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Determining the Instantaneous Bruising Pattern in a Sample Potato Tuber Subjected to Pendulum Bob Impact through Finite Element Analysis

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Keywords:	Bruise progression, pendulum impact test, finite element analysis, explicit dynamics, potato

TITLE PAGE (Original Research)

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Running Head (abbreviated title)

Bruising Pattern in a Potato under Pendulum Bob Impact

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Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution Statement (based on CRediT -Contributor Roles Taxonomy)

[1,*] H. Kursat CELIK, PhD, Assoc. Prof.	: Project administration, Investigation, Visualization, Formal analysis, Writing – original draft
[1] Ibrahim AKINCI, PhD, Prof.	: Conceptualization, Methodology, Resources
[2] Mustafa ERKAN, PhD, Prof.	: Data curation, Methodology
[3] Allan E.W. RENNIE, PhD, Prof.	: Supervision, Writing – review and editing

Highlights

- Study investigates instant bruising progression in potato tubers under mechanical impacts.
- FEM-based explicit dynamics simulation technique used to simulate deformation behaviour.
- Simulations conducted for four pendulum bob impact cases on tubers.
- Analysis outputs clearly exhibit tuber's instantaneous deformation behaviour.
- Study provides a guiding strategy for complex deformation simulations.

Practical applications

This research aims to tackle the challenge of accurately representing the immediate internal bruising pattern in potato tubers resulting from mechanical impact. Conventional methods, such as physical or analytical expressions, may not fully capture the distribution of bruising experienced by the tubers. To overcome this limitation, an engineering simulation approach is proposed to provide a more precise depiction of the instantaneous bruising pattern. By advancing the understanding of complex deformation and bruising in solid agricultural products, this research contributes to improving the efficiency and quality of agricultural production in the industry. Additionally, this study offers a step-by-step guide on how to conduct these simulations effectively.

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Determining the Instantaneous Bruising Pattern in a Sample Potato Tuber Subjected to Pendulum Bob Impact through Finite Element Analysis

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Abstract

Potato bruising resulting from mechanical impact during production operations including harvest and post-harvest is a significant concern within the potato production sector, leading to consumer complaints and economic losses. The detection of instantaneous internal bruising poses a particular challenge as it can progress over time during storage or transportation, making it difficult to identify immediately after external impact. This study aims to investigate the progression of bruising and accurately represent the instantaneous dynamic deformation behaviour of potato tubers under four pendulum bob impact cases (pendulum arm angles of 30°, 45°, 60° and 90°). To analyse the dynamic impact deformation characteristics of the tubers, solid modelling based on a reverse engineering approach and explicit dynamic engineering simulations were employed. The simulation results yielded valuable numerical data and visual representation of the deformation progression. The loading conditions considered in this study indicated that the maximum stress values, reaching 0.818 MPa at a pendulum arm angle of 90°, remained below the bio-yield stress point of the tuber flesh (1.05 MPa) determined through experimental compression tests. Therefore, it was concluded that the impact did not cause permanent deformation (i.e. permanent bruising) in the tuber. However, the numerical analysis clearly demonstrated the sequence of stress occurrences, which is a key contributing factor to potential permanent bruising. In this regard, the bruising energy threshold of 318.314 mJ (R^2: 0.96) was interpolated. The numerical findings presented in this study can aid in evaluating the susceptibility of tuber samples to bruising. By employing nonlinear explicit dynamics simulations, this research contributes to the advancement of understanding complex deformation and bruising in solid agricultural products. Moreover, the application of these techniques holds significant industrial implications for enhancing the handling and transportation of agricultural produce.

Keywords: Bruise progression, pendulum impact test, finite element analysis, explicit dynamics, potato

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1. INTRODUCTION

Potato production and related industries play a crucial role in global agriculture and the economy. Potatoes serve as a fundamental food crop, ensuring food security and providing essential nutrients to hundreds of millions of people worldwide. According to the Food and Agriculture Organization (FAO) of the United Nations, the global potato production reached approximately 376,120 MT in the latest data for 2021. China, with a production quantity of 94.30 MT, India with 54.23 MT, and Ukraine with 21.36 MT were the top three potato-producing countries. The corresponding gross production value worldwide was estimated at 88,844,248 thousand US dollars (current) in 2021 according to FAOSTAT data (FAOSTAT, 2019). These statistics highlight the significant contribution of the potato industry to agricultural output and the global economy. Additionally, potato production plays a significant role in the context of agro-food policy and the Sustainable Development Goals (SDG) 2030 agenda. FAO reports that the approach focused in the agenda has been synthesized as better production; better nutrition; a better environment; and a better life, leaving no one behind (FAO, 2022). By aligning potato production with the SDGs, agro-food policies can promote sustainable agricultural practices, enhance food security, reduce poverty, and support rural development, as potatoes are a staple crop that can provide nutrition and income for millions of people globally. The production and trade of potatoes not only meets the demand for food but also generates substantial economic value, employment opportunities, and international trade relations. The continued growth and development of the potato industry is crucial for ensuring food availability, economic stability, and sustainable agricultural practices. However, mechanical damage to potatoes during harvesting, handling, and transportation poses significant challenges. Bruising and physical injuries reduce the quality and marketability of potatoes, leading to economic losses for farmers, processors, and distributors. The consequences of mechanical damage extend to end users as well. Consumers expect visually appealing, high-quality potatoes, free from blemishes and bruising. Damaged potatoes have reduced shelf life and negatively impact taste and texture, resulting in consumer dissatisfaction and decreased confidence in potato products. Minimizing mechanical damage is crucial for the industry's sustainability and meeting consumer expectations. Implementing proper handling techniques, improving transportation and storage conditions, and adopting advanced technologies can help reduce bruising. By addressing these challenges, the industry can deliver high-quality potatoes, maintain consumer satisfaction, and protect market demand.

Gaining a comprehensive understanding of the immediate deformation response to dynamic impact loading is a critical challenge in the development of efficient agricultural and food product processing and packaging systems within relevant industries. This is particularly important considering the complexities associated with the long-term storage of these products. During the initial design stages of machinery systems, it is essential to accurately define certain aspects, such as engineering properties, deformation behaviour, and bruise susceptibility of agricultural products under dynamic deformation scenarios. However, describing these features can be highly intricate (Celik, 2017). Opara and Pathare (2014) conducted a study focusing on measuring and analysing the mechanical damage caused to fresh horticultural produce, specifically addressing the issue of bruising. The study revealed the absence of a universally accepted criterion for assessing bruise susceptibility. Nevertheless, two commonly utilised physical measurements for evaluating mechanical damage are the bruise area and bruise volume, in addition to calculating absorbed energy. Quantifying the amount of damage relative to the absorbed impact or compression energy is crucial in determining bruise susceptibility (Brusewitz & Bartsch, 1989; Celik, 2017; Garcia et al., 1988; Holt & Schoorl, 1977; Opara & Pathare, 2014; Pang et al., 1996). While bruise volume is frequently employed as a measure of bruise damage, Pang et al. (1996) argue that bruise surface area is a more suitable parameter for assessing product damage, offering different perspectives on this aspect.

In any case, the primary objective in assessing studies focused on agricultural product damage features is related to determine the internal stress distribution and progression pattern occurring above the bio-yield stress point in organic materials under mechanical impact. This critical finding provides valuable insights into the nature and extent of damage experienced by the product.

The literature on determining the bruising of agricultural products under dynamic impact loading has explored various destructive and non-destructive experimental methods. The pendulum test has been widely utilised as a destructive method by researchers (Abedi & Ahmadi, 2013; Eissa et al., 2012; Komarnicki et al., 2016; Nikara et al., 2020; W. Bajema & M. Hyde, 1998; Xia et al., 2021; Xie et al., 2020, 2023; Yeşiloğlu Cevher, 2022). Non-destructive damage detection of agricultural products through various technologies has also been commonly studied (Chen & Sun, 1991; El-Mesery et al., 2019; Firouzjaei et al., 2018; Lu & Lu, 2017; Nturambirwe & Opara, 2020; Wang et al., 1988). Moreover, specific to potato products, experimental research studies have been conducted to elucidate the mechanical deformation associated with product bruising (Alvarez et al., 2002; Bentini et al., 2009; Deng et al., 2020; Hepworth & Bruce, 2000; Shahgholi, Latifi, Imani, et al., 2020; Stropek & Gołacki, 2022). However, these experimental methods have limitations in illustrating and describing the instantaneous internal bruise phenomenon that occurs during dynamic deformation cases, such as impact loading during the mechanical pendulum impact of a product. This is because bruising involves subcutaneous tissue failure without rupturing the skin of the product (Mohsenin, 1986). Therefore, numerical methods-based engineering analysis and simulation techniques, such as Finite Element Analysis (FEA), offer a promising approach to address such complex loading conditions of fruits and vegetables. FEA has been found useful in the research field of deformation analysis of agricultural products (Cardenas-Weber et al., 1991; Celik, 2017; Celik et al., 2011; Puri & Anantheswaran, 1993; Silveira Velloso et al., 2018; Zulkifli et al., 2020, 2021). By employing simulation techniques, it becomes possible to better understand the internal bruise phenomenon and its impact on the agricultural products deformations during dynamic loading scenarios.

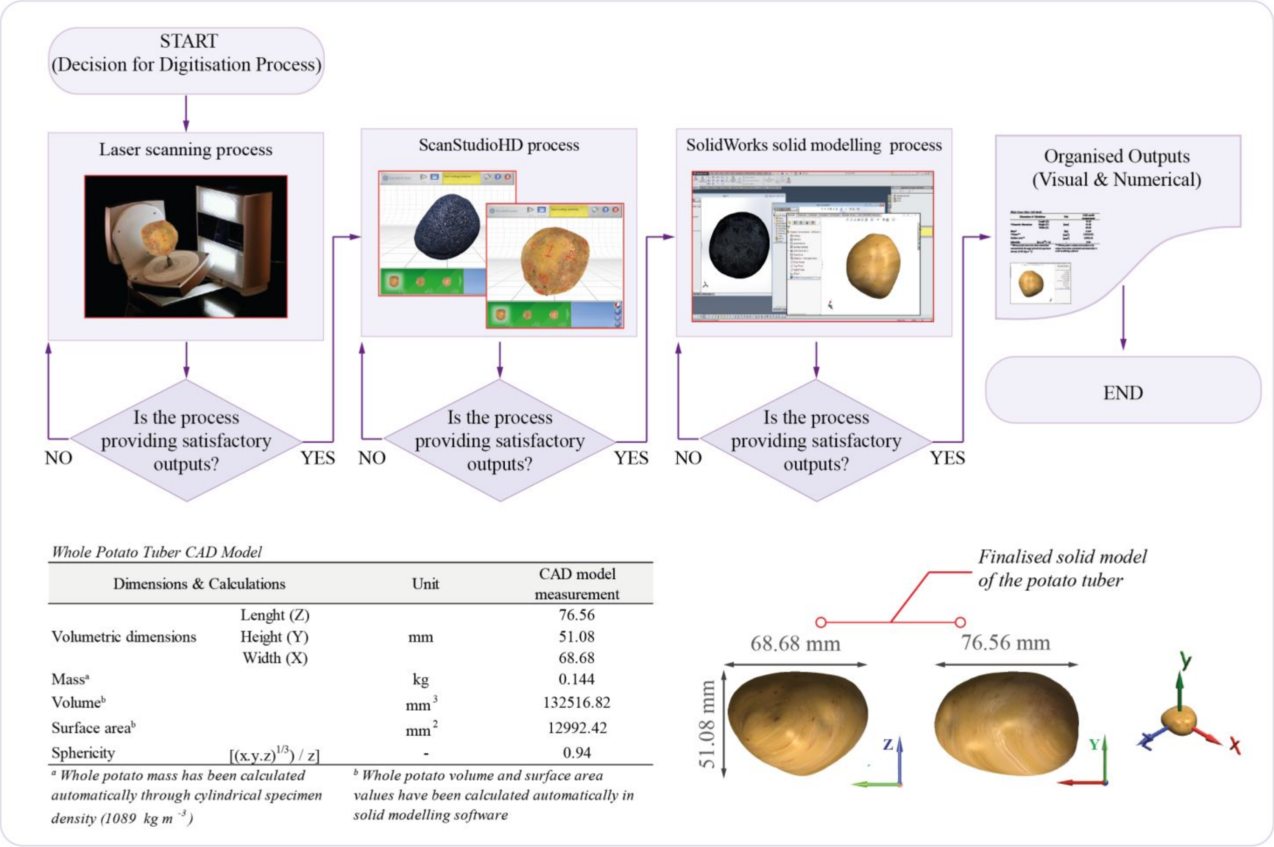
In a specific test method, the pendulum impact test is vital for assessing the mechanical properties of solid agricultural products like potatoes. It provides insights into their durability, resistance to damage, and impact energy absorption. This information is crucial for developing packaging, handling protocols, and storage conditions that minimize damage and ensure higher quality. The test also measures toughness and impact strength, aiding in variety selection, process optimization, and reducing post-harvest losses. Overall, the pendulum impact test is an indispensable tool for understanding the mechanical behaviour of agricultural products, enabling informed decisions to enhance quality and minimize economic losses.

The objective of this study is to investigate the time-dependent occurrence of instantaneous bruising in a sample potato tuber when exposed to dynamic loading caused by various pendulum bob impacts. To achieve this, explicit dynamics simulations based on the finite element method (FEM) were employed and instantaneous deformation and stress distribution progression of a sample potato tuber were simulated.

2. MATERIALS AND METHODS

2.1. Tuber Solid Model

The potato tubers, classified as solid-like agricultural crops, serve as an appropriate subject for investigating instantaneous bruising simulation applications such as pendulum bob impact case handled in this research. The tuber samples used in the experiment were Agria variety and they were randomly sourced from a supermarket in Antalya, Turkey. The digitisation process employed a NextEngine-2020i 3D desktop laser scanner and Scan-StudioHD software. Realistic three-dimensional (3D) computer-aided design (CAD) data of the potato tuber was obtained by utilising advanced solid modelling techniques including reverse engineering approach. Subsequently, SolidWorks, a 3D parametric solid modelling software, was used for the final refinement and additional modelling operations. Figure 1 provides a visual representation of the algorithmic digitisation process, highlighting the essential geometrical features of the scanned tuber sample.



Whole Potato Tuber CAD Model

Dimensions & Calculations		Unit	CAD model measurement
Volumetric dimensions	Lenght (Z)	mm	76.56
	Height (Y)		51.08
	Width (X)		68.68
Mass[a]		kg	0.144
Volume[b]		mm^3	132516.82
Surface area[b]		mm^2	12992.42
Sphericity	$[(x.y.z)^{1/3}) / z]$	-	0.94

[a] *Whole potato mass has been calculated automatically through cylindrical specimen density (1089 kg m $^{-3}$)*

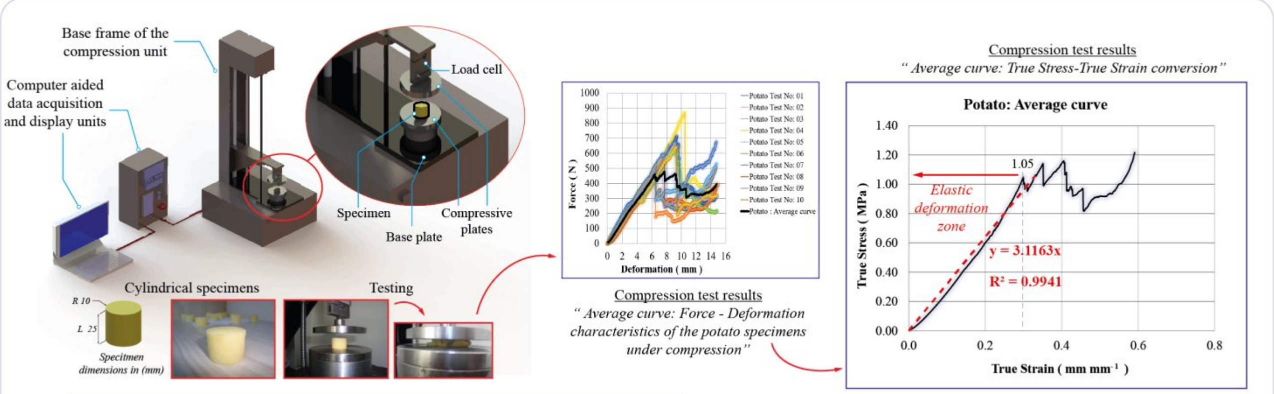
[b] *Whole potato volume and surface area values have been calculated automatically in solid modelling software*

Figure 1. Digitising procedure of the potato tuber specimen

2.2. Determination of the material properties

The physical measurement and material testing procedures for the potato specimens in this study were based on data from previous research, as documented in the literature (Caglayan et al., 2018). Experimental studies were conducted at the Biological Material Test Laboratory, Department of Agricultural Machinery and Technology Engineering, Akdeniz University, Antalya, Turkey. The compression tests followed the ASAE S368.4 W/Corr. 1 DEC2000 (R2017) standard for food materials (ASABE Standard, 2017).

True stress-strain data were derived from the measurements of force-deformation progression obtained in the experiments. These data were used to calculate the modulus of elasticity, a critical parameter for determining the extent of deformation during the linear elastic loading phase of the materials (Blahovec, 1988; Ihueze & Mgbemena, 2017; Mohsenin, 1986; Shelef & Mohsenin, 1967; Sitkei, 1987; Stroshine, 1986). Beyond the elastic deformation range, certain scenarios may involve plastic deformation cases. Plastic deformation of materials can be considered a type of material failure. Plasticity is a characteristic displayed by materials that undergo initial elastic deformation but transition into plastic deformation once a yield stress is reached (Chaboche, 2008). In fact, this phenomenon can also be observed in the deformation of agricultural products and this applies to the majority of organic materials. Hence, stress values exceeding the yield stress point can be defined as bruising for agricultural products. In this regard, an idealised homogeneous linear elastic material model can be described by utilising average true stress-true strain curves obtained from experimental tests on the potato flesh. Brusing threshold was assumed to be the material's yield stress point (may be known as the bio-yield stress point). The resulting true stress-strain curves from the tests on potato specimens are presented graphically at the conclusion of the testing procedures. Figure 2 provides detailed information about the testing procedures and the graphical representations.



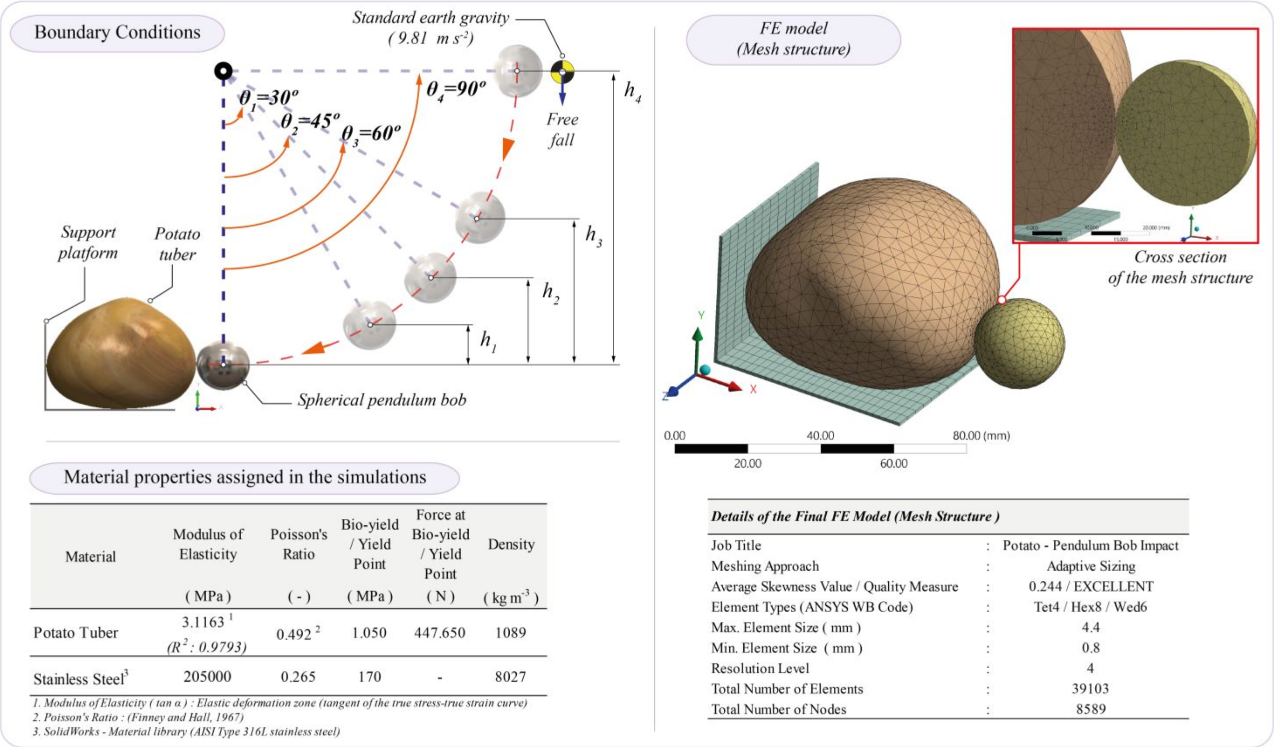
Experimental Test Details		
Test Method	:	Compression
Specimen Type & Dimension	:	Cylindrical (dia.20 mm × height 25 mm)
Test Device Capacity	:	2000 N (ESIT load cell)
Specimen Moisture Content	:	85.25 ± 2.81% (wet-base, 10 specimens)
Ambient Room Temperature	:	20 °C
Nominal Compression Traveling Speed	:	5 mm min^{-1}
Data Recording Sample Rate during Test	:	10 Hz
Number of Specimens utilised in the Test	:	10 Specimens
Referenced Test Standard	:	ASAE S368.4 W/Corr. 1 DEC2000 (R2017)

Figure 2. The testing procedures and the graphical representations

2.3. Simulation Set-up

In the simulation scenarios, a stainless-steel spherical pendulum bob with a diameter of 25 mm and a mass of 65.67 g was utilised to simulate freefall impact. The pendulum bob was released from predefined pendulum arm angles onto the potato tuber placed on a fixed stainless-steel platform. The simulation considered real-life test conditions, and the impact period was set at 1 s. The length of the pendulum arm (*L*) of 248.742 mm, measured from the bob's centre to the arm's rotation centre, was calculated using the equation $T=2\pi[(L g^{-1})^{0.5}]$, where *T* represents the time period of the pendulum (s), *L* is the length of the pendulum arm (m), and g is the gravitational constant (9.81 m s^{-2}). Four impact scenarios were simulated, corresponding to initial arm angles of 30°, 45°, 60° and 90°. The input velocity at impact moment in the simulation was calculated using the equation $V=(2gh)^{0.5}$, where *g* is the gravitational constant (9.81 m s^{-2}) and h is the drop height (m). The frictional coefficients of static and dynamic parameters were assigned as 0.424 and 0.373, respectively (Yurtlu et al., 2011).The simulations were conducted using the explicit dynamics module of the ANSYS Workbench commercial finite element method (FEM) code. The potato tuber model used in the simulation assumed a homogeneous flesh structure. The simulation settings included frictional (nonlinear) contact definitions and an idealised homogeneous linear elastic material model for the solid models. The simulation treated the impact scenarios as time-dependent engineering problems, considering the effects of standard gravity (9.81 m s^{-2}).

The finite element (FE) model, representing the mesh structure, was created using the meshing functions available in the FEA code. To ensure accurate results, part-based meshing approaches were utilised, where smaller element sizes were assigned to specific contact zones. The determination of the appropriate element size for the FE model involved conducting pre-trials to achieve optimal mesh quality. To assess the accuracy and quality of the FE model, an internal verification process was conducted. In this process, a skewness metric was employed, which measures the deviation of the elements from equilateral cells. A skewness value of 0 indicates perfect cell quality, while a value of 1 indicates fully degenerated cells. The range of values between 0 and 1 allows for the classification of cell quality: 0 to 0.25 is considered excellent, 0.25 to 0.50 is good, 0.50 to 0.75 is fair, 0.75 to 0.9 is poor, and values above 0.9 indicate bad or degenerate cell quality. By employing this skewness metric, the FE model's mesh quality was assessed, ensuring that the elements were properly shaped and conducive to accurate simulations. This internal verification step contributed to the overall reliability and validity of the FE model used in the analysis (ANSYS Product Doc., 2019a; Brys et al., 2004). The FE model exhibited an average skewness metric value of 0.244. This indicated that the FE model demonstrates its capability to accurately represent the geometry and physics of the problem under investigation. For the bob impact simulation, a solve time of 0.01 seconds was chosen, taking into account the relevant time intervals associated with the impact moment, deformation progression, and rebound period. This duration allows for accurate analysis of the system's behaviour and the energy absorption process. The existing literature on non-linear FEM-based analyses extensively covers non-linearity within three primary categories: boundary conditions (contact) nonlinearity, material nonlinearity, and geometry nonlinearity (SolidWorks Doc., 2010; Wakabayashi et al., 2008). In the context of this FEA study, the emphasis is placed on boundary conditions, particularly the non-linearities arising from geometry and contact. The investigation specifically targets the effects of geometry and contact nonlinearity. By focusing on these aspects, the study aims to gain a comprehensive understanding of how non-linear boundary conditions, resulting from geometry and contact, impact the behaviour of the system being analysed. To ensure reliable and efficient analysis solving, the workstation utilised for the simulations was equipped with high-performance components. It featured an Intel Core i7-4910Q processor operating at 2.9 GHz, 32 GB of RAM, and an NVIDIA Quadro K2100M graphics card with 2 GB of DDR5 memory. Schematic description of the boundary conditions, FE model details and material properties assigned in the simulation are given in Figure 3 (Finney & Hall, 1967; SolidWorks Product, 2019).



Material	Modulus of Elasticity (MPa)	Poisson's Ratio (-)	Bio-yield / Yield Point (MPa)	Force at Bio-yield / Yield Point (N)	Density (kg m^{-3})
Potato Tuber	3.1163 [1] *(R^2: 0.9793)*	0.492 [2]	1.050	447.650	1089
Stainless Steel[3]	205000	0.265	170	-	8027

1. Modulus of Elasticity (tan α) : Elastic deformation zone (tangent of the true stress-true strain curve)
2. Poisson's Ratio : (Finney and Hall, 1967)
3. SolidWorks - Material library (AISI Type 316L stainless steel)

Details of the Final FE Model (Mesh Structure)		
Job Title	:	Potato - Pendulum Bob Impact
Meshing Approach	:	Adaptive Sizing
Average Skewness Value / Quality Measure	:	0.244 / EXCELLENT
Element Types (ANSYS WB Code)	:	Tet4 / Hex8 / Wed6
Max. Element Size (mm)	:	4.4
Min. Element Size (mm)	:	0.8
Resolution Level	:	4
Total Number of Elements	:	39103
Total Number of Nodes	:	8589

Figure 3. Schematic description of the boundary conditions, FE model details and material properties

3. RESULTS AND DISCUSSION

The experimental compression testing of the material enabled the construction of the stress-strain curve for the flesh of the tuber. From these test data, the modulus of elasticity and the bio-yield stress point were determined to be 3.12 MPa and 1.05 MPa, respectively. These findings underline that the tuber's modulus of elasticity, as determined in the experiments, align reasonably well with the findings reported in relevant literature (Bentini et al., 2009; Finney & Hall, 1967; Huff, 1971; Shahgholi, Latifi, & Jahanbakhshi, 2020; Timbers et al., 1965). Furthermore, the experimental results revealed that the bruising threshold force, corresponding to the bio-yield stress point (1.05 MPa), was measured to be 447.65 N for the tuber flesh under quasi-static compression. Once the setup stage, which involved assigning experimental material properties, was completed, simulation scenarios were executed and the results were recorded. The simulation results provided valuable numerical data and visual representations of the deformation progression. The visual outputs effectively demonstrated the time-dependent and instantaneous stress progression and distribution on the tuber during the pre-described impact of the pendulum bob. In Figure 4 to Figure 7, which corresponds to the simulation output, the total energy progression, reaction force at the fixed platform, and stress sequence on the tuber are illustrated graphically. This includes simulation visual outputs for the bob impact case described in the FEA-A, FEA-B, FEA-C, and FEA-D scenarios, with pendulum arm angles of 30°, 45°, 60°, and 90°, respectively. The simulation capabilities enabled the investigation of stress and deformation progression from the impact moment to the rebound moment, providing insights into the mechanical stress development and the peak point deformation shape of the product. This valuable information can be utilised to design structures and mechanisms for postharvest and packaging operations. The simulation results indicated that there were nonlinear variations in stress levels over time during the impact of the pendulum bob. Representing this complex event through physical experiments is highly challenging. The numerical findings revealed that the maximum equivalent stress values, occurring at different time intervals, were 0.528 MPa (at 0.003 s), 0.626 MPa (at 0.002 s), 0.702 MPa (at 0.002 s), and 0.818 MPa (at 0.002 s) for the scenarios FEA-A, FEA-B, FEA-C, and FEA-D, respectively. Additionally, the corresponding absorbed (internal) energy values in the simulations were determined as 21.20 mJ, 46.30 mJ, 79 mJ, and 158 mJ, respectively. Furthermore, it was observed in all free-fall pendulum bob impact cases, as described in the simulation scenarios, that potential energy was converted to kinetic energy during the tuber's impact and subsequently transformed into internal and contact energy (energy absorbed by the tuber) upon impact.

In Figure 4 to Figure 7, the simulation results demonstrate that upon the initial contact of the bob at impact, there is a nonlinear increase in stress levels. The peak stress values occur at approximately 0.003 s for FEA-A and 0.002 s for FEA-B, FEA-C, and FEA-D, across the scenarios. After reaching the peak, the stress values gradually disperse throughout the inner structure until the tuber comes into contact with the fixed support platform. Upon contact with the platform, a decrease in stress is observed, followed by a second increase in stress levels at around 0.006 s for FEA-A and 0.005 s for FEA-B, FEA-C, and FEA-D, respectively. The progression of reactions aligns with the stress progressions observed in the results. However, in the FEA-D scenario, there is a fluctuation in the peak regions of the reaction forces, likely due to the higher impact on the tuber and the subsequent rebound from the platform.

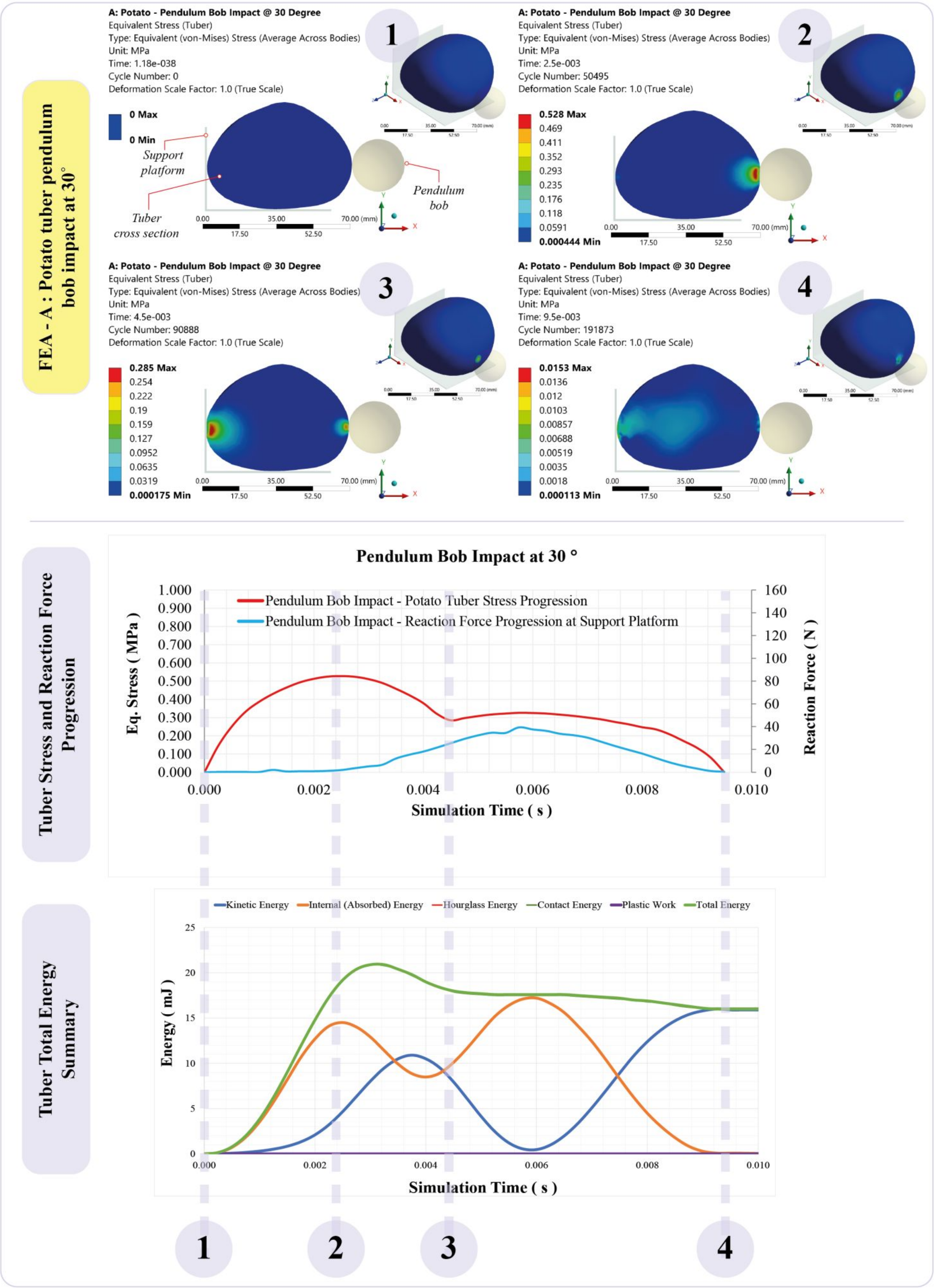


Figure 4. Simulation output (FEA-A)

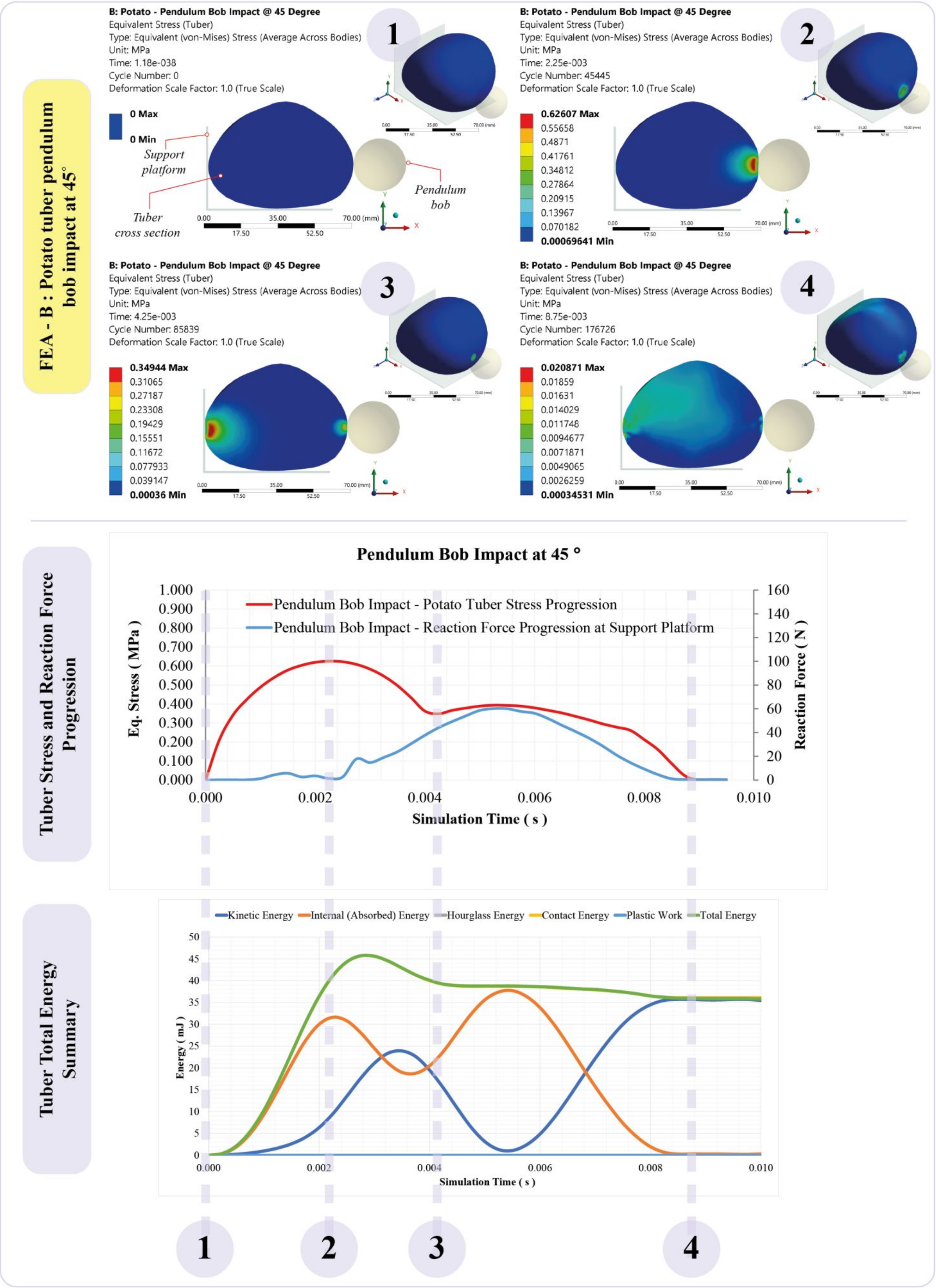


Figure 5. Simulation output (FEA-B)

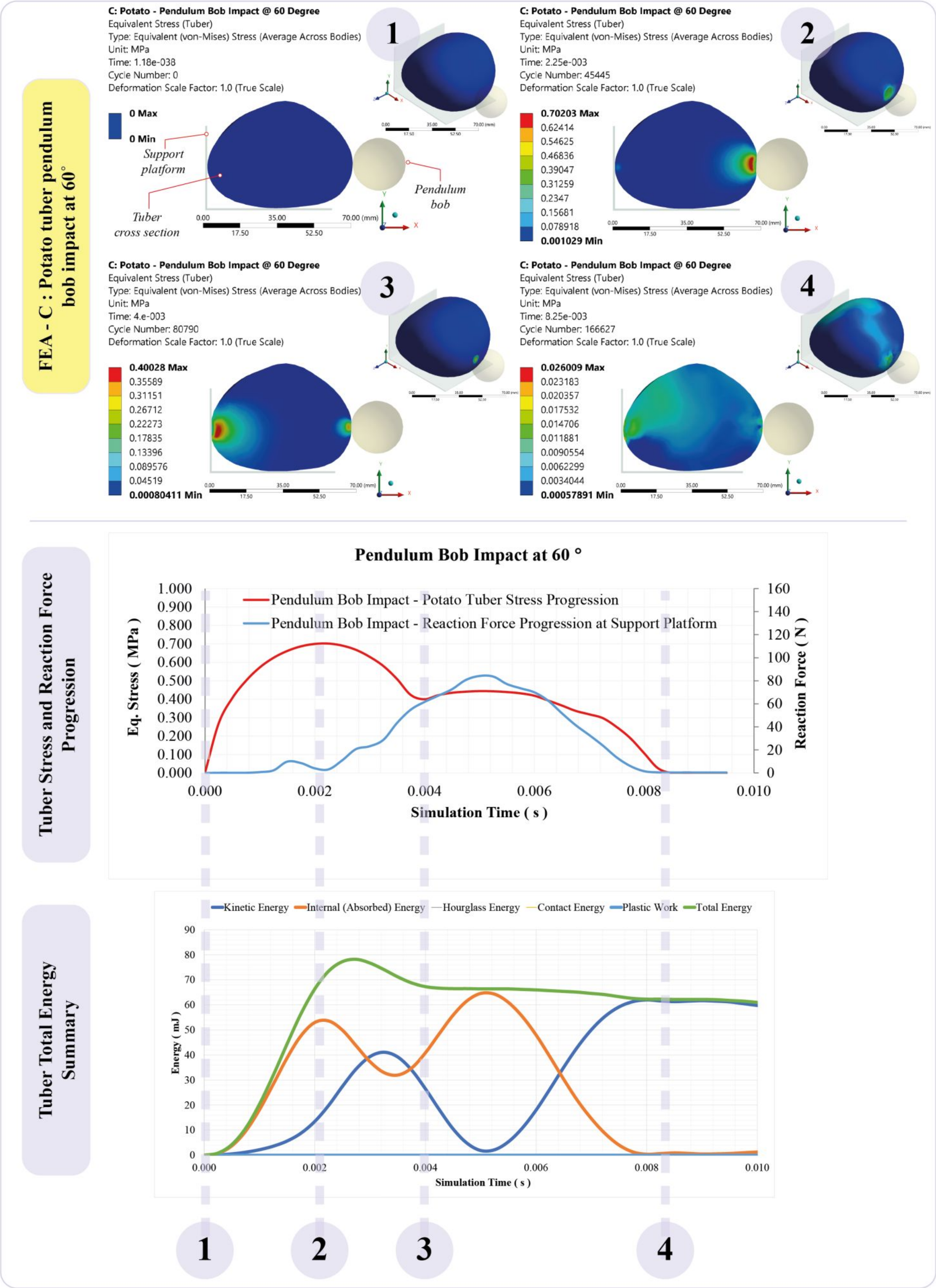


Figure 6. Simulation output (FEA-C)

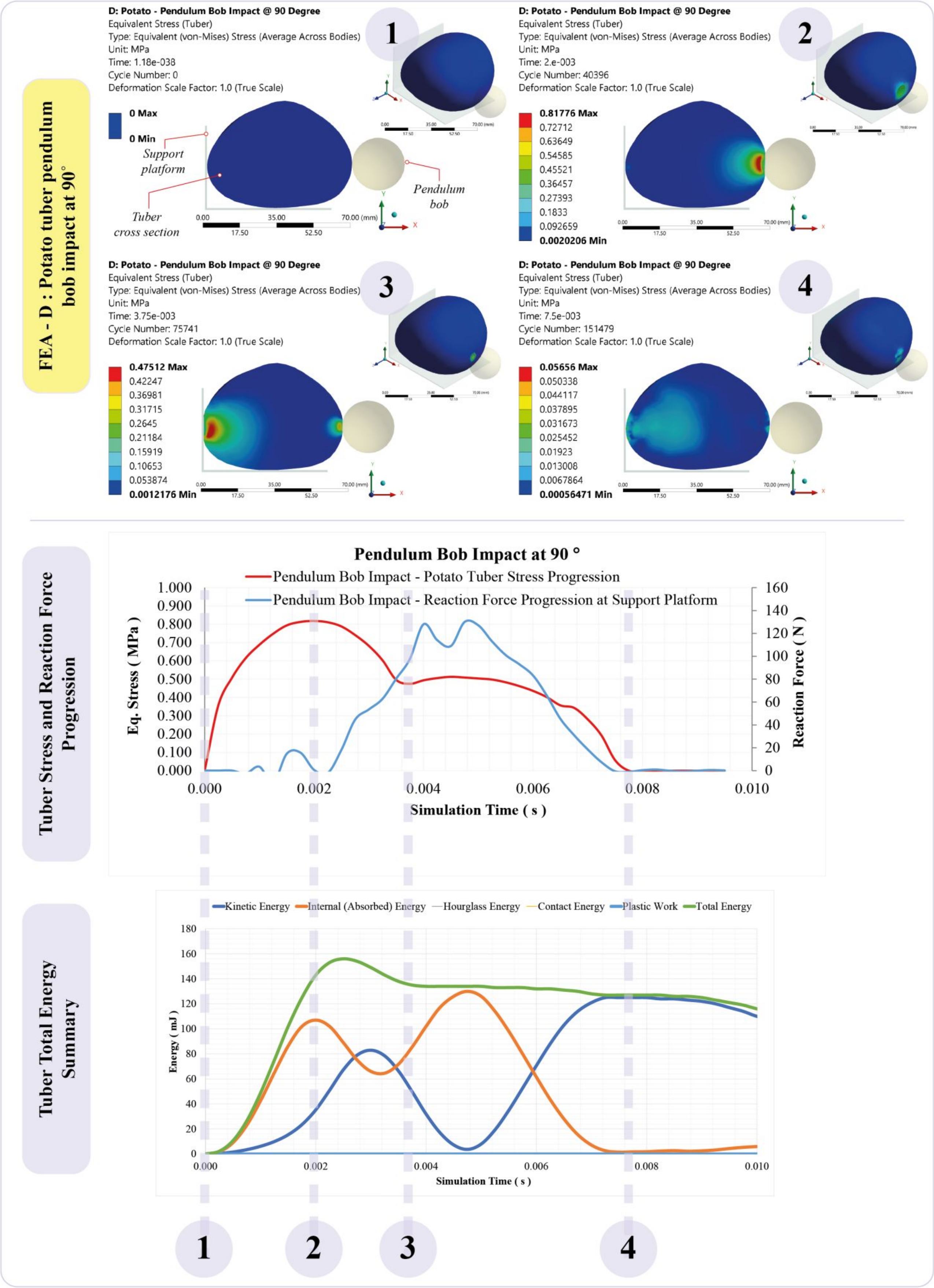
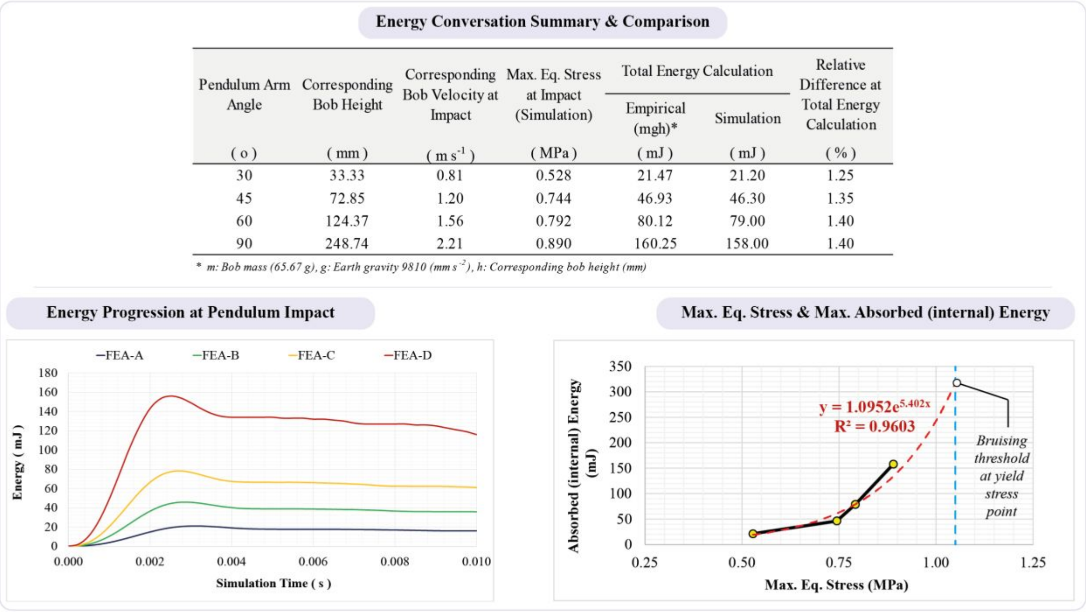


Figure 7. Simulation output (FEA-D)

All the simulation results consistently indicated that there was no disruption in the conservation of energy. The results demonstrated a stable conservation of energy state. To validate this observation, a comparative analysis was conducted between the empirical and FEA results for total energy. The relative differences were calculated as 1.25%, 1.35%, 1.40%, and 1.40% for FEA-A, FEA-B, FEA-C, and FEA-D, respectively. These results indicate a good correlation between empirical and simulation studies. The stress values obtained from the simulations were determined to be below the bruising threshold, also known as the bio yield stress point. This implies that the tuber experienced only temporary deformation under the specified boundary conditions, indicating the absence of permanent bruising in the predefined impact scenarios. However, there is a possibility that an increase in the bob's mass could lead to permanent bruising on the tuber. In this regard, when examining the exponential extrapolation between stress and internal energy in relation to the tuber's material yield stress point (1.05 MPa), which represents the threshold for permanent bruising, the energy absorption (internal energy) at the bruising threshold was estimated to be 318.314 mJ (R^2: 0.96). Consequently, this finding indicates that a minimum energy level of 318.314 mJ is required to induce bruising through impact on the investigated tuber model. Figure 8 illustrates the maximum stress and absorbed energy values with exponential extrapolation, provides a summary of energy conservation, and presents a comparison of the potential energy calculations.

Additionally, to assess the accuracy of the FE model and simulation results, an important aspect to consider is the energy activity summary derived from the explicit dynamics simulations. This summary involves the examination of various energy components, including kinetic energy, internal (absorbed) energy, contact energy, and hourglass energy activities. Hourglassing refers to a type of deformation that does not cause any changes in volume or strain in the hex/quad meshes within a FE model. It is essentially an undesired mode of deformation that arises from the excitation of degrees of freedom with zero energy. Consequently, this energy activity is commonly referred to as hourglass energy or zeromode energy in the existing literature (Hallquist, 2006; Stewart et al., 2006; Wallmeier et al., 2015). In the literature, it has been suggested that the hourglass energy should not exceed 5-10% of the internal energy (ANSYS Product Doc., 2019b; Björkmon, 2010; Dilek & Gedikli, 2014). The energy summaries derived from the simulations indicated that the hourglass energy did not exceed 5-10% of the internal energy values in any of the simulation scenarios described in this study. Therefore, it can be concluded that the size of the FEA is appropriate, and the accuracy of the FE model is deemed satisfactory.



Energy Conversation Summary & Comparison

Pendulum Arm Angle	Corresponding Bob Height	Corresponding Bob Velocity at Impact	Max. Eq. Stress at Impact (Simulation)	Total Energy Calculation		Relative Difference at Total Energy Calculation
				Empirical (mgh)*	Simulation	
(o)	(mm)	(m s^{-1})	(MPa)	(mJ)	(mJ)	(%)
30	33.33	0.81	0.528	21.47	21.20	1.25
45	72.85	1.20	0.744	46.93	46.30	1.35
60	124.37	1.56	0.792	80.12	79.00	1.40
90	248.74	2.21	0.890	160.25	158.00	1.40

* *m: Bob mass (65.67 g), g: Earth gravity 9810 (mm s^{-2}), h: Corresponding bob height (mm)*

Figure 8. The maximum stress and absorbed energy values with exponential extrapolation, summary of energy conservation, and comparison of the potential energy calculations

4. CONCLUSION

In this study, the objective was to determine the instantaneous bruising progression of a potato tuber under various pendulum impact scenarios using a FEM-based explicit dynamics simulation technique. The study successfully achieved this goal and effectively described the parameters associated with the tuber's deformation behaviour. Additionally, a simulation strategy specifically designed for potato tubers was introduced, which can be customized for similar agricultural crops. The findings contribute to a deeper understanding of dynamic bruising in potato tubers caused by mechanical impacts, relevant to transportation, harvesting, post-harvest processes, and industrial product processing stages.

Some key points derived from this study can be summarised as follows:

1. The application of reverse engineering to the potato tuber model yielded a more realistic depiction of its deformation behaviour. This innovative approach shows promise in developing digital models and accurate simulations for diverse irregularly shaped agricultural and food products.
2. The material properties obtained from the compression tests were utilised to establish simplified material models, which were effectively incorporated into the FEA framework. These material models may be further employed in computer-aided rheological analyses of similar potato varieties, facilitating future research endeavours.
3. The simulation work generated informative deformation visuals and graphs that complemented the numerical results, enhancing the comprehension of product deformation under various pendulum impact scenarios.
4. The FEA outputs revealed that the tuber did not undergo bruising during the impact case, considering the pre-described boundary conditions, as the magnitude of maximum stress on the tuber (0.818 MPa) remained below the material's bio-yield stress point (1.05 MPa).
5. The extrapolation results between stress and internal energy suggest that a minimum energy threshold of 318.314 mJ is necessary to cause bruising through impact on the examined tuber model.
6. The study established the logical consistency of the simulation setup. The verified simulation results, based on empirical energy conservation, can be considered a reliable benchmark for simulation studies of related to deformation of organic materials.
7. This study contributes to advancing research by leveraging numerical methods and nonlinear explicit dynamics simulations to investigate complex deformation and bruising in solid agricultural products. Its potential implications for the industry make it a significant step forward in this field.

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