) and dual-sensor optical-mechanical configurations, offer clear methodological advantages (An et al., 2022; Chen et al., 2021; Fan et al., 2022b). These approaches provide higher spatial resolution and allow deformation behavior to be monitored directly in real time, thereby improving the reliability of Poisson's ratio estimation. In contrast, methods based on finite element modelling, vibration analysis, or Rayleigh wave propagation generally rely on assumed or literature-derived Poisson's ratio values without explicit lateral

strain measurement (An et al., 2022; Arai et al., 2021; Sirisomboon et al., 2012). This distinction highlights that the validity of Poisson's ratio in fruit biomechanics depends primarily on the measurement system's ability to resolve transverse deformation directly. Within this context, static compression remains one of the most practical and mechanically interpretable experimental approaches for determining Poisson's ratio in biological materials, particularly when combined with simultaneous axial and lateral deformation tracking (An et al., 2022; Fan et al., 2022b).

Recent developments in viscoelastic modelling further highlight the limited experimental grounding of Poisson's ratio in horticultural materials. For instance, advanced fractional viscoelastic models, such as the Caputo-based formulation, have demonstrated the ability to capture time-dependent mechanical behavior associated with storage effects in fruits and vegetables (Mahiuddin et al., 2020). However, in such approaches, Poisson's ratio is typically not measured through direct axial–lateral deformation analysis, but instead adopted from literature or assumed to complete the constitutive formulation. This pattern reflects a broader trend in which Poisson's ratio is treated as a fixed input parameter rather than an experimentally validated variable. Similarly, recent studies on fruit firmness evolution during storage have focused on predictive modelling without explicitly incorporating Poisson's ratio as a governing parameter (Luo et al., 2025). Collectively, these findings indicate that current mathematical models describing fruit mechanical behavior remain highly dependent on assumed Poisson's ratio values, underscoring a persistent lack of direct experimental validation.

This limitation is closely linked to experimental constraints in measuring deformation in intact fruits. Most available studies have focused on tissue-level characterization, including peel tissues of tomato and citrus, flesh tissues of apple and carrot, and fibrous plant materials, rather than whole-fruit systems (Khodabakhshian, 2012; Sirisomboon et al., 2012). While such approaches provide valuable insight into localized mechanical properties, they do not fully capture the integrated deformation behavior of intact fruits under realistic loading conditions. As a result, Poisson's ratio values derived from isolated tissues may not be representative of whole-fruit response, where global geometry, internal structure, and multi-layer interactions govern deformation. This gap highlights the need for measurement systems capable of simultaneously capturing global and lateral deformation at the whole-fruit scale to obtain mechanically representative Poisson's ratio values.

Priority Research Agenda

Future research on Poisson's ratio in fruits should prioritize the development of reliable experimental methods for direct whole-fruit measurement under realistic loading conditions. Current evidence is largely derived from tissue-level or simplified specimens, which do not fully represent the integrated mechanical response of intact fruits during handling, compression, or impact (Herold et al., 2001; Sirisomboon et al., 2012). Advancing this field therefore requires measurement systems capable of simultaneously capturing axial and lateral deformation in heterogeneous, viscoelastic biological structures (Fan et al., 2022b). In parallel, the establishment of standardized testing protocols is essential to improve data comparability across commodities, studies, and experimental conditions (Zulkifli et al., 2020).

In addition, Poisson's ratio should be re-examined as a dynamic and condition-dependent parameter rather than a fixed elastic constant. Future studies should explicitly investigate its variation with maturity, storage time, moisture content, and tissue degradation, and integrate these changes with viscoelastic and rheological behavior (Khodabakhshian, 2012; Mahiuddin et al., 2020). Such an approach would enable a more mechanistically meaningful interpretation of fruit deformation and provide stronger linkage between mechanical properties and physiological processes. At the same time, modelling studies, particularly finite element simulations used for bruise prediction and postharvest system design, should incorporate experimentally validated Poisson's ratio values to improve predictive accuracy and physical realism (An et al., 2022; Arai et al., 2021).

Progress in fruit biomechanics will depend on treating Poisson's ratio within an integrated, multiscale framework that links tissue structure, deformation behavior, and engineering application. Once experimentally validated, this parameter can strengthen constitutive modelling and improve the design of postharvest systems aimed at reducing mechanical damage and maintaining product quality (Mahiuddin et al., 2020; Zulkifli et al., 2020).

Research Gaps and Future Research Directions

Despite recent progress in the mechanical characterization of plant-based biological materials, the literature reviewed in this study reveals several unresolved gaps that continue to limit the scientific and practical use of Poisson's ratio in fruits. The most evident gap is the scarcity of direct measurements on intact whole fruits. Most available values have been derived from peel, flesh, core, or simplified cylindrical tissue samples, which are useful for controlled mechanical analysis but may not adequately represent the integrated deformation behavior of whole fruits during actual postharvest handling (Herold et al., 2001; Li et al., 2012). This limitation is critical because bruise development, compression damage, and handling-related stress occur at the whole-fruit scale rather than within isolated tissues (An et al., 2022).

A second major gap concerns the lack of methodological standardization. Current studies differ substantially in sample geometry, loading configuration, strain measurement technique, deformation range, and data interpretation. As a result, reported Poisson's ratio values are often difficult to compare across commodities and experimental setups. This inconsistency weakens the reliability of inter-study synthesis and limits the transferability of reported values into engineering design and constitutive modelling (Sirisomboon et al., 2012; Zulkifli et al., 2020). Therefore, future work should prioritize the development of standardized testing protocols specifically adapted to soft, viscoelastic, and geometrically irregular horticultural materials.

Another important gap is the persistent use of assumed Poisson's ratio values in finite element modelling and non-destructive mechanical assessment. Although such assumptions are often made for practical reasons, they reduce the physical validity of simulated deformation fields, bruise prediction, and stress distribution analysis (An et al., 2022; Arai et al., 2021). This issue is particularly relevant for fruits with strong tissue heterogeneity, high water content, and maturity-dependent softening. Future studies should therefore move toward experimentally validated parameterization, in which Poisson's ratio is measured under the same biological and loading conditions used in modelling.

The literature also remains limited in explaining how Poisson's ratio interacts with other mechanical and rheological properties during fruit softening, storage, and ripening. Most existing studies treat Poisson's ratio as an isolated elastic parameter, whereas in reality it is likely coupled with changes in viscoelasticity, water redistribution, turgor loss, and cell wall disassembly (Goulao & Oliveira, 2008; Mahiuddin et al., 2020). This opens an important opportunity for future research to integrate Poisson's ratio with time-dependent mechanical models, such as creep, stress relaxation, and viscoelastic constitutive analysis, in order to obtain a more physiologically meaningful interpretation of fruit deformation.

Methodologically, future advances will likely depend on improved strain-tracking systems capable of capturing axial and lateral deformation simultaneously with high spatial and temporal resolution. In this regard, optical measurement systems, digital image correlation, image-based deformation tracking, and integrated dual-sensor mechanical platforms appear particularly promising (Fan et al., 2022b). Their application to intact fruits under realistic compression or impact scenarios could substantially improve the reliability and engineering relevance of Poisson's ratio data.

Progress in this field depends on moving beyond reporting Poisson's ratio values toward validating it as an indicator of tissue condition, deformation behavior, and damage susceptibility. This shift would directly improve bruise prediction, finite element modelling, and the engineering of safer fruit handling systems (An et al., 2022; Zulkifli et al., 2020).

REFERENCE

- An, X., Liu, H., Fadji, T., Li, Z., & Dimitrovski, D. (2022). Prediction of the temperature sensitivity of strawberry drop damage using dynamic finite element method. *Postharvest Biology and Technology*, 190. <https://doi.org/10.1016/j.postharvbio.2022.111939>
- Arai, N., Miyake, M., Yamamoto, K., Kajiwara, I., & Hosoya, N. (2021). Soft Mango Firmness Assessment Based on Rayleigh Waves Generated by a Laser-Induced Plasma Shock Wave Technique. *Foods*, 10(2), 323. <https://doi.org/10.3390/FOODS10020323>
- Bramer, W. M., de Jonge, G. B., Rethlefsen, M. L., Mast, F., & Kleijnen, J. (2018). A systematic approach to searching: an efficient and complete method to develop literature searches. *Journal of the Medical Library Association*, 106(4), 531-541–531–541. <https://doi.org/10.5195/jmla.2018.283>
- Campbell, M., McKenzie, J. E., Sowden, A., Katikireddi, S. V., Brennan, S. E., Ellis, S., Hartmann-Boyce, J., Ryan, R., Shepperd, S., Thomas, J., Welch, V., & Thomson, H. (2020). Synthesis without meta-analysis (SWiM) in systematic reviews: reporting guideline. *BMJ*, 368. <https://doi.org/10.1136/bmj.l6890>
- Chavoshi, E., ahmadi, ebrahim, Alavi Nia, A., & Seifi, R. (2022). Determination of Dynamic Deformation Behavior of Apple Using Finite Element Method and its Validation by Scanning Electron Microscopy. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.4119419>
- Chen, T. Y. F., Dang, N. M., Wang, Z. Y., Chang, L. W., Ku, W. Y., Lo, Y. L., & Lin, M. T. (2021). Use of Digital Image Correlation Method to Measure Bio-Tissue Deformation. *Coatings 2021*, Vol. 11, 11(8). <https://doi.org/10.3390/coatings11080924>
- Dai, F., Zhao, W. Y., Han, Z. S., & Zhang, F. W. (2013). Experiment on Poisson's Ratio Determination about Corn Kernel. *Advanced Materials Research*, 781–784, 799–802. <https://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMR.781-784.799>
- Ekrami-Rad, N., Khazaei, J., & Khoshtaghaza, M. H. (2011). Selected mechanical properties of pomegranate peel and fruit. *International Journal of Food Properties*, 14(3), 570–582. <https://doi.org/10.1080/10942910903291920>
- Esehaghbeygi, A., Pirnazari, K., Kamali, M., & Razavi, J. (2013). Physical, and Mechanical Properties of Three Plum Varieties (*Prunus domestica* L.). *Www.Thaiagj.Org Thai Journal of Agricultural Science*, 46(2), 95–101. www.thaiagj.org
- Fan, J., Li, Y., Wang, B., Gu, F., Wu, F., Yang, H., Yu, Z., & Hu, Z. (2022a). An Experimental Study of Axial Poisson's Ratio and Axial Young's Modulus Determination of Potato Stems Using Image Processing. *Agriculture 2022*, Vol. 12, 12(7). <https://doi.org/10.3390/agriculture12071026>
- Fan, J., Li, Y., Wang, B., Gu, F., Wu, F., Yang, H., Yu, Z., & Hu, Z. (2022b). An Experimental Study of Axial Poisson's Ratio and Axial Young's Modulus Determination of Potato Stems Using Image Processing. *Agriculture 2022*, Vol. 12, Page 1026, 12(7), 1026. <https://doi.org/10.3390/AGRICULTURE12071026>
- Gidado, M. J., Gunny, A. A. N., Gopinath, S. C. B., Ali, A., Wongs-Aree, C., & Salleh, N. H. M. (2024). Challenges of postharvest water loss in fruits: Mechanisms, influencing factors, and effective control strategies – A comprehensive review. *Journal of Agriculture and Food Research*, 17(7), 101249. <https://doi.org/10.1016/j.jafr.2024.101249>
- Goulao, L. F., & Oliveira, C. M. (2008). Cell wall modifications during fruit ripening: when a fruit is not the fruit. *Trends in Food Science & Technology*, 19(1), 4–25. <https://doi.org/10.1016/J.TIFS.2007.07.002>
- Greaves, G. N., Greer, A. L., Lakes, R. S., & Rouxel, T. (2011). Poisson's ratio and modern materials. *Nature Materials* 2011 10:11, 10(11), 823–837. <https://doi.org/10.1038/nmat3134>

- Grotte, M., Duprat, F., Piétri, E., & Loonis, D. (2002). Young's modulus, poisson's ratio, and Lamé's coefficients of Golden Delicious apple. *International Journal of Food Properties*, 5(2), 333–349. <https://doi.org/10.1081/JFP-120005789>
- Herold, B., Geyer, M., & Studman, C. J. (2001). Fruit contact pressure distributions — equipment. *Computers and Electronics in Agriculture*, 32(3), 167–179. [https://doi.org/10.1016/S0168-1699\(01\)00160-0](https://doi.org/10.1016/S0168-1699(01)00160-0)
- Higgins, J. P. T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J., & Welch, V. A. (2019). *Cochrane handbook for systematic reviews of interventions*. *Cochrane Handbook for Systematic Reviews of Interventions*, 1–694. <https://doi.org/10.1002/9781119536604>
- Ikeda, T., Choi, P. K., Ishii, T., Arai, I., & Osawa, M. (2015). Firmness evaluation of watermelon flesh by using surface elastic waves. *Journal of Food Engineering*, 160, 28–33. <https://doi.org/10.1016/j.jfoodeng.2015.03.020>
- Khalifa, S., Komarizadeh, M. H., & Tousei, B. (2011). Usage of fruit response to both force and forced vibration applied to assess fruit firmness—a review. In *AJCS* (Vol. 5, Number 5).
- Khodabakhshian, R. (2012). Poisson's ratio of pumpkin seeds and their kernels as a function of variety, size, moisture content and loading rate. *Agric Eng Int: CIGR Journal*, 14(3), 203–209. <http://www.cigrjournal.org>
- Khodabakhshian, R., & Emadi, B. (2015). Development of a finite element method model to determine mechanical behavior of pumpkin seed. *International Journal of Food Properties*, 18(2), 231–240. <https://doi.org/10.1080/10942912.2013.822883>
- Kiani Deh Kiani, M., Maghsoudi, H., & Minaei, S. (2011). Determination of poisson's ratio and young's modulus of red bean grains. *Journal of Food Process Engineering*, 34(5), 1573–1583. <https://doi.org/10.1111/J.1745-4530.2009.00391.X>
- Kuna-Broniowska, I., Gładyszewska, B., & Ciupak, A. (2012). Effect of storage time and temperature on poisson ratio of tomato fruit skin. *International Agrophysics*, 26(1), 39–44. <https://doi.org/10.2478/v10247-012-0006-x>
- Li, Z., Li, P., Yang, H., Liu, J., & Xu, Y. (2012). Mechanical properties of tomato exocarp, mesocarp and locular gel tissues. *Journal of Food Engineering*, 111(1), 82–91. <https://doi.org/10.1016/j.jfoodeng.2012.01.023>
- Li, Z., & Thomas, C. (2014). Quantitative evaluation of mechanical damage to fresh fruits. *Trends in Food Science & Technology*, 35(2), 138–150. <https://doi.org/10.1016/J.TIFS.2013.12.001>
- Luo, X., Zhao, Y., Tian, S., Yu, Y., Rao, X., Xu, W., Ying, Y., & Xu, H. (2025). Characterize Firmness Changes of Nectarine and Peach Fruit Associated With Harvest Maturity and Storage Duration Using Parameters of Force–Displacement Curves. *Journal of Texture Studies*, 56(1), e70003. <https://doi.org/10.1111/JTXS.70003;ISSUE:ISSUE:DOI>
- MacFarlane, A., Russell-Rose, T., & Shokraneh, F. (2022). Search strategy formulation for systematic reviews: Issues, challenges and opportunities. *Intelligent Systems with Applications*, 15, 200091. <https://doi.org/10.1016/j.iswa.2022.200091>
- Mahiuddin, M., Godhani, D., Feng, L., Liu, F., Langrish, T., & Karim, M. A. (2020). Application of Caputo fractional rheological model to determine the viscoelastic and mechanical properties of fruit and vegetables. *Postharvest Biology and Technology*, 163. <https://doi.org/10.1016/j.postharvbio.2020.111147>
- Opara, U. L., & Pathare, P. B. (2014). Bruise damage measurement and analysis of fresh horticultural produce—A review. *Postharvest Biology and Technology*, 91, 9–24. <https://doi.org/10.1016/j.postharvbio.2013.12.009>
- Paniagua, A. C., East, A. R., Hindmarsh, J. P., & Heyes, J. A. (2013). Moisture loss is the major cause of firmness change during postharvest storage of blueberry. *Postharvest Biology and Technology*, 79, 13–19. <https://doi.org/10.1016/j.postharvbio.2012.12.016>

- Paniagua, C., Posé, S., Morris, V. J., Kirby, A. R., Quesada, M. A., & Mercado, J. A. (2014). Fruit softening and pectin disassembly: an overview of nanostructural pectin modifications assessed by atomic force microscopy. *Annals of Botany*, 114(6), 1375. <https://doi.org/10.1093/aob/mcu149>
- Rethlefsen, M. L., Kirtley, S., Waffenschmidt, S., Ayala, A. P., Moher, D., Page, M. J., Koffel, J. B., Blunt, H., Brigham, T., Chang, S., Clark, J., Conway, A., Couban, R., de Kock, S., Farrah, K., Fehrmann, P., Foster, M., Fowler, S. A., Glanville, J., ... Young, S. (2021). PRISMA-S: an extension to the PRISMA Statement for Reporting Literature Searches in Systematic Reviews. *Systematic Reviews* 2021 10:1, 10(1), 39-. <https://doi.org/10.1186/s13643-020-01542-z>
- Schreier, H., Orteu, J. J., & Sutton, M. A. (2009). Image correlation for shape, motion and deformation measurements: Basic concepts, theory and applications. *Image Correlation for Shape, Motion and Deformation Measurements: Basic Concepts, Theory and Applications*, 1–321. <https://doi.org/10.1007/978-0-387-78747-3>
- Shirmohammadi, M., Yarlagađa Maryam Shirmohammadi, P. K. D. V., & Yarlagađa, P. K. D. V. (2018). Determining of Poisson's Ratio and Young's Modulus of Pumpkin Tissue-Using Laser Measurement Sensors. *Materials Today: Proceedings*, 5(5), 11507–11515. <https://doi.org/10.1016/J.MATPR.2018.02.118>
- Sirisomboon, P., Tanaka, M., & Kojima, T. (2012). Evaluation of tomato textural mechanical properties. *Journal of Food Engineering*, 111(4), 618–624. <https://doi.org/10.1016/j.jfoodeng.2012.03.007>
- Słupska, M., Kuprianiuk, S., Stopa, R., & Figiel, A. (2026). Finite element modeling of apple tissue mechanics: A comparative study of elastic and elastoplastic behavior across ripening stages. *Journal of Food Engineering*, 402. <https://doi.org/10.1016/j.jfoodeng.2025.112696>
- Słupska, M., Stopa, R., & Figiel, A. (2025). Ripening Stage in Mechanical Properties of Chopin Apples for Static FEM Model Construction. <https://doi.org/10.20944/preprints202409.0825.v2>
- Waldron, K. W., Parker, M. L., & Smith, A. C. (2003). Plant Cell Walls and Food Quality. *Comprehensive Reviews in Food Science and Food Safety*, 2(4), 128–146. <https://doi.org/10.1111/j.1541-4337.2003.tb00019.x>
- Xia, X., Xu, Z., Yu, C., Zhou, Q., & Chen, J. (2021). Finite Element Analysis and Experiment of the Bruise Behavior of Carrot under Impact Loading. <https://doi.org/10.3390/agriculture>
- Zulkifli, N., Hashim, N., Harith, H. H., & Mohamad Shukery, M. F. (2020). Finite element modelling for fruit stress analysis - A review. *Trends in Food Science and Technology*, 97, 29–37. <https://doi.org/10.1016/j.tifs.2019.12.029>