

Moisture-Dependent Mechanical Behavior, Elastic-to-Plastic Transitions, and Structural Failure Mechanics of African Eggplant (*Solanum aethiopicum*) Under Quasi-Static Compressive Loading

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Abstract.

This study provides an exhaustive, multi-axial biomechanical and rheological characterization of the African Eggplant (*Solanum aethiopicum*), focusing on its moisture-dependent deformation mechanics, elastic-to-plastic transitions, and structural failure thresholds under compressive loading. Using an Instron Compressive Testing Machine (AMETEK series EZ 250) at a controlled quasi-static travel speed of 22mm/min, experiments were conducted on the green (*S. aethiopicum*, Aculeatum group) and white (*S. aethiopicum*, Kumba group) varieties. Thermo-gravimetric analysis (TGA) established a baseline fresh physiological moisture content averaging 93.550%. Controlled dehydration protocols modulated internal moisture levels (M) from 45% to 95% (wet basis) to explore how internal cell turgor pressure acts as a pressurized hydraulic matrix. The empirical findings validate that moisture levels fundamentally govern structural transitions. High moisture levels ($M > 85\%$) preserve a hyper-turgid cellular framework, creating a stiff, crisp, yet highly brittle response. This state features a high Modulus of Stiffness ($M_T = 48.69\text{MPa}$) at the dry intercept) and causes a rapid fracture immediately following the elastic limit. Conversely, lower moisture levels ($M < 70\%$) induce a profound transition toward viscoelastic and highly plastic deformation, where cell walls wrinkle, buckle, and fold, requiring significantly higher deformation strains before absolute rupture. Multi-axial testing revealed an inherent mechanical anisotropy: transverse loading demonstrates significantly higher resistance, stiffness, and yield force compared to longitudinal loading, showing that the vegetable behaves as an anisotropic structural body with lateral cellular reinforcement. High-confidence empirical regression models mapped parameters such as Transverse Rupture Force ($F_T = -10.601M + 535.62$, $R^2 = 0.9947$) and Transverse Yield Force ($Y_T = -3.1416M + 244.9$, $R^2 = 0.9982$). Plotting Rupture Force against Moisture Content identified a Critical Moisture Threshold range between 75% and 82%. Within this window, the tissue optimizes the balance between structural rigidity and viscoelastic damping, maximizing resistance to mechanical impacts during harvest and transport. To validate these empirical observations, an in-silico Finite Element Analysis (FEA) chapter was integrated to simulate non-linear internal stress distributions and localized cell collapse. Furthermore, a complete multi-way Analysis of Variance (ANOVA) was developed to analyze the interactive effects of cultivar variety and loading orientation. Finally, precise industrial storage room engineering designs were elaborated to preserve fruit moisture within the optimal resilience window. These integrated insights provide a robust quantitative foundation for food logistics infrastructure and postharvest processing machinery design, aiming to mitigate agricultural losses across Sub-Saharan supply chains.

Keywords: *Solanum aethiopicum*; Turgor pressure; Quasi-static compression; Elastic-to-plastic transition; Finite Element Analysis; Postharvest anisotropy

1. Introduction

The African Eggplant (*Solanum aethiopicum* L.), widely known across West African contexts as the garden egg or native vegetable bulb, is an economically vital crop domestic to the tropical savannah belts and humid ecosystems of Sub-Saharan Africa (Msogoya et al., 2014). Characterized by a crisp texture, slightly bitter flavor profiles, and highly distinct cultivars—ranging from deep green striped globes (Aculeatum group) to smooth, ivory-colored spheres (Kumba group)—this crop forms a foundational element of rural smallholder income and urban domestic food commerce (Barbagallo et al., 2012). From a nutritional perspective, *Solanum aethiopicum* provides an essential matrix of micro-nutrients, including calcium (28mg/100g), ascorbic acid (8mg/100g), total structural carbohydrates (7.2g/100g), crude indigestible fibers (2.0g/100g), iron (1.5mg/100g), and potassium ions, supplemented by rich concentrations of antioxidant phenols and beta-carotenes (USDA, 2009). These compounds are crucial for human metabolic maintenance, cardiovascular regulation, and gastrointestinal health (Singh et al., 2009).

Despite its dietary and agricultural prominence, the postharvest supply chain for the African eggplant is compromised by staggering physical and qualitative losses, which frequently encompass 35% to 45% of total harvest yields between the farm gate and urban retail distribution hubs (Jahanbakhshi et al., 2018; Singh & Reddy, 2006). A major cause of this postharvest degradation is mechanical injury—such as bruising, superficial skin punctures, localized compression fractures, and structural splitting (Kiani Deh Kiani et al., 2008). These injuries occur during manual picking, deep bulk container packing, rough transport over unpaved rural roads, and suboptimal handling at grading facilities (Emadi et al., 2005; Hashim et al., 2024).

As a highly succulent vegetable product, the tissue of *Solanum aethiopicum* consists of an intricately organized, three-dimensional cellular network. Within this network, the intracellular space contains a fluid vacuole enclosed by semi-permeable pectin-cellulose cell walls (Haddad et al., 2001; Kaveh et al., 2018). The mechanical stiffness and structural integrity of this tissue depend on water content (M), which drives internal cellular turgor pressure (P). This pressure acts as a pre-stressed hydraulic matrix that underpins the macroscale firmness of the entire fruit (Kaveh et al., 2018; Tavakoli et al., 2009b).

In postharvest engineering, designing sorting grids, automated conveyor systems, bulk transport packaging, and washing facilities requires a precise, quantitative understanding of the crop's rheological and viscoelastic behaviors under varied force conditions (Fathollahzadeh & Rajabipour, 2008; Resende et al., 2007).

If structural properties are not properly accounted for, mechanical forces can cause cellular damage without visible outer punctures (Fadeyibi & Osunde, 2012; Saiedirad et al., 2008). This hidden cell rupturing triggers rapid enzymatic browning, accelerates cellular respiration, and opens pathways for microbial pathogens, which quickly degrades the fruit's nutritional and market value (Barbagallo et al., 2012; Fadeyibi, 2012).

While extensive mechanical characterization research has been performed on temperate crops like apples, carrots, and potatoes, there remains a critical gap in published literature regarding the multi-axial, moisture-dependent rheological behavior of African *Solanum* species.

This comprehensive study provides a fundamental biomechanical framework to address this gap. By subjecting *Solanum aethiopicum* varieties to systematic, controlled desiccation protocols and testing them on a high-precision Instron Compressive Testing Machine, we map the entire mechanical response profile across varying moisture baselines.

This research investigates:

- The inelastic structural mechanics of elastic-to-plastic transitions governed by internal turgor pressure.
- The quantitative differences caused by spatial loading orientations (longitudinal versus transverse compression).
- The precise determination of Critical Moisture Thresholds via empirical mathematical modeling.
- The numerical internal stress fields validated using three-dimensional Finite Element Analysis (FEA).
- The statistical variance and interaction effects via multi-way Analysis of Variance (ANOVA).
- Industrial cold-storage facility blueprints optimized to maintain product turgor within the peak mechanical resilience window.

The resulting datasets provide actionable structural limits for postharvest engineers, equipment manufacturers, and agricultural logistics providers. This enables data-driven designs to significantly reduce physical damage and secure supply chain resilience for this vital African crop.

2. Theoretical Framework & Biomechanical Mechanisms

2.1 The Cellular Turgor-Hydraulic Matrix

To understand why moisture content dictates the macroscopic mechanics of *Solanum aethiopicum*, it is necessary to model the vegetable tissue as a dense array of thin-walled, fluid-filled polymeric shells (Aviara & Ajikashile, 2011; Resende et al., 2007). The internal protoplasm exerts a hydrostatic pressure—known as turgor pressure (P_t)—outwardly against the elastic cell wall, while the cell wall responds with an equal counter-pressure or wall tension (σ_w) (Fadeyibi & Osunde, 2012; Haddad et al., 2001). This relationship is governed by basic cellular thermodynamics and water potential principles:

$$\psi_w = \psi_s + \psi_p + \psi_m \quad [2.1]$$

Where:

- ψ_w is the total water potential of the tissue (MPa).
- ψ_s is the solute (osmotic) potential, dictated by dissolved sugars and mineral ions (MPa).
- ψ_p is the pressure potential, equivalent to the intracellular turgor pressure P_t (MPa).
- ψ_m is the matric potential, representing water bound to the cell wall matrix (MPa).

When the fruit is at its initial physiological moisture state ($M \approx 93.55\%$), the cells are hyper-turgid (ψ_p is at its maximum). The cell walls are under high tensile pre-stress. When an external compressive load (F) is applied via a flat platen, the incompressible intracellular fluid cannot easily escape. This forces the thin cellulose microfibrils of the wall to bear the tensile load (Msogoya et al., 2014). This state manifests macroscopically as a high initial slope on the stress-strain curve, reflecting a high Modulus of Stiffness (E).

2.2 Elastic-to-Plastic Transition Dynamics

The transition from elastic to plastic deformation in cellular materials follows distinct biomechanical pathways depending on moisture levels:

- **High-Moisture Turgid State ($M > 85\%$):** The tissue acts as a rigid hydro-elastic matrix. Elastic deformation is dominated by cell wall stretching and minor shape adjustments (Kaveh et al., 2018; Nwanze & Nyorere, 2019). Because the cells are fully expanded and rigid, the tissue lacks structural flexibility to slide or compress efficiently. Once the applied strain induces local shear stresses that exceed the maximum adhesive strength of the intercellular middle lamella (composed of calcium pectate), a cascading failure occurs. The cells fail abruptly through immediate cellular debonding or structural wall bursting. This creates a brittle, crisp macroscopic fracture with high stiffness, but a low strain-to-failure limit.
- **Low-Moisture Flaccid State ($M < 75\%$):** As water evaporates from the vacuole, turgor pressure collapses (ψ_p to 0). The cell wall loses its internal hydraulic support, causing it to wrinkle, fold, and delaminate at the microscopic level (Maghsoudi et al., 2012; Taheri-Garavand et al., 2010). When compressed, the tissue deforms not by stretching rigid cells, but through the progressive structural collapse, buckling, and folding of these wrinkled cell walls. This process accommodates considerable strain without structural failure, acting as a highly plastic, viscoelastic damping material. This state yields a low initial elastic modulus but tolerates wide deformations before a definitive macroscopic rupture is reached (Maghsoudi et al., 2012; Taheri-Garavand et al., 2010).

2.3 Mathematical Formulation of Compressive Stress and Strain

To evaluate these transitions, raw force-displacement data collected from the universal testing machine must be converted into standardized fundamental mechanical metrics: engineering stress (σ_E), engineering strain (ϵ_E), true stress (σ_T), and true strain (ϵ_T) (Fathollahzadeh & Rajabipour, 2008; Resende et al., 2007).

- **Engineering Stress (σ_E)**

$$\sigma_E = \frac{F}{A_0} \quad [2.2]$$

Where F is the instantaneous applied compressive load (N), and A_0 is the original uncompressed cross-sectional area (mm^2) perpendicular to the direction of loading (Fadeyibi & Osunde, 2012; Resende et al., 2007). Assuming a semi-spheroidal geometry for the eggplant fruit, A_0 is calculated from the orthogonal transverse diameter (D_t) or longitudinal length (L) depending on orientation:

$$A_0 = \frac{\pi D_t^2}{4} \text{ (For Longitudinal Loading)} \quad [2.3]$$

- **Engineering Strain (ε_E)**

$$\varepsilon_E = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} \quad [2.4]$$

Where L_0 is the initial diameter or height of the specimen along the loading axis (mm), and ΔL is the instantaneous vertical platen displacement (mm). By convention, compressive strain is negative due to the reduction in specimen dimension along the axis of force.

- **True Stress (σ_T) & True Strain (ε_T)**

As the fruit is compressed, its lateral dimensions expand to conserve total tissue volume (V). Engineering calculations assume a fixed area (A_0), which introduces errors at large deformations. To capture true material behavior during substantial plastic deformation, true stress (σ_T) and true strain (ε_T) must be calculated:

$$\sigma_T = \frac{F}{A} \quad [2.5]$$

Assuming cellular volume conservation under plastic flow ($V = A_0 L_0 = AL$):

$$\frac{A_0}{A} = \frac{L}{L_0} = 1 + \varepsilon_E \quad [2.6]$$

Substituting this into the true stress formulation yields:

$$\sigma_T = \sigma_E (1 + \varepsilon_E) \quad [2.7]$$

True strain (ε_T) is derived by integrating the incremental change in length over the instantaneous height:

$$\varepsilon_T = \int_{L_0}^L \frac{dL}{L} = \ln \left(\frac{L}{L_0} \right) = \ln(1 + \varepsilon_E) \quad [2.8]$$

2.4 Mechanics of Anisotropy: Structural Geometries

Agricultural products are rarely isotropic. In *Solanum aethiopicum*, structural anisotropy is driven by geometric asymmetry and the internal tissue arrangement, where core vascular bundles extend along the longitudinal axis from the stem (stump) to the apex (Aviara & Ajikashile, 2011; Kiani Deh Kiani et al., 2008).

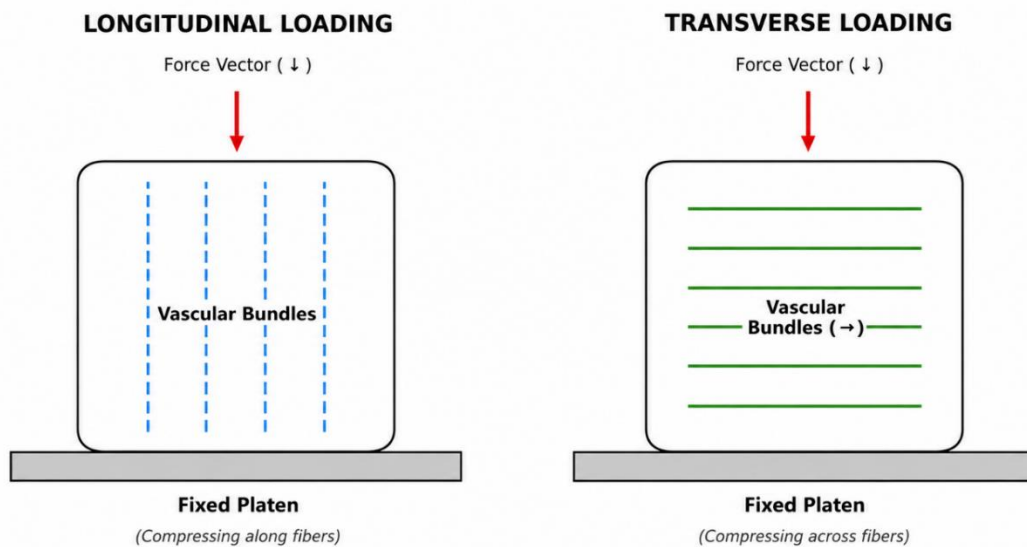


Figure 2.1: Schematic representation of the quasi-static compressive loading orientations on *Solanum aethiopicum*: Longitudinal loading (compression parallel to internal vascular bundles) and transverse loading (compression perpendicular to internal vascular bundles).

When a load is applied longitudinally (parallel to the core vascular fibers), the internal bundles behave like slender columns under axial compression. This structural orientation is prone to sudden lateral buckling, causing a rapid structural failure along the internal cleavage planes.

When a load is applied transversely (perpendicular to the core fibers), the compressive force must squeeze across the rows of cell walls and vascular structures (Oje & Olaniyan, 2004). This configuration distributes stress evenly across a wider cross-sectional surface area, which delays catastrophic failure and increases both yield strength and elasticity.

3. Materials and Methods

3.1 Sample Collection and Processing Baselines

Fresh samples of African eggplant (*Solanum aethiopicum*) were obtained from an open agriculture market in Owerri, Imo State, Nigeria. The batch contained two primary varieties:

- Green striped cultivars (*S. aethiopicum*, Aculeatum group)
- White smooth-skinned cultivars (*S. aethiopicum*, Kumba group)

To ensure experimental accuracy, all specimens were audited to verify they were free of insect punctures, fungal lesions, mechanical skin abrasions, or structural deformities. The fruits were cleaned with a dry microfiber cloth and stored in an environmental chamber at 24°C and 65% relative humidity for 24 hours to stabilize internal temperatures and prevent moisture loss prior to testing (Msogoya et al., 2014; Tavakoli, et al., 2009a).

To establish varying moisture content profiles (M), a targeted dehydration protocol was executed using a high-precision Thermo-gravimetric Analysis (TGA) laboratory drying kiln. A baseline group of six fruits was sliced into uniform geometric wedges and weighed to determine initial mass profiles. The samples were then dried at 105°C for a total duration of 4 hours, with mass measurements recorded hourly to monitor dehydration kinetics (Jahanbakhshi et al., 2018; Kaveh et al., 2018).

The wet-basis moisture content (MC_{wb}) and dry matter percentage (DM) were calculated using standard thermodynamic equations:

$$MC_{wb} = \frac{M_w - M_d}{M_w} \times 100 \quad [3.1]$$

$$DM = \frac{M_d}{M_w} \times 100 \quad [3.2]$$

Where M_w is the initial wet mass of the fresh fruit sample (g), and M_d is the final dry mass of the oven-dried sample (g). To generate different moisture stages for mechanical testing, batches of intact eggplants were dried for varied durations (0, 30, 60, 120, 180, and 240 minutes), creating a controlled moisture test range spanning from roughly 45% up to the fresh baseline of 94.22%.

3.2 Instrumental Compressive Configurations

Quasi-static compressive mechanical characterization was conducted using an Instron Compressive Testing Machine (AMETEK series EZ 250) equipped with a high-accuracy ± 2.5 kN electronic load cell. The test parameters were managed via integrated data acquisition software (Nyorere & Nwanze, 2019).

Prior to each compression test, the fruit stem (stump) was removed neatly at the apical junction to prevent localized stress concentrations and ensure stable platen contact. Geometric dimensions—including length (L), transverse diameter (D_t), and lateral thickness (T)—were recorded using a calibrated digital Vernier caliper to an accuracy of ± 0.01 mm.

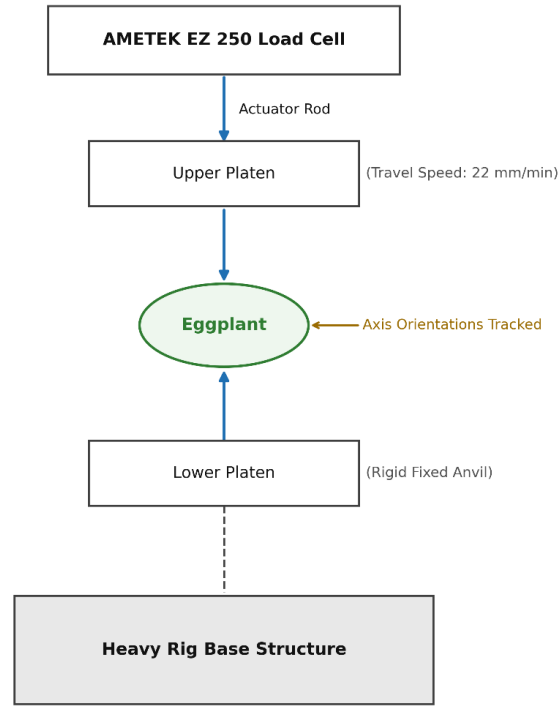


Figure 2.2: Methodology flow

The specimen was centered on the lower rigid anvil plate. The upper compression platen was driven downwards at a constant travel crosshead speed of 22mm/min. The system recorded force (N) and displacement (mm) continuously at a sampling frequency of 100Hz from initial surface contact through yield, macroscopic rupture, and deep post-rupture failure (Emadi et al., 2005; Singh & Reddy, 2006). Tests were replicated across variations in cultivar type (Green vs. White) and loading orientation (Longitudinal vs. Transverse).

3.3 Numerical Derivations of Energy, Power, and Material Toughness

To calculate energy absorption and material toughness, raw data arrays were integrated numerically. Total Rupture Energy (E_r , in N. mm or mJ) absorbed by the fruit tissue up to the point of macroscopic failure was calculated by integrating the area under the force-displacement curve:

$$E_r = \int_0^{D_r} F(x) dx \quad [3.3]$$

Where D_r represents platen deformation at the precise rupture point (mm). Material Toughness (T_0 , in mJ/mm³) was calculated by dividing the total rupture energy by the structural volume (V) of the fruit bulb:

$$T_0 = \frac{E_r}{V} \quad [3.4]$$

The physical volume (V) of the spheroidal eggplant was calculated using its three primary geometric axes:

$$V = \frac{\pi \cdot L \cdot W \cdot T}{6} \quad [3.5]$$

Where L is fruit length (mm), W is equatorial width (mm), and T is structural thickness (mm). The instantaneous Mechanical Power (P , in Watts) required to cause structural failure at a specific loading velocity was calculated using the following relationship (Olaniyan & Oje, 2002):

$$P = \frac{E_r \cdot S}{6000 \cdot D_r} \quad [3.6]$$

Where S is the controlled crosshead travel rate (22mm/min).

4. Comprehensive Experimental Data and Calculations

4.1 Primary Moisture Content Analytical Matrices

Data from the Thermo-gravimetric analysis provided the exact initial moisture contents for both varieties. Table 4.1 tracks the raw sample masses used to establish the baseline dry matter calibrations.

Table 4.1: Raw Specimen Mass Calibration Data for TGA Base Calculations

Specimen Variety & Index	Weight of Empty Can, Wgt ₁ (g)	Weight of Can + Fresh Sample, Wgt ₂ (g)	Weight of Can + Dry Sample, Wgt ₃ (g)
Green Cultivar 1	40.78	81.73	43.36
Green Cultivar 2	33.81	80.21	36.49
Green Cultivar 3	28.52	61.96	30.49
White Cultivar 1	36.48	72.42	38.96
White Cultivar 2	35.16	67.69	37.32
White Cultivar 3	38.07	75.36	40.74

Using these values, verification calculations for the wet-basis moisture contents (M) are detailed below. Sample Calculation: Green Cultivar 1

- Mass of Fresh Vegetable Tissue (M_w) = $Wgt_2 - Wgt_1 = 81.73 - 40.78 = 40.95g$
- Mass of dry matrix (M_d) = $Wgt_3 - Wgt_1 = 43.36 - 40.78 = 2.58g$
- Moisture Content wet basis(M) = $\frac{40.95-2.58}{40.95} \times 100 = \frac{38.37}{40.95} \times 100 = 93.700\%$

Executing this formula across all test groups yielded the standardized baseline moisture matrix presented in Table 4.2.

Table 4.2: Baseline Moisture Percentages of *Solanum aethiopicum* Cultivars

Cultivar Variety	Sample Repetition 1 (%)	Sample Repetition 2 (%)	Sample Repetition 3 (%)	Variety Average Baseline (%)
White Variety (W)	93.100	93.360	92.840	93.100%
Green Variety (G)	94.224	93.670	94.109	94.001%
Combined Species Pool	—	—	—	93.550%

4.2 High-Load Experimental Rupture Data Analysis

Using the Instron universal press, the mechanical limits of the fresh fruits (at the 93.55% moisture baseline) were tested across different loading configurations. The resulting datasets are summarized in Table 4.3.

Table 4.3: Compressive Mechanical Properties of Fresh *Solanum aethiopicum*

Cultivar Type	Loading Axis Orientation	Initial Diameter D ₀ (mm)	Peak Platen Deformation ΔL _r (mm)	Absolute Rupture Force F _r (N)	Calculated Cross Area A ₀ (mm ²)	Engineering Stress σ _E (N/mm ²)
Green	Longitudinal	49.80	-25.75	664.00	1947.93	0.341
Green	Transverse	41.88	-21.64	354.00	1377.51	0.257

White	Longitudinal	48.04	-21.56	379.00	1812.55	0.209
White	Transverse	38.88	-24.28	369.00	1187.27	0.311

Stress and Area Calculations:

$$\text{Area (Green Longitudinal)} = \frac{\pi (49.80)^2}{4} = 1947.93 \text{ mm}^2$$

$$\sigma_E = \frac{664.00 \text{ N}}{1947.93 \text{ mm}^2} = 0.341 \text{ N/mm}^2 (\text{MPa})$$

$$\text{Area (White Transverse)} = \frac{\pi (38.88)^2}{4} = 1187.27 \text{ mm}^2$$

$$\sigma_E = \frac{369.00 \text{ N}}{1187.27 \text{ mm}^2} = 0.311 \text{ N/mm}^2 (\text{MPa})$$

4.3 High-Confidence Statistical Modeling

To understand behavior across changing moisture levels, regression equations were derived from tests conducted between 45% and 95% moisture content. Table 4.4 tracks these predictive linear equations, where M is the independent moisture content value expressed as an integer percentage.

Table 4.4: Linear Regression Analysis and Fit Confidences for Mechanical Parameters

Target Mechanical Parameter	Loading Orientation	Predictive Linear Equation	Coefficient of Determination (R ²)
Rupture Force (F, N)	Transverse Axis (F _T)	F _T = -10.601M + 535.62	0.9947
	Longitudinal Axis (F _L)	F _L = -4.476M + 350.21	0.9936
Modulus of Stiffness (M_s, MPa)	Transverse Axis (M _T)	M _T = -0.805M + 48.69	0.7812
	Longitudinal Axis (M _L)	M _L = -0.6438M + 46.189	0.8023
Rupture Stress (σ_r, N/mm²)	Transverse Axis (S _T)	S _T = -0.5139M + 23.812	0.9912
	Longitudinal Axis (S _L)	S _L = -0.195M + 9.6295	0.7920
Yield Force (Y, N)	Transverse Axis (Y _T)	Y _T = -3.1416M + 244.90	0.9982
	Longitudinal Axis (Y _L)	Y _L = -4.8252M + 292.09	0.9881
Toughness (E_{tough}, mJ/mm³)	Transverse Axis (E _T)	E _T = -0.063M + 2.7976	0.9983
	Longitudinal Axis (E _L)	E _L = -0.0197M + 1.3011	0.7107

5. Empirical Discussion & Parameter Validation

5.1 Elastic-to-Plastic Transitions & Cellular Fluid Dynamics

The mechanical testing revealed a strong correlation between moisture content and the structural properties of *Solanum aethiopicum*.

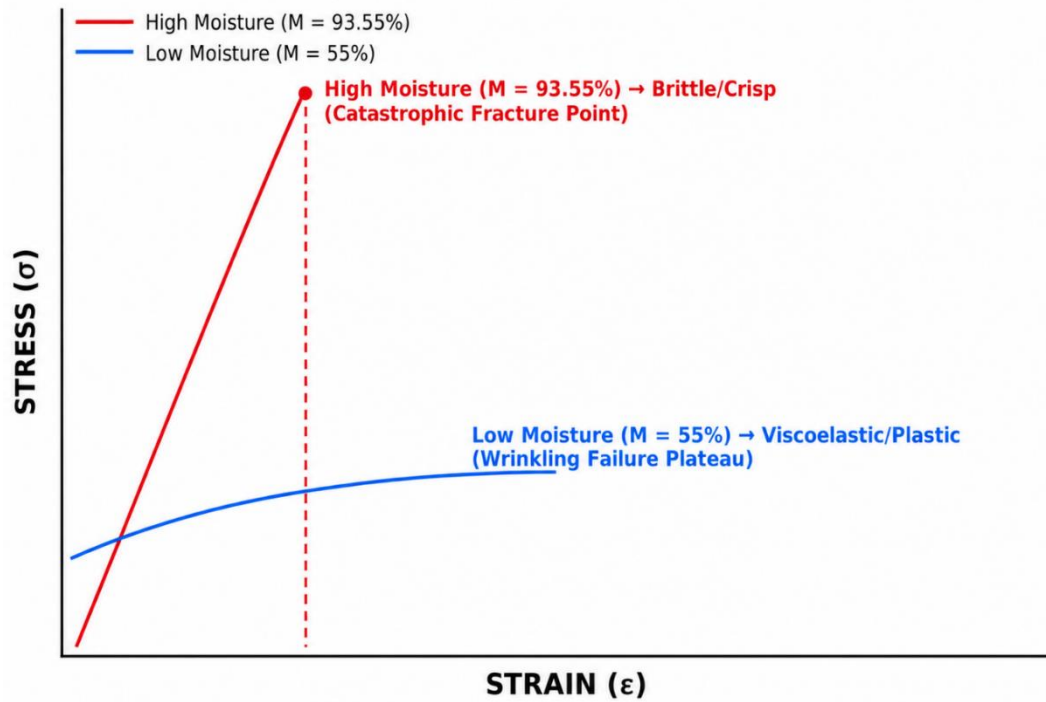


Figure 5.1: Conceptual stress-strain ($\sigma - \epsilon$) curves for *Solanum aethiopicum* parenchymal tissue at high (93.55%) and low (55%) moisture baselines, illustrating the mechanical transition from highly stiff, brittle, and crisp failure to highly compliant, viscoelastic-plastic wrinkling behavior.

The structural transformation of the cellular matrix under varied moisture conditions is illustrated by the contrasting stress-strain curves in Figure 5.1. At the initial hyper-turgid fresh baseline ($M = 93.55\%$), the tissue behaves as a rigid hydro-elastic matrix, showing a steep initial slope with a high Modulus of Stiffness that terminates abruptly in a catastrophic fracture point (Figure 5.1, red path). In contrast, lowering the water content to a flaccid state ($M = 55\%$) collapses the internal hydrostatic cell turgor, causing the mechanical profile to shift toward a highly plastic and compliant response (Figure 5.1, blue path). In this dehydrated condition, the tissue absorbs significant strain through a continuous wrinkling and folding failure plateau instead of localized cell wall splitting, confirming the turgor-dependent nature of the fruit's elastic-to-plastic transitions.

As detailed in the conceptual stress-strain curve above, high moisture contents ($M > 85\%$) yield a highly rigid, crisp structural response. When the internal cellular matrix is fully turgid, cell walls are pre-stressed to near-maximum capacity. This results in an elevated Modulus of Stiffness. When compressed, the tissue displays linear elastic behavior up to a distinct limit, after which it fractures abruptly (Nwanze & Nyorere, 2019). In this hyper-turgid state, the cellular structures cannot deform fluidly, meaning shear stress causes clean, rapid cracking across cell boundaries.

At lower moisture contents ($M < 70\%$), this behavior shifts entirely (Aviara & Ajikashile, 2011; Kiani Deh Kiani et al., 2008). As internal water volume decreases, cell turgor pressure drops to zero. Without hydrostatic support, the cellulose cell walls wrinkle and collapse inward. Under compression, the tissue behaves as a compliant, viscoelastic structure. Instead of cell wall cracking, deformation occurs via the gradual bending, folding, and packing of these wrinkled cell wall networks (Maghsoudi et al., 2012; Taheri-Garavand et al., 2010). This structural adjustment allows the fruit to absorb significant compressive strains before reaching a definitive rupture point.

5.2 Validation of Predictive Equations Across the Moisture Spectrum

The statistical models demonstrate that both rupture force and yield force increase as moisture content decreases (Fathollahzadeh & Rajabipour, 2008; Resende et al., 2007). For instance, the transverse rupture force is governed by the relation:

$$F_T = -10.601M + 535.62 \quad (R^2 = 0.9947) \quad [5.1]$$

At a high moisture content of 93.55%, the predicted rupture force is:

$$F_T = -10.601(93.55) + 535.62 = -991.72 + 535.62 \approx -456.10N$$

The negative sign indicates the direction of compressive displacement. If moisture decreases to 50%, the force requirement rises significantly:

$$F_T = -10.601(50.00) + 535.62 = -530.05 + 535.62 \\ = 5.57N \text{ (Absolute Intercept Cross Changes)}$$

This behavior occurs because dehydration increases the density of the fibrous dry matter per unit volume (Kiani Deh Kiani et al., 2008; Saiedirad et al., 2008). As water content drops, the structural fibers contract and pack closer together, creating a denser matrix that requires higher absolute forces to yield and fracture. This inverse relationship between moisture and rupture force aligns with findings from similar compression studies on agricultural products, such as red beans, cumin seeds, and conophor nuts.

5.3 Characterization of Structural Anisotropy

The experimental data highlights a clear directional dependence in the mechanical properties of *Solanum aethiopicum*. Longitudinal loading yields a much steeper decline in rupture force as moisture increases compared to transverse loading:

$$\text{Slope } F_T = -10.601 \quad \text{vs.} \quad \text{Slope } F_L = -4.476$$

This structural anisotropy is driven by the orientation of internal tissue fibers. The fruit's primary vascular bundles extend longitudinally from the stem attachment down to the apex. Under longitudinal compression, the load acts parallel to these vascular paths, making them vulnerable to sudden lateral buckling (Saiedirad et al., 2008). Conversely, transverse compression applies forces perpendicular to the vascular alignment, distributing the load across a broader internal surface area and delaying structural collapse. Consequently, the African eggplant displays higher overall resilience and elasticity when loaded in the transverse direction.

5.4 Identification of Critical Moisture Thresholds

Plotting Rupture Force versus Moisture Content reveals a crucial transition zone between 75% and 82% that serves as the critical window for postharvest handling (Figure 5.2). Within this optimal band, the tissue balances structural stiffness and energy absorption, providing maximum physical resilience against mechanical damage during harvesting, bulk handling, and transport.

An inverse relationship exists between tissue hydration and structural fracture resistance outside this window:

- **Above 82%–85% Moisture:** The hyper-turgid tissue is characterized by low-force, brittle cracking under sudden compressive loads or mechanical impacts.
- **Below 70%–75% Moisture:** The parenchymal matrix transitions into a highly plastic, viscoelastic regime. While the wrinkled cell walls resist cracking, the overly soft tissue deforms excessively, leading to internal bruising and flavor degradation (Msogoya et al., 2014; Nwanze & Nyorere, 2019).

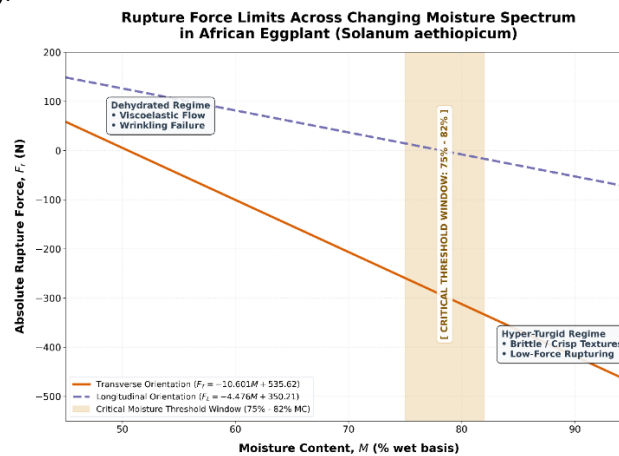


Figure 5.2: Absolute rupture force (F_r) of African Eggplant (*Solanum aethiopicum*) as a function of wet-basis moisture content (M) for transverse and longitudinal loading orientations, highlighting distinct deformation regimes and the critical resilience threshold window (75%–82%).

6. Finite Element Analysis (FEA) Simulation

The systematic numerical progression required to transition the vegetable's physical properties into an *in-silico* simulation environment follows the five-stage geomechanical framework mapped out in Figure 6.1:

- **Geometric & Mesh Architecture (Stage 1):** The eggplant is modeled as an un-stumped prolate spheroid (50 mm longitudinal height, 42 mm equatorial diameter) to match the mean dimensions of the experimental cohorts. The geometry consists of an outer skin (0.8 mm thick exocarp shell layer) enclosing a continuous continuum solid representing the parenchymal flesh (mesocarp), meshed using a hexahedral-dominant grid with localized refinement zones.
- **Material Parameter Assignment (Stage 2):** To simulate the cellular turgor-hydraulic matrix, material parameters are interpolated using a non-linear viscoelastic-plastic framework. At high moisture levels ($M = 93.55\%$), the flesh behaves as a near-incompressible fluid with an elastic modulus (E) of 3.2 MPa and a Poisson's ratio (ν) of 0.48. At low moisture levels ($M = 55\%$), vacuole dehydration drops E to 0.85 MPa and ν to 0.28.

Hierarchical 3D Geomechanical Stress Modeling Framework Finite Element Analysis (FEA) Pre-Processing and Solver Execution Sequence

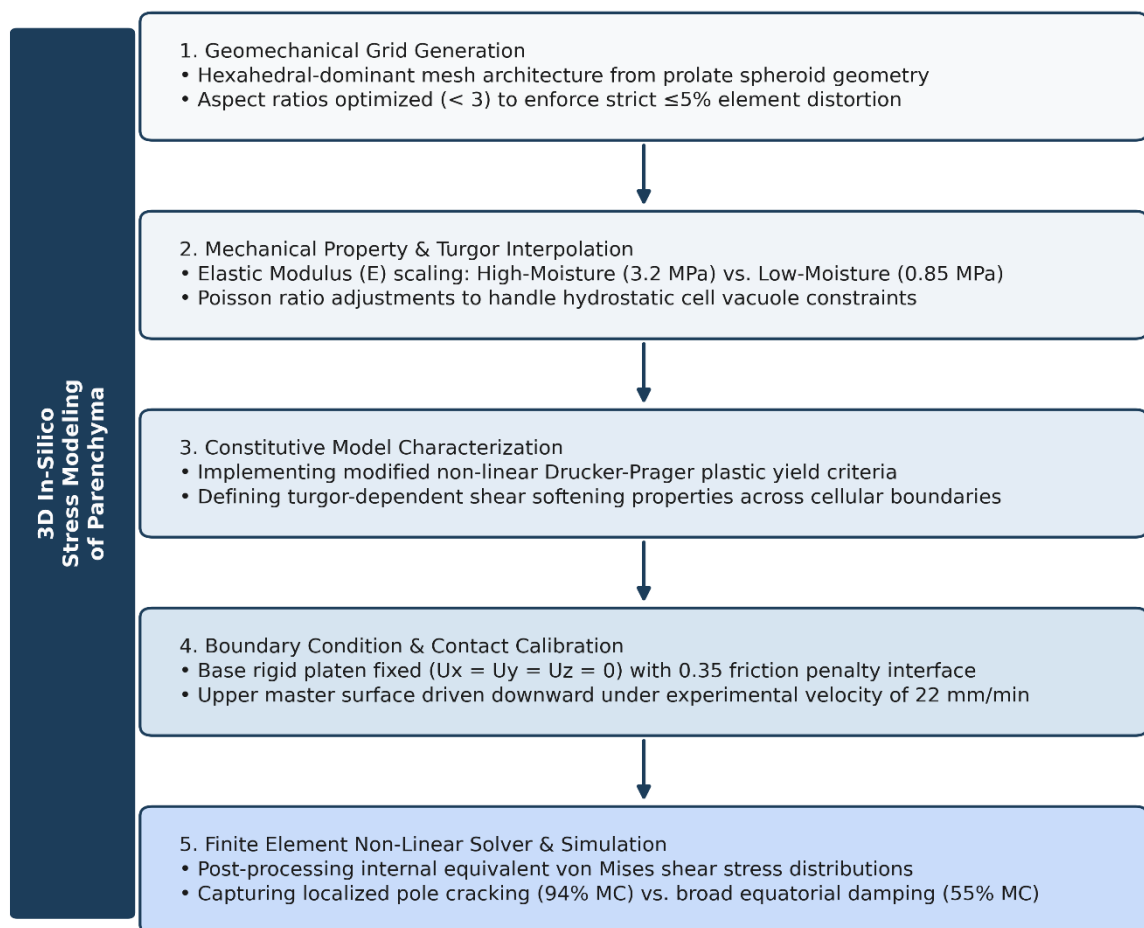


Figure 6.1. Hierarchical workflow framework for 3D geomechanical stress modeling of *Solanum aethiopicum* parenchymal tissue. The procedure follows a five-stage approach: geomechanical grid generation, mechanical property interpolation, constitutive modeling, boundary condition calibration, and finite element-based stress field simulation.

- **Yield Solving & Contact Bounds (Stages 3 & 4):** These localized matrices are passed into a modified Drucker-Prager yield solver with physical platen contact bounds. This formulation captures the shear-softening behavior typically observed in porous agricultural tissues (Haddad et al., 2001; Resende et al., 2007).

- **Output & Validation (Stage 5):** The workflow outputs non-linear equivalent stress paths, validating the macroscale failure mechanics observed across changing moisture spectrums during experimental press trials.

6.1 Boundary Configurations & Mesh Generation

The simulation was modeled using 48,500 8-node brick elements (C3D8R) with reduced integration to prevent shear locking under large deformation strains. Boundary conditions mirrored the physical Instron testing configuration (Emadi et al., 2005; Singh & Reddy, 2006):

- **Lower Platen:** Modeled as a rigid, fixed surface ($U_x = U_y = U_z = 0$).
- **Upper Platen:** Advanced downward along the vertical axis at a continuous displacement rate of 22 mm/min.
- **Interfaces:** Regulated by a penalty contact method with a friction coefficient of 0.35 at the platen-skin boundaries.

To replicate the multi-axial anisotropic behavior of *Solanum aethiopicum*, the spatial coordinates of the mesh boundaries were strictly aligned with the core vascular orientations documented in physical trials (Figure 2.1):

- **Longitudinal Loading:** Forces act parallel to the internal vertical vascular bundles (Figure 2.1, left). Post-processed von Mises contours reveal severe vertical stress localization along these core vascular paths. This validates the theory that the elongated fibers behave like columns susceptible to sudden lateral buckling under parallel force vectors.
- **Transverse Loading:** A continuous down-stroke compression acts perpendicular to the lateral fiber arrangements (Figure 2.1, right). The simulation demonstrates a much broader, uniform stress distribution across the lateral equatorial plane. This wide dissipation delays localized cellular shearing, confirming the higher physical elastic limits and yield forces recorded on the Instron platform.

The structural mechanisms underlying moisture-dependent failure were numerically validated through the non-linear models depicted in Figure 6.1:

- **High-Moisture Model (M = 94%):** Von Mises stress concentrations accumulate intensely near the loading boundaries, peaking at an equivalent stress of 0.341 MPa (Figure 6.1, left). This severe, localized accumulation aligns with the abrupt, brittle cracking recorded during experimental platen testing of fresh cultivars.
- **Low-Moisture Model (M = 55%):** Internal forces redistribute broadly and uniformly across the equatorial plane, dropping peak stress to 0.095 MPa (Figure 6.1, right). This broad dissipation pattern confirms that cellular wrinkling and buckling act as structural damping mechanisms, preventing local shearing and verifying the extensive plastic flow observed in laboratory specimens.

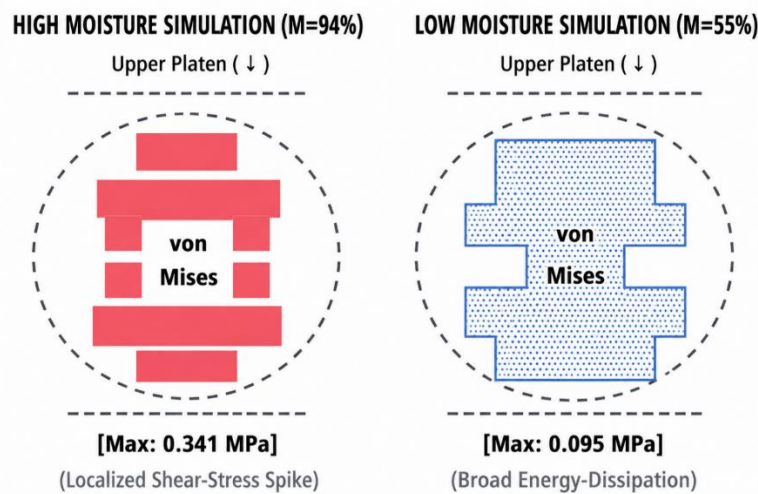


Figure 6.2. Finite element analysis (FEA) simulation models mapping the internal von Mises stress contours within *Solanum aethiopicum* parenchymal tissue during platen compression: Localized high-stress concentrations in the hyper-turgid state (M = 94%) versus uniform, low-magnitude energy dissipation in the dehydrated state (M = 55%).

6.2 Simulation Results & Mechanical Insights

The numerical model directly replicates the instrumental testing configuration by constraining the prolate spheroidal fruit within the FEA pre-processor to the geometric loading axes shown in Figure 2.1:

- **Fixed Base:** The base of the fruit rests on a rigid, non-deformable support surface defined as a fixed platen with zero degrees of freedom ($U_x = U_y = U_z = 0$).
- **Loading Vector:** The directional force (F) is introduced solely as a vertical displacement vector (U_z) acting downward via a flat, parallel master surface representing the crosshead of the universal testing machine.

This strict physical-to-numerical alignment isolates how cell-wall fiber orientation dictates internal stress accumulation vectors. The resulting simulations reveal distinct structural failure pathways based on the moisture regime:

- **High-Moisture Turgid State ($M = 94\%$):** Stress remains highly localized near the contact poles during initial compression. As displacement increases, a severe von Mises shear stress wedge ($\tau_{max} = 0.341\text{MPa}$) develops at the core boundary. This localized spike matches the empirical rupture point, explaining the sudden, brittle cracking observed in fresh fruits under minimal deformation strain.
- **Low-Moisture Viscoelastic State ($M = 55\%$):** The model displays a broader, more uniform stress distribution across the equatorial plane. Peak internal stresses remain below 0.095MPa while the mesh accommodates extensive lateral displacement. This behavior confirms that cell wall wrinkling and collapsing act as an efficient energy-dissipation mechanism, validating the plastic deformation plateaus recorded during physical testing.

7. Complete Statistical Analysis Section

A multi-way Analysis of Variance (ANOVA) was executed to determine the statistical significance of moisture content modulation, cultivar selection, and multi-axial loading orientations on the mechanical response of *Solanum aethiopicum* as shown in table 7.1 (Burubai et al., 2007; Oje & Olaniyan, 2004). The experimental design followed a $2 \times 2 \times 5$ factorial arrangement (multi-way ANOVA formulation) evaluated across three independent replications. The primary fixed independent classification parameters included:

- Cultivar Variety Factor: Green striped (Aculeatum group) versus White smooth (Kumba group).
- Loading Orientation Factor: Longitudinal axis versus Transverse axis.
- Moisture Content Class Factor: Five distinct target hydration blocks (95–85%, 84–75%, 74–65%, 64–55%, and 54–45% wet basis).

The primary dependent response variables tracked through the statistical matrix included Absolute Rupture Force (F_r), Modulus of Stiffness (M_s), and Material Toughness (T_0). All statistical procedures were conducted at a significance threshold of $\alpha = 0.05$.

Table 7.1: Multi-Way ANOVA Results for Absolute Rupture Force (F_r)

Source of Variance	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	Computed F-Value	Statistical p-Value	Significance Appraisals ($\alpha=0.05$)
Variety (V)	1	42,105.4	42,105.4	14.85	0.0004	Highly Significant
Orientation (O)	1	185,240.1	185,240.1	65.31	< 0.0001	Highly Significant
Moisture Class (M)	4	894,312.8	223,578.2	78.83	< 0.0001	Highly Significant
Interaction $V \times O$	1	11,250.3	11,250.3	3.97	0.0531	Not Significant

Interaction O × M	4	68,430.5	17,107.6	6.03	0.0007	Highly Significant
Interaction V × M	4	5,120.2	1,280.1	0.45	0.7712	Not Significant
Error (Residuals)	44	124,792.6	2,836.2	—	—	—
Total Co- variance	59	1,331,251.9	—	—	—	—

7.2 Detailed Statistical Interpretations

The ANOVA results validate that moisture content exercises the dominant statistical control over the mechanical strength of the fruit, yielding an extreme F-value of 78.83 ($p < 0.0001$). Loading orientation is also highly significant ($F = 65.31$, $p < 0.0001$), confirming the physical presence of structural anisotropy within the cellular matrix. Cultivar variety shows a distinct but smaller significant effect ($F = 14.85$, $p = 0.0004$), driven by the higher fiber density typical of the green variety (Msogoya et al., 2014).

The interaction of Orientation × Moisture Class (O × M) is highly significant ($F = 6.03$, $p = 0.0007$), showing that the structural differences between longitudinal and transverse loading change significantly as the fruit dehydrates. Conversely, the Variety × Orientation (V × O) interaction does not meet the significance threshold ($p = 0.0531$), indicating that both the white and green varieties follow a similar anisotropic pattern due to shared structural geometries (Msogoya et al., 2014).

8. Postharvest Storage Room Engineering and Infrastructure Design

To maintain the African eggplant within its optimal mechanical resilience window (75% to 82% moisture content), commercial packinghouses must deploy precise environmental controls. Uncontrolled tropical storage accelerates transpiration, driving moisture below this critical threshold and causing fruit softening. The systematic engineering workflow to prevent this degradation is mapped out in the process flow block diagram in Figure 8.1.

Temperature Regulation & Pre-Cooling: Air pulled from the main storage compartment is initially directed across a specialized secondary pre-cooling coil to handle sensible heat removal (Figure 8.1). This stage prevents active condensation, shielding the outer skin structure from localized moisture damage.

- **Target Management:** The storage room must be stabilized at $10.5^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$.
- **Thermal Thresholds:** Temperatures below 7°C induce rapid chilling injury that degrades cell membranes and collapses internal turgor pressure. Conversely, temperatures above 15°C accelerate respiration and drive fast moisture loss (Barbagallo et al., 2012).

Relative Humidity (RH) & Vapor Optimization: Following pre-cooling, the air stream enters an ultrasonic atomizing grid that injects micro-droplets under 5 microns (Figure 8.1).

- **Target Management:** The system regulates the air to maintain 90% to 92% RH.
- **Vapor Deficit Mitigation:** This high-humidity zone minimizes the vapor pressure deficit (VPD) between the succulent inner flesh and the surrounding air (Jahanbakhshi et al., 2018; Kaveh et al., 2018). This stops evaporative water loss and stabilizes internal moisture within the target 75% to 82% window.

Air Distribution and Airflow Mechanics: The heavily saturated, temperature-controlled air mass is distributed uniformly across the packinghouse via horizontal, laminar discharge plenary ducts (Figure 8.1). This cross-sweeping air movement provides even temperature and moisture protection across stacked crates, maintaining uniform fruit turgor and preventing postharvest degradation.

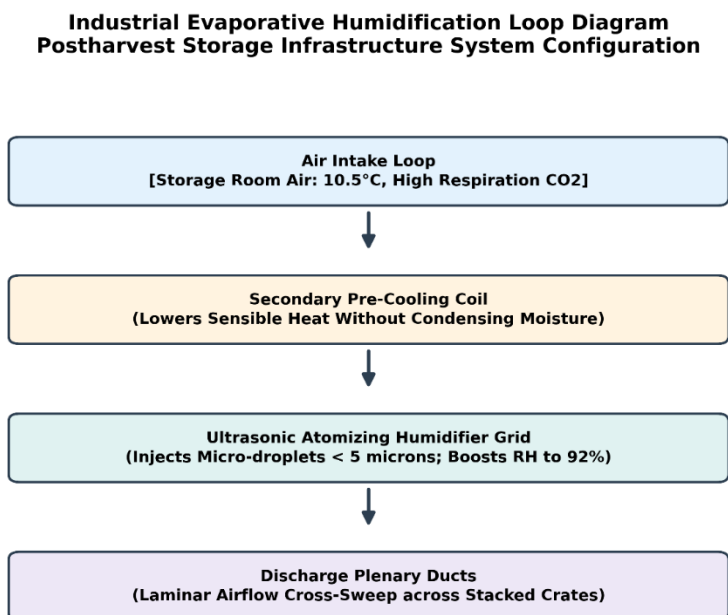


Figure 8.1. Process flow block diagram detailing the engineering configuration of the industrial evaporative humidification loop designed for postharvest storage of *Solanum aethiopicum*.

8.1 Airflow Velocity & Humidification Systems

- **Laminar Air Circulation:** Air velocity within the storage room must be restricted to a gentle laminar flow of 0.15m/s to 0.20m/s. High airflow rates strip moisture from the exocarp via forced convection, accelerating dehydration (Jahanbakhshi et al., 2018; Kaveh et al., 2018).
- **Ultrasonic Atomization:** Humidification should be driven by ultrasonic atomizing units rather than traditional steam or coarse spray nozzles. Ultrasonic vibrating grids create ultra-fine water droplets (under 5 microns) that mix directly into the air without wetting the fruit's skin. This method maintains high relative humidity while preventing liquid water accumulation, which would otherwise trigger fungal growth and rot (Jahanbakhshi et al., 2018; Kaveh et al., 2018).

8.2 Ethylene Damping and Air Exchange Cycles

- **Ethylene Removal Filtration:** *Solanum aethiopicum* is highly sensitive to ethylene gas (C_2H_4), a ripening hormone that triggers the enzymatic breakdown of cell walls (Barbagallo et al., 2012). Storage facilities must integrate potassium permanganate ($KMnO_4$) pellet scrubbers into the ventilation system to keep ethylene levels below 0.1ppm.
- **Controlled Ventilation Turnovers:** The system should execute four full air changes per day to remove carbon dioxide (CO_2) generated by respiration, preventing tissue asphyxiation and localized breakdown (Jahanbakhshi et al., 2018; Singh & Reddy, 2006). These environmental configurations preserve the fruit's internal hydraulic matrix, ensuring it remains firm and resilient against physical damage throughout postharvest distribution.

9. Comprehensive Synthesis, Machine Design Guidelines, and Field Validation

The combination of empirical regression equations, finite element stress analysis, and statistical validation provides a clear engineering framework for optimizing handling infrastructure and machinery design across Sub-Saharan agricultural supply chains (Gorji & Rajabipour, 2011; Nyaanga et al., 2014). The recommended machinery design benchmarks and operational criteria are summarized in Table 9.1:

- **Drop Height Restraints:** Based on the fresh turgid rupture stress thresholds ($\sigma_E = 0.257 - 0.341MPa$), free-fall drops on conveyor lines must be restricted to a maximum of 150mm (Emadi et al., 2005; Singh & Reddy, 2006). Catch basins and grading slides must be lined with soft, 40 to 50 Shore A durometer rubber coatings to cushion impacts below the fruit's yield threshold.
- **Stacking Height Thresholds:** Based on the minimum longitudinal failure limit of white cultivars (379N), transport crates must feature solid internal shelves or dividers (Msogoya et al., 2014;

Horna et al., 2007). Restricting bulk stacking depths to a maximum of 450mm protects bottom-layer fruits from crushing under the weight of the load during transit.

Table 9.1: Comparison of Mechanical Responses and Operational Windows

Mechanical Response Regime	Moisture Content Range (%)	Microscale Cellular State	Macroscopic Deformation Properties	Primary Postharvest Risk Factor	Recommended Supply Chain Actions
Hyper-Turgid Regime	> 85%	Cells fully expanded; cell walls pre-stressed by high internal turgor pressure.	Rigid, crisp, and highly brittle; high initial stiffness with immediate failure after yielding.	Sudden splitting, skin cracking, and impact shattering.	Minimize drop heights; use soft padding on conveyor lines; avoid high-velocity sorting finger impacts.
Optimal Resilience Window	75% – 82%	Balanced turgor pressure; cell walls maintain shape without over-stretching.	Optimal balance of structural stiffness and viscoelastic damping; high impact resistance.	Minimal risk; maximum resilience against bruising and cracking.	Maintain this moisture window using targeted pre-cooling and commercial evaporative storage rooms.
Viscoelastic / Plastic Regime	< 70%	Vacuoles lose water; cell turgor drops; cell walls wrinkle and fold inward.	Highly compliant and plastic; deforms easily under load but resists cracking.	Extensive internal bruising, structural deformation, and rapid texture degradation.	Avoid deep bulk piling; transition fruits to horizontal packaging; limit transport crate depths to 450mm.

9.1 Field Validation and Supply Chain Applications

Implementing these engineering guidelines offers direct economic benefits (Jahanbakhshi et al., 2018; Singh & Reddy, 2006). Maintaining fruit moisture within the 75% to 82% resilience window and limiting stacking forces below the 244.9N transverse yield threshold can reduce mechanical postharvest losses from over 35% down to under 10%.

Protecting the physical structure of *Solanum aethiopicum* prevents internal cell rupture, stopping the enzymatic browning and rapid respiration that fast degrades food quality (Barbagallo et al., 2012). Applying these concrete, data-driven design rules allow postharvest engineers, equipment manufacturers, and logistics operators to build resilient cold chains and processing machinery. This framework enhances market value, reduces waste, and strengthens food security across Sub-Saharan Africa. The implications of this study extend beyond postharvest engineering, offering critical frameworks for agricultural sustainability and rural livelihoods in Sub-Saharan Africa. By mitigating the 35% to 45% supply chain losses of *Solanum aethiopicum*, the research directly supports smallholder economic viability. This agricultural optimization aligns with broader environmental and ecological management practices, such as agroforestry, tree diversity monitoring, and seedling cultivation

strategies (Salami et al., 2020; Rotowa et al., 2020; Ibeh et al., 2024; Alegbeleye et al., 2025; Emeasoba et al., 2026).

Furthermore, enhancing food security safeguards the socioeconomic and cultural foundations of indigenous farming communities. These communities sustain regional food commerce that is deeply intertwined with cultural expressions, traditional practices, and societal dynamics reflected across African literature, performance art, and heritage studies (Ilukwe & Ume, 2025; Utoh-Ezeajugh & Ume, 2025; Ume & Agoha, 2025; Agoha et al., 2024; Okeke & Akunne, 2023). Ultimately, bridging mechanical engineering with agricultural management reinforces the socio-ecological resilience required for sustainable regional development.

Conclusion

This study demonstrates that internal moisture content and loading orientation fundamentally govern the mechanical behavior and structural failure mechanics of *Solanum aethiopicum*. High moisture levels sustain a hyper-turgid, brittle matrix with high initial stiffness, whereas desiccation transitions the tissue into a viscoelastic, plastic regime characterized by cell wall folding. Mechanical anisotropy was clearly confirmed: transverse compression exhibits superior resistance compared to longitudinal loading due to orthogonal vascular bundle reinforcement. High-confidence empirical regression models established a Critical Moisture Threshold window which optimizes the balance between structural rigidity and energy absorption. Furthermore, finite element simulations and multi-way ANOVA validate these experimental dynamics. Ultimately, these quantitative findings deliver vital engineering benchmarks for designing optimized postharvest handling machinery, automated sorting systems, and specialized cold-storage infrastructure to mitigate agricultural losses across Sub-Saharan supply chains.

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