TRANSPORTATION VIBRATION EFFECTS ON APPLE BRUSING

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ABSTRACT

Mechanical damage, particularly bruising, is a major cause of postharvest losses in fresh produce, significantly impacting fruit quality and marketability. Apples, being highly susceptible, experience external forces during handling, storage, and transportation, primarily from vibrations, impacts, and compression. This study analyzes the effects of vibration parameters (intensity and duration), truck suspension systems, apple varieties, and packaging configurations on minimizing apple bruising under realistic transportation conditions. Two apple varieties, Fuji and Jonagold, were packaged in corrugated boxes with trays, reusable plastic containers (RPCs) with trays, and volume packing systems. They were exposed to random vibration profiles based on ASTM D4169, simulating leaf-spring and air-ride suspensions at intensities 0.2, 0.3, 0.5 and 0.7 Gravity Root Mean Square (Grms) for 1, 3, and 5 hours. Additionally, a multi-layer packaging setup was tested to evaluate damage distribution across layers. Results demonstrated that vibration intensity, duration, and suspension type significantly influence bruising. Leaf-spring suspensions caused more damage than air-ride systems, especially at higher intensities and longer durations. Apples in the top layer of stacked packages experienced the most damage, while lower layers benefited from load distribution. Among packaging types, corrugated board with Hexcel wrap outperformed others, offering improved protection and recyclability. To further assess factor importance, Random Forest Regression was applied, revealing vibration intensity as the most influential factor, followed by duration, packaging type, and apple variety. These findings support the need for optimized packaging and vibration control strategies. This study highlights the importance of combining vibration testing, sustainable packaging materials, and multi-layer designs to reduce apple bruising. It also suggests the development of new ASTM/ISTA test profiles tailored to produce distribution, including multi-axis vibration testing for improved simulation accuracy.

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CHAPTER 1 – INTODUCTION

1-1 Research Motivation

Apples are one of the most widely consumed fruits globally, valued for their nutritional qualities, adaptability, and economic importance (Al-Dairi et al., 2022; Fadiji et al., 2024). However, their journey from orchards to consumers presents considerable challenges, as apples are highly susceptible to mechanical damage during transportation and handling (Figure 1). External forces such as vibrations, impacts, and compression can cause bruising, abrasions, and structural deformations, diminishing the fruit's visual appeal and reducing its market value. These mechanical damages not only lead to significant economic losses but also contribute to postharvest food waste, which is a pressing global concern (Lin et al., 2023).

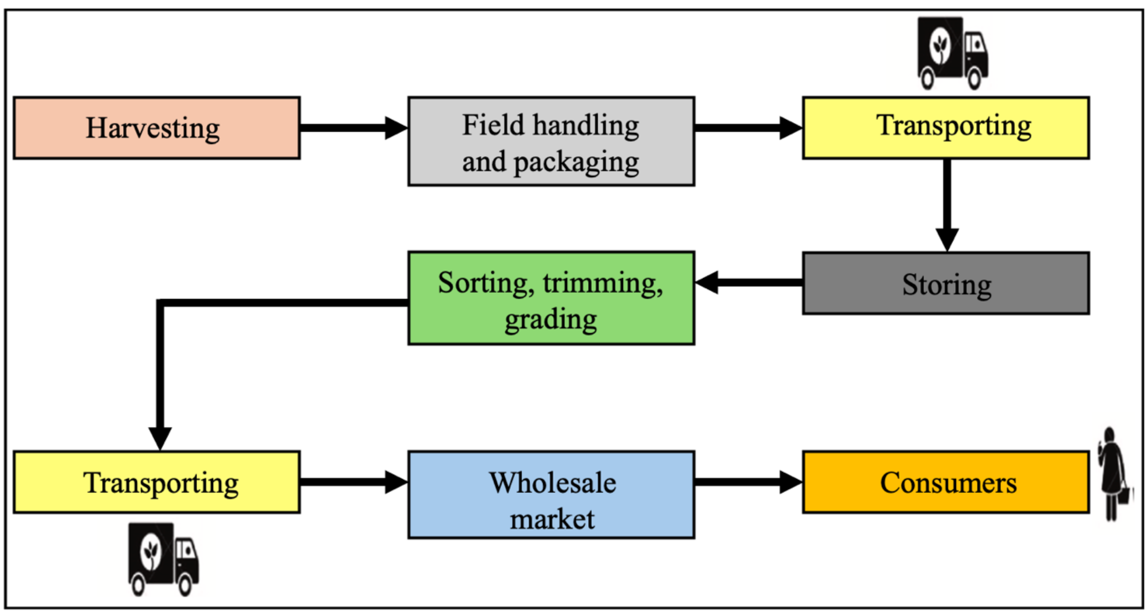


Figure 1. Postharvest supply chain of fresh produce

The transportation phase in the supply chain plays a pivotal role in determining the quality and safety of apples upon arrival at their destination. Factors such as road conditions, vehicle suspension systems, transport duration, and packaging design contribute to the mechanical stresses experienced by produce during transit. Poor road infrastructure and suboptimal suspension systems amplify vibrations and shocks, increasing the likelihood of fruit-to-fruit contact and internal bruising (Garcia-Romeu-Martinez et al., 2008; Zhou et al., 2007). Inadequate or poorly designed packaging exacerbates these risks by failing to provide sufficient protection against these dynamic forces (Fernando et al., 2020).

Packaging is a critical element in mitigating transportation-related damage, serving as a buffer between produce and external mechanical stresses. Traditional packaging solutions, including corrugated fiberboard boxes and rigid plastic crates, have been widely utilized for their structural integrity and cost-effectiveness. However, the performance of these conventional systems varies under different transportation conditions, leaving room for innovation and improvement (Mukama et al., 2020a; U. L. Opara & Fadiji, 2018). Recent advancements in packaging technologies, including sustainable materials like paper-based cushioning and multi-layer configurations, offer new possibilities for improving protection compared to traditional packaging solutions, such as standard corrugated boxes and rigid plastic containers, while also addressing environmental concerns. Despite these innovations, their efficacy under a comprehensive combined packaging and distribution features remains underexplored. Existing research often isolates specific variables, such as vibration intensity, transport duration, or packaging material, without considering the complex interactions of these factors in real-world conditions (S. P. Singh et al., 1992).

Hexcel wrap (Figure 2) is a paper-based cushioning material featuring an interlocking honeycomb structure designed for shock absorption and product protection. Unlike traditional foam or plastic-based cushioning materials, it provides a sustainable alternative that is recyclable. While its effectiveness in static environments is well documented, its ability to mitigate vibration-induced damage under dynamic transportation conditions remains underexplored.

These gaps highlight the need for a more comprehensive approach to studying the combined effects of transportation variables and packaging configurations on produce quality.

Figure 2. Hexcel Wrap

1-2 Study Objective

This research aims to systematically improve packaging and transportation strategies that reduce bruise damage to apples during their journey from orchard to consumer. Specifically, the study focuses on the following objectives:

1. Examine the Role of Transportation Variables: Investigate how factors like vibration intensity and duration, as well as truck suspension type (air-ride vs. leaf-spring), influence the extent of fruit damage. This includes simulating a range of real-world transportation conditions from smooth to rough road scenarios to provide a comprehensive understanding of their effects on apple quality.

2. Assess the Impact of Different Packaging Types: Evaluate the protective qualities of various packaging configurations, such as one-piece corrugated cartons and reusable plastic containers with trays, as well as volume packing, where apples are packed in plastic bags without individual

separators. The goal is to determine which packaging type most effectively reduces bruising and other mechanical damage to apples during transport.

3. Explore Apple Varietal Differences: Analyze how mechanical damage susceptibility varies among the tested two apple varieties, Jonagold and Fuji.

4. Initiate additional case studies for future investigations:

   a. Analyze Multi-Layer Packaging Systems: Investigate the damage distribution across layers in multi-layer packaging systems and identify configurations that provide reduced damage at all levels.

   b. Hexcel wrap: Evaluate the effectiveness of Hexcel wrap, a sustainable, paper-based cushioning material with a honeycomb structure designed to absorb shocks and vibrations. In this study, Hexcel wrap is used as tray cushioning within the packaging system. It is placed on the tray to provide additional shock absorption and reduce apple bruising during transportation. This study aims to incorporate Hexcel wrap into packaging systems to show its potential in reducing apple bruising during transit while supporting environmental sustainability. The analysis shows the performance of Hexcel wrap in different packaging configurations and under various transportation conditions, providing insights into its potential to enhance protection compared to packaging system without additional cushioning materials and to minimize mechanical damage.

5. Provide Actionable Recommendations: 1) Develop evidence-based guidelines for packaging engineers and supply chain professionals to improve postharvest handling, packaging designs, and transportation strategies. 2) Recommend that organizations such as ASTM (American Society for Testing and Materials) and ISTA (International Safe Transit Association), which develop test

standards, consider creating a dedicated distribution test specifically for fresh produce, as well as incorporating multi-axis vibration testing to more realistically simulate transportation conditions. The insights from this study aim to contribute to sustainable supply chains by reducing bruising damage, enhancing produce quality, and reducing environmental impact.

1-3 Document Structure

The remainder of this thesis is organized as follows. Chapter 2 presents a comprehensive review of the existing literature, highlighting key research gaps and emphasizing the need for integrated studies on mechanical damage in fresh produce. Chapter 3 details the materials and methods employed in this research, including descriptions of the experimental setup, packaging configurations, vibration simulations, and the statistical analyses used to evaluate the significance of different factors affecting apple bruising. Additionally, a machine learning-based feature importance analysis is introduced to assess the relative contribution of each parameter to mechanical damage. Chapter 4 discusses the results, examining the combined effects of vibration parameters, packaging systems, and multi-layer designs on apple bruising. This chapter also includes the findings from ANOVA, Tukey's HSD tests, and feature importance analysis, providing a data-driven assessment of key influencing factors. Chapter 5 offers recommendations for optimizing apple packaging and distribution to minimize mechanical damage during transportation. Chapter 6 provides the conclusions, summarizing the key findings and their practical implications for improving packaging performance. Finally, Chapter 7 outlines the study's limitations and proposes directions for future research, with a particular focus on sustainable packaging solutions and advanced testing methods.

CHAPTER 2 – REVIEW OF LITERATURE

2-1 Mechanical Damage in Fresh Produce

Mechanical damage is one of the most widespread challenges in the postharvest handling of fresh produce, particularly apples. This form of damage compromises structural integrity, accelerates physiological deterioration, and reduces marketability and shelf life. Mechanical damage is predominantly caused by external forces, including impact, compression, and vibrations, during various stages of the supply chain, such as harvesting, packaging, transportation, and unloading (Hussein et al., 2020; L. U. Opara, 2007). The resulting defects, such as bruising, abrasions, and dents, contribute to substantial postharvest losses, which are estimated to reach 30–40% globally for fresh produce (Barchi et al., 2002).

2-1-1 Causes of Mechanical Damage

Mechanical damage to apples occurs due to the cumulative effects of various forces encountered during the supply chain. These forces can be categorized as below:

1. Impact Forces

Impact forces occur when apples collide with surfaces or other fruits during handling operations, such as harvesting, packaging, or transportation. Even small drop heights can generate forces that exceed the fruit's mechanical strength, resulting in surface bruising and internal tissue damage (Vursavuş & Özgüven, 2004). Chaiwong et al. (2023a) highlighted that unprotected packaging systems exacerbate the effects of impacts, increasing the likelihood of damage. Their study further analyzed cushioning materials and found that while foam inserts or rubber latex can reduce impact forces, the effectiveness varies depending on the packaging configuration. These finding highlight the need to choose cushioning strategies that are specifically suited to transportation and handling conditions to apples, rather than depending on traditional cushioning methods.

2. Compression Stresses

Compression stresses arise from stacking or pressing apples together during storage or transportation. These stresses create localized pressure points that deform the tissue, often causing internal damage that is not immediately visible (Ahmadi, 2012). Prolonged exposure to compression stresses can significantly reduce apple firmness, making the fruit more susceptible to subsequent handling damage. Fernando et al. (2020) found that rigid packaging systems, such as plastic crates, amplify compression forces, while flexible materials like corrugated paperboard distribute these forces more evenly.

3. Vibrational Energy

Vibrations encountered during transportation are among the most significant contributors to mechanical damage in apple. Repeated exposure to low- and high-frequency vibrations can cause fruit-to-fruit contact and micro-movements within packaging systems, exacerbating bruising over time (Lin et al., 2023). Vehicles traveling on rough roads or equipped with rigid suspension systems further amplify vibrational energy, increasing damage severity (Garcia-Romeu-Martinez et al., 2008).

2-1-2 Physiological Impact of Mechanical Damage

Mechanical damage initiates a cascade of physiological changes that accelerate the deterioration of fresh produce. These changes include:

1. Respiration Rates

Bruise damage significantly affects physiological processes in fresh produce, including respiration, moisture loss, and biochemical changes such as increased ethylene production, elevated carbon dioxide output, and enzymatic activity that weakens cell wall integrity. These changes lead to faster senescence, increased susceptibility to spoilage, and a reduction in overall quality (Hussein et al., 2020). The resulting metabolic imbalance, including higher respiration rates, accelerates deterioration and shortens the fruit's shelf life.

2. Ethylene Production

Mechanical damage stimulates ethylene production in apples, accelerating ripening and senescence. The resulting surge in ethylene shortens shelf life, softens tissues, and increases susceptibility to decay, emphasizing the importance of minimizing mechanical stress to maintain postharvest quality (Kays, 1991).

3. Enzymatic Browning

Bruising causes the rupture of cell membranes, leading to the interaction of phenolic compounds and oxidative enzymes such as polyphenol oxidase (PPO). This enzymatic activity results in browning of the damaged tissue, which is visually undesirable for consumers (Lin et al., 2023).

4. Increased Susceptibility to Microbial Decay

Bruised or damaged tissues provide entry points for pathogens, such as bacteria and fungi, increasing the risk of spoilage. Van Zeebroeck et al. (2007) observed that microbial activity significantly increased in mechanically damaged apples, particularly during prolonged storage.

2-1-3 Factors Influencing Mechanical Damage

The susceptibility of apples to mechanical damage is influenced by several intrinsic and extrinsic factors, including:

1. Variety and Ripeness

Variety and ripeness significantly influence the mechanical strength and bruise susceptibility of fruits. Studies on kiwifruit and apricots have demonstrated that softer fruits are more prone to mechanical damage compared to firmer ones, with ripeness further increasing susceptibility due to reduced firmness and structural cohesion (Vursavuş & Özgüven, 2004). Similar patterns can be observed in apples, where softer varieties, such as Jonagold, are more susceptible to bruising than firmer varieties like Fuji (Mureșan et al., 2022).

In addition to recent studies on apple varieties, earlier research from the 1990s established apple damage thresholds, demonstrating how different cultivars respond to impact forces, vibration, and compression during handling and transportation (Schulte et al., 1992). Click or tap here to enter text.While these earlier studies are dated, they remain foundational in understanding varietal differences in bruise susceptibility and continue to inform modern packaging and transportation strategies.

2. Environmental Conditions and Fruit Firmness

Temperature and humidity significantly affect the mechanical properties of fruits, including apples. As observed in studies on peaches, low humidity accelerates moisture loss, reducing tissue elasticity, while temperature fluctuations weaken the fruit's structure, increasing susceptibility to bruising (Dagdelen & Aday, 2021). Similarly, apples with higher moisture content exhibit greater elasticity, which helps reduce bruising during handling. However, prolonged dehydration during storage decreases tissue turgor pressure and firmness, making apples more vulnerable to mechanical damage under external forces. These findings can be extended to apple varieties, where environmental conditions and moisture content are critical in determining their resistance to mechanical stress.

3. Handling and Packaging Practices

Improper handling practices, such as dropping or overloading apples, generate excessive impact and compression forces that significantly increase bruising risks. Lin et al. (2023) emphasized the importance of using protective packaging systems to stabilize loads and absorb mechanical forces during transit.

2-1-4 Transportation as a Major Source of Damage

Transportation is among the most critical phases of the supply chain, during which mechanical damage is most likely to occur due to:

1. Road Conditions

Poorly maintained or unpaved roads amplify vibrational forces, increasing mechanical damage. Zhou et al. (2007) highlighted that rough road conditions significantly increase the risk of fruit-to-fruit contact and packaging deformation, both of which exacerbate bruising.

2. Suspension Systems

The type of vehicle suspension system has a significant impact on damage severity. Vehicles equipped with leaf-spring suspensions transmit higher frequencies and intensities of vibrations compared to air-ride systems, which provide smoother ride profiles (Garcia-Romeu-Martinez et al., 2008; S. P. Singh et al., 1992).

3. Duration of Transit

Longer transport durations result in cumulative damage.Zheng et al. (2022) observed that minimal bruising occurs during the initial hours of transit, but damage rates increase substantially beyond three hours due to the continuous transfer of vibrational energy.

2-2 Packaging Solutions for Damage Mitigation

Packaging serves as a critical component in minimizing mechanical damage during the handling, storage, and transportation of fresh produce. Effective packaging stabilizes produce loads, absorbs external forces, and reduces fruit-to-fruit contact, ensuring the quality and marketability of fruits like apples. This section reviews traditional packaging systems, innovative cushioning materials, sustainable packaging designs, and the role of load stability and palletization in damage mitigation.

2-2-1 Traditional Packaging Systems

Traditional packaging systems, such as corrugated boxes (CBs), reusable plastic containers (RPCs), and pulp trays, remain widely utilized for their affordability and effectiveness. Among these, CBs stand out due to their structural efficiency and versatility in protecting fruits from mechanical damage.

CBs consist of an orthotropic sandwich structure, with a corrugated layer (flute) placed between flat liners. The flute type and liner properties significantly influence the box's ability to withstand mechanical stresses, such as vibrations and compression (U. L. Opara & Pathare, 2014). Single-wall CBs have larger pressurized areas than double-wall boxes, which offer superior protection against compression stresses. Studies have highlighted that CB designs with optimized dimensions and ventilation, such as the MK4 package, which features a higher length-to-height ratio (1.86), longer trays, and increased ventilation areas, provide better protection against fruit damage during transportation. In contrast, MK6 package with a lower length-to-height ratio (1.45) and different ventilation patterns, has been shown to increase susceptibility to bruising and mechanical damage (Fadiji et al., 2016; U. L. Opara & Fadiji, 2018).

While RPCs are durable and stackable, their rigid structure amplifies vibrations, increasing the likelihood of damage to the produce. This limitation necessitates supplementary cushioning materials to enhance their protective capabilities (Lin et al., 2023). Pulp trays, commonly used in conjunction with CBs or RPCs, provide compartmentalized spaces that stabilize fruit loads and reduce contact. Mukama et al. (2020a, 2020b) emphasized that the combination of corrugated boxes with pulp trays offers robust protection against vibration and compression forces during transport.

Pulp trays, typically used with CBs or RPCs, provide compartments that stabilize fruit loads and reduce contact. They are an eco-friendly option made from recycled materials, but their effectiveness depends on design features, such as wall thickness and tray structure (Fadiji et al., 2023).

2-2-2 Cushioning Technologies

Cushioning materials are integral to mitigating mechanical damage by absorbing shocks and vibrations during transportation. Foam nets have demonstrated significant effectiveness, reducing apple damage by up to 63% compared to paper wrapping or no packaging (Eissa et al., 2012). However, foam materials are non-biodegradable, raising environmental concerns.

Paper-based solutions, such as honeycomb-structured paperboard, provide a sustainable alternative. Honeycomb designs efficiently dissipate mechanical forces, making them ideal for protecting produce during transport (Wang et al., 2018). Zhou et al., (2007) demonstrated that foam nets offered superior vibration damping for Huanghua pears compared to paper wrapping. Conversely, Wongsuriyasak and Srichandr (2012) reported that paper pulp molds outperformed foam nets in preserving mango firmness and reducing weight loss, highlighting the importance of tailoring material choice to the specific fruit.

Vacuum packaging has also emerged as an innovative approach to reducing mechanical damage. By restricting fruit movement, vacuum systems effectively minimize vibration-induced bruising. Fernando et al. (2020) demonstrated that vacuum-tightened packaging reduced damage in bananas by over 70%, particularly in the top and bottom layers. Similarly, Jiang et al. (2021) found that semi-vacuum packaging decreased vibration amplitudes during the express delivery of Chinese bayberries, improving fruit quality retention.

Emerging studies have further explored the use of cushioning innovations. Natural rubber latex cushioning, for example, has shown promise as an eco-friendly material that reduces vibration-induced damage during fruit transport (Chaiwong et al., 2023b). However, these innovations require further investigation to optimize their performance for large-scale operations.

2-2-3 Sustainable Packaging Innovations

Sustainability is a driving force behind modern packaging design. Biodegradable plastics, such as polylactic acid (PLA) and starch-based polymers, have been explored as alternatives to conventional plastics (Yu et al., 2024). Honeycomb paperboard and other recyclable materials are increasingly adopted for their ability to balance protective performance with environmental responsibility.

Recent advancements in paper-based cushioning materials, such as Hexcel wrap (Figure 2) introduced in this study, effectively combine shock absorption with recyclability. While these sustainable packaging solutions show promise, they often face challenges, including higher production costs and performance variability under real-world conditions. The relatively high cost of eco-friendly alternatives compared to traditional plastic options remains a significant barrier to widespread adoption. Balancing cost-effectiveness with reliable performance is a critical area of research, particularly for large-scale fresh produce transportation, to encourage broader implementation of these sustainable materials.

2-2-4 Role of Load Stability and Palletization

Load stability and palletization are key factors influencing mechanical damage during transportation. Proper load stability minimizes movement within packaging systems, reducing fruit-to-fruit contact and structural deformation. Improper stacking patterns and load distribution amplify vibrations, creating damage hotspots within the packaging (Garcia‐Romeu‐Martinez et al., 2008).

Palletization techniques, such as stretch wrap films and interlocking stacking patterns, enhance stability and minimize mechanical stresses. Zhou et al. (2007) emphasized that secure palletization reduces vibrations, particularly in multi-layer configurations. Ventilation within palletized systems also plays a critical role, maintaining airflow to prevent spoilage while reducing internal pressure buildup (Lin et al., 2023). However, excessive ventilation can compromise structural integrity, highlighting the need for balanced designs.

Mukama et al. (2020a) noted that integrating load stability strategies with optimized packaging designs, such as reinforced CBs and cushioning materials, significantly reduces mechanical damage. Future research should explore advanced palletization techniques that complement sustainable materials to enhance protection and reduce environmental impact.

2-3 Transportation Parameters and Vibrational Forces

Transportation is a critical phase in the fresh produce supply chain, during which mechanical damage is significantly influenced by external forces. Vibrational forces, often compounded by poor road conditions, vehicle suspension systems, and prolonged transit durations, contribute substantially to bruising, compression, and tissue deformation in apples and other fresh produce.

These forces are transmitted through packaging systems, leading to cumulative damage over time if not adequately mitigated. This section explores the key transportation parameters that impact vibrational forces and their influence on produce quality.

2-3-1 Characteristics of Vibrational Forces

The vibrational forces experienced during transportation consist of multi-directional movements, including three translational vibrations of vertical (also called heave, up-down direction, aligned with the gravitational axis), longitudinal (front-back), and lateral (side-to-side) and three rotational vibrations of Pitch (rotation about lateral axis), Roll (rotation about longitudinal axis), and Yaw (rotation about heave axis). These forces vary in intensity and frequency based on factors such as road quality, vehicle dynamics, and payload distribution. The frequency range encountered during transit typically spans 2–100 Hz, with vibrations in the 10–40 Hz range being particularly damaging to fresh produce, as identified by (S. P. Singh et al., 1992). This is because these frequencies resonate with the natural frequencies of packaging systems, amplifying mechanical stresses and increasing the risk of bruising (Zhou et al., 2007). Lower frequencies, often associated with smooth and consistent surfaces like highways, generate less severe damage compared to higher frequencies induced by rough roads and poorly maintained transport routes.

Lin et al. (2023) emphasized that multi-directional vibrations are significantly more damaging than single-axis vibrations because they expose produce to dynamic forces from multiple angles, resulting in fruit-to-fruit contact, packaging deformation, and cumulative stress. Therefore, while the current single-axis vibration tests practiced by industry and research centers provide an acceptable estimation, they are limited in estimating highly accurate simulations for real-world transportation dynamics. Zhou et al. (2007) further highlighted the need for multi-axis simulations to better understand how combined vibrational forces interact with packaging materials and produce, exacerbating mechanical damage under dynamic transit conditions.

2-3-2 Influence of Suspension Systems

The type of suspension system significantly influences the magnitude and intensity of vibrations transmitted to packaged produce during transportation. Vehicles equipped with leaf-spring (known also as over-the-road) suspensions, commonly found in older and cost-effective transport systems, transmit higher vibrational forces due to their rigid design. These amplified vibrations increase mechanical stresses on the cargo, resulting in higher bruising rates for sensitive fruits such as apples (Garcia-Romeu-Martinez et al., 2008; Zhou et al., 2007).

In contrast, air-ride suspensions, which use pneumatic systems to absorb and dissipate vibrations, provide a smoother ride by reducing the intensity of oscillations transmitted to the cargo. Studies by Fernando et al. (2020); Garcia-Romeu-Martinez et al. (2008); Zheng et al. (2022) have consistently shown that fruits transported in vehicles with air-ride suspensions experience significantly less damage compared to those transported with leaf-spring systems. The smoother ride profile of air-ride suspensions not only reduces peak vibration magnitudes but also helps maintain load stability, particularly for fragile produce like apples.

Despite their advantages, air-ride suspensions face barriers to widespread adoption due to their higher implementation costs and limited availability in some regions and industries. These challenges highlight the need for cost-effective solutions, such as retrofitting existing vehicles or optimizing packaging systems, to mitigate vibrational forces in vehicles with leaf-spring suspensions.

2-3-3 Effect of Road Quality and Transport Routes

Road conditions play a pivotal role in determining the magnitude and intensity of vibrational forces experienced during transit. Smooth and well-paved roads, such as highways, generate consistent low-frequency vibrations that are less damaging to produce. In contrast, poorly maintained roads, unpaved surfaces, or mountainous routes produce high-frequency disturbances, which significantly increase the severity of mechanical stresses (Zhou et al., 2007).

Garcia-Romeu-Martinez et al. (2008) observed that rough road conditions not only amplify vibrational forces but also introduce additional shocks and jolts, exacerbating bruising and other mechanical damage to fresh produce. Furthermore, the combination of poor road surfaces and suboptimal suspension systems creates a highly dynamic environment, amplifying the frequency spectrum of vibrations and challenging packaging systems to absorb a broader range of forces without compromising load stability. Frequent stops and starts encountered on urban transportation routes further contribute to horizontal movements of packaged produce, increasing damage risks (Zheng et al., 2022).

Chonhenchob et al. (2009) demonstrated that rough road conditions, particularly in mountainous areas, significantly amplified vibrational forces, leading to increased bruising and damage to packaged produce. Their study on truck transport of fresh produce in Thailand revealed that poorly maintained roads between farms and packing houses resulted in the highest vibration levels and damage rates. These findings highlight the importance of optimizing transport routes to prioritize smoother roads and reducing transit duration to minimize cumulative vibrational stresses.

To mitigate these challenges, researchers emphasize the importance of optimizing transport routes to prioritize smoother roads and reducing transit duration to minimize cumulative vibrational stresses. Lin et al. (2023) highlighted that highway routes are preferable for long-haul transportation, as they generate fewer dynamic disturbances compared to rural and urban alternatives, helping to preserve the quality and integrity of transported produce.

2-3-4 Impact of Transport Duration

Transport duration is a critical parameter influencing the extent of mechanical damage to fresh produce, as prolonged exposure to vibrational forces results in cumulative damage. Vibrational energy is repeatedly transferred to the produce, weakening its structural integrity and increasing susceptibility to bruising and deformation over time. Zheng et al. (2022) observed minimal damage during the initial 3 hours of transit; however, bruising rates increased significantly beyond this threshold, highlighting the cumulative effects of extended exposure to vibrations.

The impact of transport duration is particularly pronounced in packaging systems with inadequate cushioning. Fernando et al. (2020) found that rigid plastic crates, which lack energy-dissipating properties, resulted in higher bruising rates during extended transit compared to corrugated boxes with volume packs. Conversely, corrugated packaging demonstrated greater resilience, as its energy-dissipating design effectively mitigated the mechanical stresses associated with prolonged exposure.

When combined with poor road quality and leaf-spring suspensions, extended transport durations create the most severe conditions for mechanical damage. These findings underscore the necessity of designing packaging solutions that maintain protective performance over long durations and incorporating effective cushioning materials to minimize cumulative damage.

2-3-5 Real-World Transport Challenges and Future Multi-Axis Testing

Traditional vibration studies often focus on single-axis movements, which is limited in replicating the multi-directional forces encountered during real-world transportation. Lin et al.

(2023); S. P. Singh et al. (1992) emphasized that multi-axis vibrations create complex dynamic interactions between packaged produce, packaging materials, and the vehicle environment, leading to increased damage rates. Zhou et al. (2007) further highlighted that the combination of vertical, longitudinal, and lateral forces amplifies fruit-to-fruit contact and causes uneven load distribution within the packaging, exacerbating mechanical damage.

Real-world transportation introduces additional challenges, such as variable vehicle loading patterns, stacking configurations, and inconsistent load stabilization. Garcia-Romeu-Martinez et al. (2008) noted that improper load distribution within vehicles can amplify vibrations, resulting in localized damage hotspots that traditional single-axis tests cannot capture. These multi-directional forces and loading inconsistencies create a dynamic environment where damage assessment becomes increasingly complex.

To address these challenges, researchers stress the importance of incorporating multi-axis vibration simulations in studies to replicate highly realistic transit environments accurately. While organizations such as ISTA are actively working on developing a multi-axis transportation vibration test standard for packaging distribution, no such standard had been officially approved at the time this study was completed. Future research should also explore optimized load distribution techniques and advanced packaging designs that stabilize loads and minimize damage under dynamic transit conditions. By better aligning testing methodologies with real-world scenarios, it will be possible to develop more effective packaging solutions and handling protocols.

2-4 Environmental Factors: Temperature and Humidity

Temperature and relative humidity (RH) are critical environmental factors that significantly influence the postharvest quality and mechanical properties of fresh produce, including apples.

Proper management of these factors is essential to mitigate mechanical damage during transportation and storage, ensuring product quality and reducing postharvest losses.

2-4-1 Influence of Temperature on Mechanical Properties

Temperature directly affects the physiological and mechanical characteristics of apples during transport. High temperatures accelerate metabolic processes, including respiration and ethylene production, leading to tissue softening and reduced mechanical strength. These weakened tissues are more prone to damage when exposed to vibrational or compressive forces during transit (Dagdelen & Aday, 2021).

Fluctuating temperatures exacerbate these issues by disrupting cellular cohesion within the fruit. Consistent refrigeration, typically between 0 °C and 4 °C, preserves tissue firmness and reduces susceptibility to mechanical damage by slowing enzymatic activities and maintaining cellular integrity (Al-Dairi et al., 2022). However, extreme deviations from this optimal range can weaken cell walls and increase susceptibility to bruising and compression stresses during transportation.

Controlled temperature environments, such as refrigerated transport systems, have been shown to mitigate these risks significantly. However, the high costs and logistical challenges associated with these systems limit their widespread application, particularly in resource-constrained settings (Garcia‐Romeu‐Martinez et al., 2008).

2-4-2 Impact of Humidity on Bruising Susceptibility

As we mentioned, relative humidity plays a pivotal role in maintaining the structural integrity of fresh produce by influencing turgor pressure and moisture content. When RH levels drop too low, apples lose moisture, leading to a decrease in turgor pressure and making the tissue more prone to bruising (Fernando et al., 2020; Zheng et al., 2022).

Conversely, excessive humidity levels above 95% can result in surface condensation, creating a favorable environment for microbial growth and decay. Poorly ventilated packaging systems exacerbate this issue, particularly during long-haul transportation. Maintaining RH within the optimal range of 85% to 95% has been shown to reduce bruising susceptibility and maintain fruit firmness, ensuring better overall quality during transit (Lin et al., 2023).

2-4-3 Combined Effects of Temperature and Humidity

The interaction of temperature and humidity creates a complex environment that directly influences the susceptibility of apples to mechanical damage. For instance, high temperatures coupled with low humidity exacerbate moisture loss, reducing tissue elasticity and increasing bruising susceptibility. Conversely, high humidity levels combined with fluctuating temperatures promote condensation, leading to microbial decay and physiological breakdown.

Innovative solutions, such as controlled atmosphere (CA) systems, have demonstrated potential in mitigating these risks by maintaining stable temperature and humidity levels. However, their high implementation costs pose challenges for widespread adoption (Zheng et al., 2022).

2-5 Research Gaps

While significant progress has been made in understanding the mechanical damage to fresh produce during transportation, several gaps remain in existing research. Most studies focus on isolated factors, such as vibration intensity, transport duration, suspension type, apple cultivars or packaging configurations, without examining their combined effects. For instance, Zhou et al. (2007b) and S. P. Singh et al. (1992) emphasized the need for multi-axis vibration simulations to better replicate real-world transportation conditions but did not explore how various packaging designs respond to such dynamic forces. Similarly, Lin et al. (2023) highlighted the limitations of single-axis vibration studies but did not evaluate the influence of multi-layer packaging configurations or cushioning materials under realistic transit scenarios.

Packaging studies have often been constrained by static or single-variable evaluations. For example, Fernando et al. (2020) and Jiang et al. (2021) demonstrated the effectiveness of vacuum and semi-vacuum packaging in minimizing vibration damage but did not consider variations in suspension systems or road conditions. Likewise, U. L. Opara and Fadiji (2018) evaluated the protective performance of corrugated fiberboard designs but did not examine their effectiveness under prolonged transport durations or in combination with cushioning materials like paper-based alternatives.

This study addresses these gaps by adopting a holistic approach that evaluates the combined effects of:

1. Vibration parameters (intensity which represents road conditions and duration).
2. Transportation vehicle factors, including suspension systems.
3. Packaging configurations, including motion-limited, cushioned, and multi-layer designs with and without sustainable materials.
4. Apple varieties, including Fuji an Jonagold

By simulating realistic transportation conditions and incorporating ASTM D4169 single-axis vibration test standard, this research provides relatively comprehensive insights into how these factors interact to influence apple bruising damage. As additional investigations for future studies, it also 1) evaluates the performance of Hexcel wrap and other sustainable materials in dynamic scenarios, addressing their untested potential in real-world applications and 2) explores the distribution of mechanical stresses within multi-layer packaging systems, offering a deeper understanding for optimizing protective solutions for fresh produce transportation.

The novelty of this study lies in its relatively comprehensive and data-driven approach to analyzing apple bruising during transportation. Specifically:

1. Unlike prior studies that often considered only a few isolated factors, this work simultaneously incorporates multiple influential variables—including vibration intensity, duration, suspension type, packaging design, and apple variety—to evaluate their combined effects on bruising. The resulting dataset also contributed to a chapter of machine learning-based PhD dissertation by student Khadijeh Shirzad at MSU's School of Packaging, who graduated in 2024.
2. It applies statistical analyses such as ANOVA to visualize trends, compare group differences, and provide deeper insights into the variability and structure of the results.
3. It ranks the relative importance of these factors using a machine learning model, offering actionable insights for packaging designers. This enables targeted damage mitigation by focusing on the most influential variables, particularly in situations where addressing all factors may not be feasible.
4. This study advocates for the development of additional test profiles by institutes such as ASTM and ISTA, including: A) multi-axis vibration tests, and B) tailored tests specifically for fresh produce, to more accurately simulate real-world transportation conditions.

Most of the results of this study have been published in a journal and conference paper (Keyhan et al., 2024).

CHAPTER 3 – MATERIALS AND METHODS

3-1 Plant material

Six bins of two varieties of fresh apples, Jonagold and Fuji, were kindly donated by the MSU Clarksville Horticultural Experiment Station (MSU Clarksville Research Center, Clarksville, MI). The healthy apples were carefully handpicked from bins to ensure uniformity in size and maturity. The latter was assessed based on color, firmness, and the absence of physical defects.

3-2 Packaging and packaging materials

Packaging materials were kindly donated by Riveridge Produce Marketing, Inc. (Sparta, MI). These were combined to create four packaging designs commonly adopted for apple transportation in the U.S. apple fruit industry. We identified them as A, B, C, and D in this study. The apples were divided into groups and each group was placed in each of the four packaging designs. The details of the packaging designs and the number of apples they contained are as follows:

- Package A comprised a corrugated paperboard Regular Slotted Container (RSC) with a molded paper pulp tray (Figure 3(a)). The dimensions of this box were 48×32×10.5 *cm*. Each molded paper pulp tray accommodated 20 apples. The total carrying capacity of the package was about 9 pounds.
- Package B used corrugated paperboard boxes, similarly to Package A; however, the molded paper pulp tray was replaced by the plastic bags, a method referred to as volume packing (Figure 3(b)). Each bag was capable of holding 4 to 5 apples, approximately 11 pounds in total.
- Package C consisted of a Reusable Plastic Container (RPC) with a molded paper pulp tray (Figure 4(a)). The container dimensions were 58×39.5×19 *cm*. Each molded paper pulp

tray accommodated 30 apples. The total weight capacity of the container was around 16 pounds.

- Package D used RPC similar to Package C but employed volume packing, with an average weight of approximately 18 pounds (Figure 4(b)).

(a) Package A

(b) Package B

Figure 3. Packaging designs used in the study: (a) Package A - Corrugated paperboard RSC with a paper pulp tray, and (b) Package B - Volume packing with a corrugated paperboard RSC

(a) Package C

(b) Package D

Figure 4. Packaging designs used in the study: (a) Package C - RPC with paper pulp tray, and (b) Package D - Volume packing with RPC

3-3 Truck Vibration Simulation

Truck vibrations were simulated using an electro-dynamic shaker (Model 10000 Vibration Test System, Lansmont) (Figure 5). The packages were placed on the shaker table without any constraints to vibrate freely thereby simulating truck transit conditions.

Figure 5. Electro-dynamic shaker and packaging setup

3-4 Vibration Profiles

Vibration profiles in accordance with ASTM D4169 standard were applied to all the packaging designs to explore the factors influencing apple damage in a simulated vibration environment. Furthermore, vibration intensities were manually adjusted to simulate additional road conditions, such as rough roads. The variables studied were transportation duration (1, 3, and 5 hours), vibration intensity (0.2, 0.3, 0.5, and 0.7 Grms), and suspension profile (air ride and leaf spring).

3-5 Bruise Measurement

Upon the completion of the lab random vibration tests, the packaged apples were kept at 70°F and 50% RH for 72 hours to allow bruises to fully develop and become more visible. Subsequently, the packages were opened, and each apple was individually examined for external damage. Apples can suffer from both external and internal damages (Fadiji et al., 2024). According to the previous studies in the literature, the depth of the damage in apples is directly related to the surface area damage (Pathare & Al-Dairi, 2021; Rehkugler & Throop, 1986). Therefore, in this study, the surface damage area of the apples is measured, which is one of the standard approaches in the industry (Fadiji et al., 2024; U. L. Opara & Pathare, 2014; S. P. Singh et al., 1992). In this study, apples were classified as 'damaged' or 'undamaged' (refer to Figure 6) based on US grade standards, which primarily consider bruising, cuts, and puncture damages (S. P. Singh et al., 1992). An apple was deemed 'damaged' if it exhibited bruising with a diameter exceeding 0.25 inches (S. P. Singh et al., 1992); otherwise, it was considered 'undamaged.' A caliper was used to measure the bruise diameter. The incidence of damage was meticulously documented for each type of packaging and vibration scenario, providing a clear indication of the percentage of apples affected by bruising within each package. This percentage represents the proportion of apples within a box that sustained any form of bruising compared to the total number of apples in the package.

(a) (b)

Figure 6. Jonagold (a) Undamaged apples (b) Damaged apples

3-6 Statistical Analysis

To assess the statistical significance of factors influencing apple bruising, this study applied Analysis of Variance (ANOVA) and Tukey's Honest Significant Difference (HSD) test to determine whether different packaging types, vibration intensities, transportation durations, and suspension profiles had a significant impact on damage levels. Additionally, Random Forest Regression (RFR) was utilized to analyze the relative importance of these factors in predicting apple damage, allowing for a more detailed understanding of the dominant contributors to mechanical damage. These statistical methods ensured that the conclusions drawn from the experiments were not only based on observed trends but also statistically validated.

3-6-1 Analysis of Variance (ANOVA)

To determine whether the tested factors led to significant differences in apple bruising, a one-way Analysis of Variance (ANOVA) was performed. ANOVA is a statistical method that compares the means of multiple groups to assess whether any of them differ significantly from one another (St & Wold, 1989). It does this by partitioning the total variability in the data into between-group variability, which arises due to differences among experimental conditions, and within-group variability, which accounts for random variation within each group.

ANOVA relies on the assumption that the distributions of the dependent variable within each group are approximately normally distributed.

The statistical measure used in ANOVA is the F-ratio, which is defined as the ratio of between-group variability to within-group variability:

$$F = \frac{MSB}{MSW}$$

where MSB (Mean Square Between groups) is the variance due to differences between group means and MSW (Mean Square Within groups) represents the variance within each group. These values are calculated as follows:

$$MSB = \frac{\sum_{i=1}^{k} n_i(\bar{X}_i - \bar{X})}{k-1}$$

$$MSW = \frac{\sum_{i=1}^{k}\sum_{j=1}^{n_i}(X_{ij} - \bar{X}_i)^2}{N-k}$$

where n_i is the sample size of group i, $\bar{X}_i$ is the mean of group i, $\bar{X}$ is the overall mean, k is the number of groups, and N is the total number of observations. A large F-value suggests that at least one group mean significantly differs from the others.

P-value is a statistical measure that helps you determine whether the differences observed between groups are likely due to chance or are statistically significant (Moore et al., 2009). In ANOVA, the p-value tells you whether at least one group's mean is significantly different from the others. A small p-value (typically ≤ 0.05) suggests that the observed differences are unlikely due to random chance, so you reject the null hypothesis (which assumes all group means are equal). A large p-value (> 0.05) suggests there is not enough evidence to say the group means are different, so you fail to reject the null hypothesis.

If the p-value associated with the F-statistic is below the significance threshold (commonly 0.05), the null hypothesis, which assumes no difference between the groups, is rejected, indicating that at least one packaging or vibration condition has a statistically significant impact on apple bruising.

3-6-2 Tukey's Honest Significant Difference (HSD) Test

After performing ANOVA, Tukey's Honest Significant Difference (HSD) test was conducted as a post-hoc analysis to determine which specific packaging types or vibration conditions exhibited statistically significant differences in bruising rates. Tukey's HSD test accounts for multiple comparisons, reducing the risk of Type I errors that may arise when performing several pairwise tests. The test calculates a critical difference value, known as the HSD value, which is given by:

$$HSD = q \times \sqrt{\frac{MSW}{n}}$$

where q is the Studentized range statistic, which depends on the number of groups and degrees of freedom, MSW is the mean square within groups (from ANOVA), and n is the sample size per group. If the absolute difference between the means of two groups exceeds the HSD value, those groups are considered significantly different. While ANOVA identifies whether a factor has an overall significant effect, Tukey's HSD test determines which specific levels within that factor differ from one another. This allows for direct pairwise comparisons, highlighting where significant differences exist among packaging types, vibration intensities, or transportation durations. By pinpointing which conditions lead to greater or lesser bruising, Tukey's HSD provides a more precise understanding of how individual factor levels contribute to apple damage, refining the interpretation of statistical significance detected by ANOVA.

3-6-3 Random Forest Regression for Feature Importance

To complement the hypothesis testing methods, Random Forest Regression (RFR) was employed to determine the relative importance of packaging type, vibration intensity, transportation duration, and suspension profile in predicting apple damage. Random Forest is an ensemble learning algorithm that constructs multiple decision trees using bootstrapped samples and aggregates their predictions to improve accuracy and reduce overfitting (Breiman, 2001). Unlike ANOVA, which identifies whether a factor has a statistically significant effect, Random Forest determines the relative contribution of each factor in explaining variations in bruising rates.

In a Random Forest model, each decision tree predicts an outcome, and the final prediction is obtained by averaging the predictions from all trees. Mathematically, the final output is represented as:

$$\hat{y} = \frac{1}{M}\sum_{m=1}^{M} T_m(X)$$

Where $\hat{y}$ is the predicted bruising rate, M is the total number of decision trees, and $T_m(X)$ represents the prediction from tree m given input variables X, which include packaging type, vibration intensity, duration, and suspension system.

The importance of each factor in predicting bruising rates is determined by how much it reduces impurity (i.e., variance) across all trees in the forest. The feature importance score for each predictor variable is calculated as:

$$FI_j = \sum_{t \in T} \frac{\Delta I_t(j)}{|T|}$$

where FI_j represents the importance score of features j, $\Delta I_t(j)$ denotes the reduction in impurity (variance) when feature j is used for splitting at node t, and $|T|$ is the total number of trees in the Random Forest. Higher values of FI_j indicate that the corresponding feature plays a greater role in predicting apple damage.

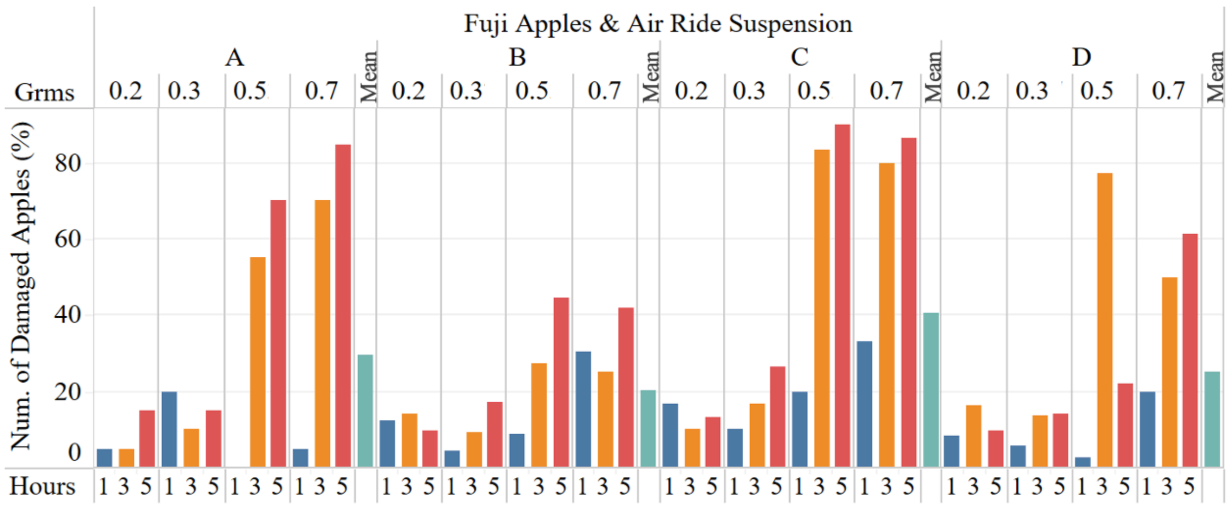
CHAPTER 4 – RESULTS

4-1 Effect of vibration parameters on apple damage

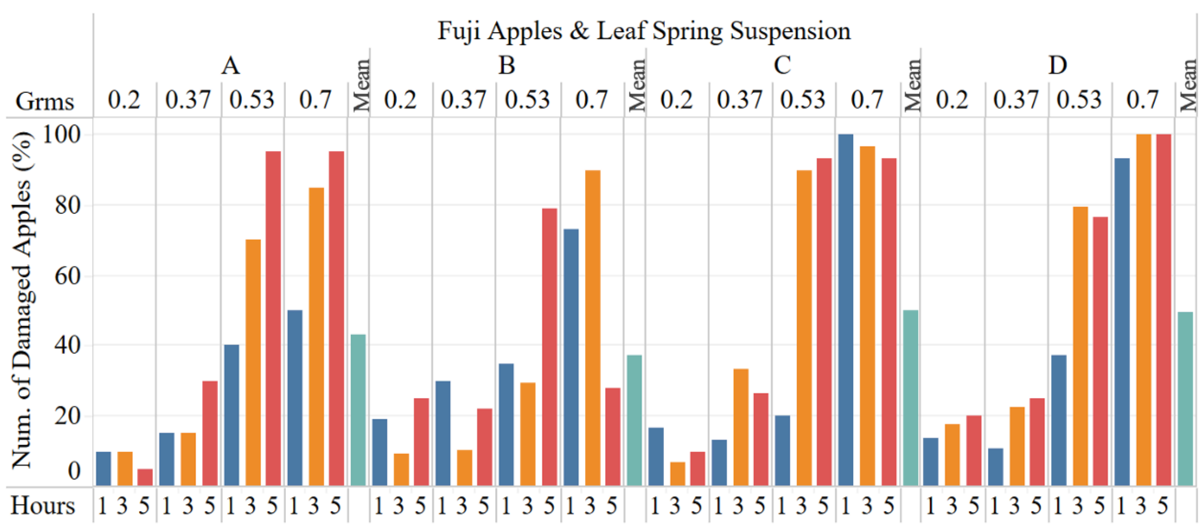
This section presents the results of the vibration simulation experiments, including raw data visualization and observations, statistical analyses, and key findings regarding the impact of suspension type, packaging configuration, vibration intensity, and transportation duration on apple bruising.

Figures 7 and 8 show the number of damaged apples under three vibration durations (1, 3, and 5 hours) indicated on the bottom x-axis, and four random vibration intensities (0.2, 0.3, 0.5, and 0.7 Grms) indicated on the top x-axis. These intensities simulate a range of road conditions from smooth (i.e., 0.2 Grms) to rough (i.e., 0.7 Grms). The figures include results for four types of packaging (A, B, C, and D) for both Fuji and Jonagold apples, following vibration simulation tests and 72 hours of post-conditioning. In all figures, the turquoise color bar at each packaging type section represents the average percentage of damages. Apples in packaging A and B are generally more effectively immobilized compared to those in packaging C and D because the bouncing movement of apples was restricted in the corrugated paperboard RSC when the box flaps were closed. Additionally, the tray and plastic materials used in these packages are stiffer than corrugated paperboard. These factors contribute to packaging B and C showing the lowest and highest percentage of damage, respectively, compared to the other packaging types.

Higher vibration intensities and durations generally increase the number of damaged apples in most cases. However, given the experimental nature of this study, there are a few exceptions. For example, in Figure 7(a), for packaging D under intensity of 0.5 Grms, it was unexpected to observe that the 3-hour vibration resulted in greater damage compared to the 5-hour vibration case. Furthermore, at the lowest intensity of 0.2 Grms and the shortest duration of 1 hour, packaging A exhibited the least damage among all packaging types. Based on these findings, it is important to consider various factors included in this study when selecting the appropriate packaging for apples.

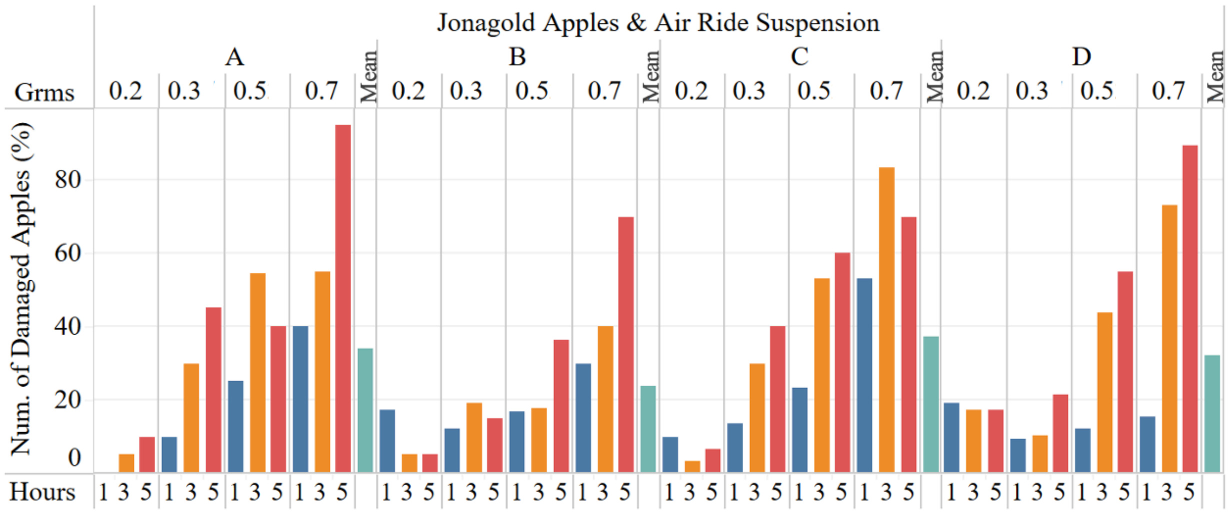


(a) Fuji Apples, Air ride truck suspension vibration simulation

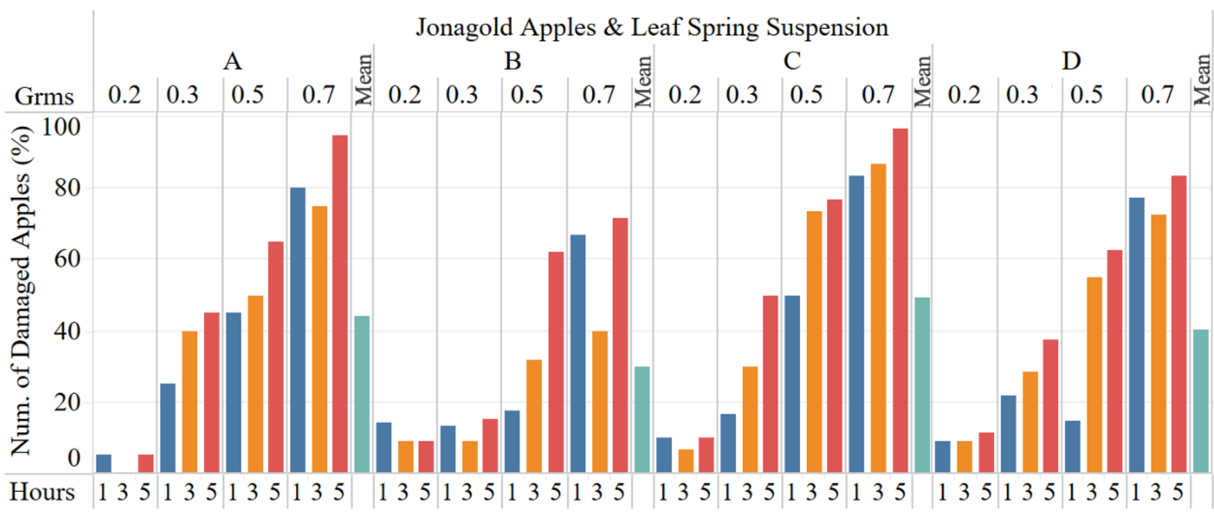


(b) Fuji Apples, Leaf spring truck suspension vibration simulation

Figure 7. Fuji Apple results for the simulated truck vibration with (a) air ride and (b) leaf spring truck suspension. The turquoise color bars are the mean value of damage numbers of all vibration durations and intensities for each packaging type: A – Corrugated board with molded pulp tray, B – Corrugated board with volume packing, C – Reusable plastic container (RPC) with tray, and D – Reusable plastic container (RPC) with volume packing



(a) Jonagold Apples, Air ride suspension truck vibration simulation



(b) Jonagold Apples, Leaf spring suspension truck vibration simulation

Figure 8. Jonagold Apple results for the simulated truck vibration with (a) air ride and (b) leaf spring truck suspension. The turquoise color bars show the mean value of damage numbers of all vibration durations and intensities for each packaging type: A – Corrugated board with molded pulp tray, B – Corrugated board with volume packing, C – Reusable plastic container (RPC) with tray, and D – Reusable plastic container (RPC) with volume packing

Besides, as reported by several other studies (Singh et al., 2006; Fernando et al., 2018; Soleimani & Ahmadi, 2015), trucks equipped with leaf spring suspension systems tend to transfer larger amounts of transportation vibrational energy to the shipping package inside the truck. This energy transfer can be investigated by several methods such as measuring the accelerations using a number of accelerometers or measuring the package damage. Figures 7(a) and 8(a), which report the results for Air Ride suspension, show lower percentage of damage compared to the results in Figures 7(b) and 8(b), which represent the Leaf Spring cases. Table 1 presents the average of all values for each apple cultivar and suspension system. The Leaf Spring suspension increased the number of damages by 36% and 22% for Fuji and Jonagold apples respectively. In the Air Ride cases, Jonagold apples showed a slightly higher number of damages compared to Fuji, whereas in the Leaf Spring vibration simulations, Fuji apples experienced more damage.

Table 1. The average value of different intensities, durations, and packaging types in the simulated vibration tests

Apple Cultivar	**Suspension Type**	**Average Percentage of Apples Damage (%)**
Fuji	Air ride	28.9
	Leaf Spring	45.1
Jonagold	Air ride	31.7
	Leaf Spring	40.9

To assess the statistical significance of key vibration parameters on apple bruising and determine statistical significance, Analysis of Variance (ANOVA) was performed, followed by Tukey's Honest Significant Difference (HSD) test for post-hoc comparisons.

Figure 9 illustrates the comparison between air-ride and leaf spring suspension systems, showing the mean percentage of bruised apples along with standard error bars. The results clearly indicate that apples transported with air-ride suspension experienced lower damage compared to those transported with leaf spring suspension.

The ANOVA results also confirmed that the choice of suspension system had a statistically significant impact on apple damage at a 95% confidence level (p-value = 0.004172). Tukey's HSD test further revealed that leaf spring suspension led to significantly higher damage rates compared to air-ride suspension, indicating that the increased vibrational energy transferred in leaf spring systems contributes more to mechanical damage. These findings validate prior studies highlighting the harsher vibrational environment associated with leaf spring systems.

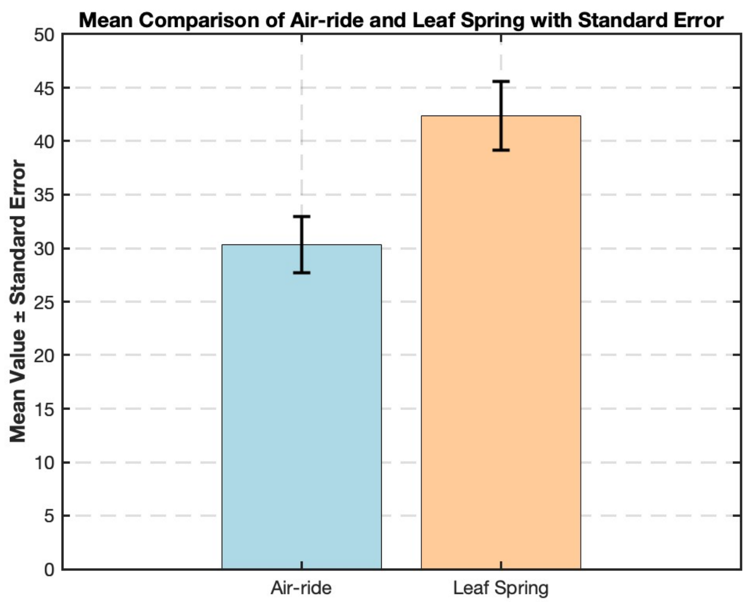


Figure 9. Mean comparison of air-ride and leaf spring suspension systems with standard error bars. Apples transported with leaf spring suspension experienced significantly higher damage than those with air-ride suspension (ANOVA p-value = 0.004172)

Damage levels varied significantly across different packaging configurations, with Package B showing the lowest bruising rates and Package C the highest. These results highlight the critical role of packaging design in minimizing apple bruising and preserving fruit quality during transportation (Figure 10).

A separate ANOVA was conducted to compare four different packaging configurations. The analysis revealed a statistically significant difference among the packaging types at a 95% confidence level (p-value = 0.031733), confirming that packaging plays a crucial role in mitigating mechanical damage during transportation. Tukey's HSD test was performed to identify specific differences between packaging configurations, showing that Package B and Package C exhibited a statistically significant difference in damage levels at the 95% confidence level. This suggests that packaging design directly influences apple bruising, emphasizing the need for optimized cushioning and structural stability to minimize mechanical stress.

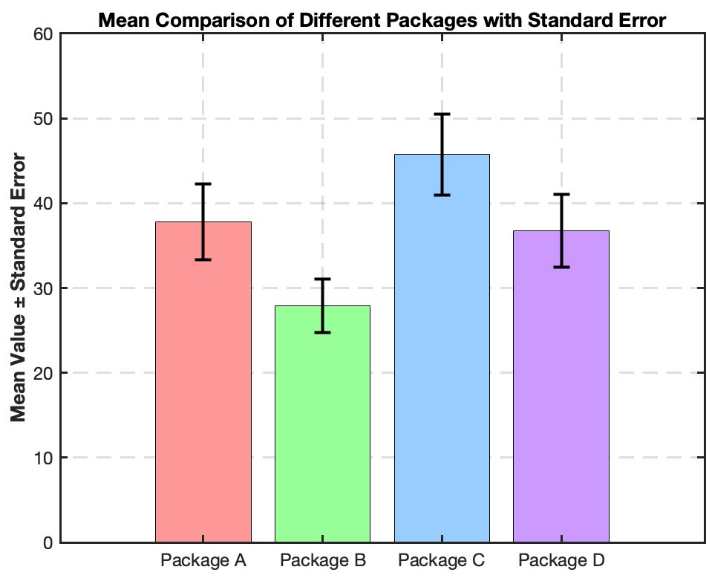


Figure 10. Mean comparison of four packaging configurations (A, B, C, and D) with standard error bars. Apples packaged in different configurations experienced significantly different damage levels (ANOVA p-value = 0.031733)

Higher vibration intensities (0.5 and 0.7 Grms) result in significantly more bruising compared to lower intensities (0.2 and 0.3 Grms), demonstrating the importance of minimizing vibration exposure to reduce fruit damage during transit (Figure 11).

To statistically validate the impact of different vibration levels, ANOVA was performed, confirming a highly significant effect on apple damage at a 95% confidence level (p-value =

1.8386e-21). The results indicate that as vibration intensity increases, the percentage of damaged apples also rises, highlighting the strong correlation between vibration severity and mechanical damage. To further examine which intensity levels were significantly different from each other, Tukey's HSD test was conducted. The results showed that each intensity level exhibited statistically significant differences compared to the others, suggesting that even small increases in vibration intensity contribute to noticeable differences in apple bruising.

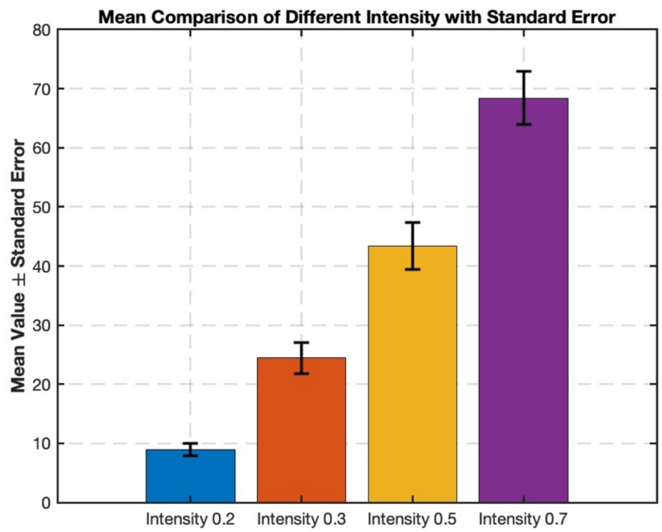


Figure 11. Mean comparison of different vibration intensities (0.2, 0.3, 0.5, and 0.7 Grms) with standard error bars. Apples exposed to higher vibration intensities experienced significantly greater damage (ANOVA p-value = 1.8386e-21)

The duration of vibration exposure is another key factor affecting the extent of apple bruising during transportation. Bruising severity increased with longer transportation durations, with 5-hour tests resulting in significantly more damage than 1-hour and 3-hour tests. This trend reinforces the importance of minimizing transit time or using improved protective packaging to reduce mechanical damage during transportation (Figure 12).

To statistically validate its impact, ANOVA was performed, confirming a significant effect at a 95% confidence level (ANOVA p-value = 0.018214). The results indicate that as transportation duration increases, the percentage of damaged apples also rises, demonstrating a direct relationship between exposure time and bruising severity. To further analyze the differences among durations, Tukey's HSD test was conducted, revealing that the damage levels varied significantly across the three tested durations.

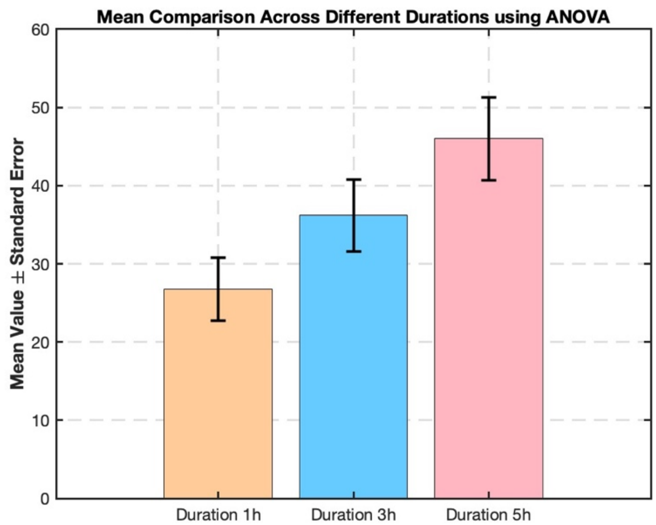


Figure 12. Mean comparison of different vibration durations (1h, 3h, and 5h) with standard error bars. ANOVA results confirmed a statistically significant effect of transportation duration on apple damage (ANOVA p-value = 0.018214)

4-2 Damage severity based on the applied intensities

Figure 13(a) clearly demonstrates that an intensity level of 0.7 Grms, simulating significant road roughness, caused visible deformation to the molded pulp tray, including indentations and weakened structural integrity. Conversely, Figure 13(b) shows that a package subjected to a lower vibration intensity of 0.2 Grms maintained the tray's original shape with minimal impact. These observations highlight the influence of road roughness on both packaging stability and fruit bruising. A vibration intensity of 0.7 Grms and its resulted apple damage rate rarely occurs on today's relatively high-quality roads and air-ride suspension trucks in the U.S. However, it can still serve as a safety factor in package design for extreme vibration conditions, such as those that may be encountered in developing countries.

(a)

(b)

Figure 13. Package damage at varying intensity levels (a) 0.7 Grms, and (b) 0.2 Grms

As outlined in Section 3, the choice of packaging design and the parameters of transportation vibration significantly influence the post-transit quality and marketability of apples. To minimize vibration-induced energy, it is crucial to explore packaging designs that more effectively restrict apple movement and offer enhanced cushioning. Ensuring smoother road conditions from farm storage facilities to final distribution centers and opting for air-ride trucks, when feasible, can further mitigate the risk of damage.

4-3 Feature Importance Analysis Using Machine Learning

To further understand the relative impact of different factors on apple bruising, a Random Forest Regression model was employed to quantify the importance of each parameter in influencing damage severity. While previous analyses, including ANOVA and Tukey's HSD tests, confirmed statistically significant differences among variables, the machine learning approach provides an additional layer of insight by ranking the contribution of each factor.

The model was trained using experimental data, incorporating vibration intensity, transportation duration, vibration profile, packaging type, and apple variety as input features. Figure 14 presents the feature importance scores, indicating how much each factor contributed to the prediction of apple damage. The results indicate that vibration intensity had the highest influence on apple bruising, significantly outweighing the other variables. This finding aligns with the ANOVA results, which demonstrated a strong correlation between increased vibration intensity and higher damage percentages.

Among the remaining factors, transportation duration was the second most influential parameter, reinforcing the observation that longer exposure to vibration exacerbates bruising severity. The packaging type, vibration profile, and apple variety had comparatively lower contributions, suggesting that while they play a role in damage mitigation, their impact is secondary to intensity and duration.

By leveraging machine learning for feature importance analysis, this study provides a data-driven confirmation of the dominant role of vibration intensity in fruit bruising. These findings underscore the need for transportation strategies that minimize exposure to high-intensity vibrations, such as selecting optimized road conditions, improving vehicle suspension systems, and utilizing protective packaging materials to reduce mechanical stress. Furthermore, the ranking of influential factors supports targeted mitigation strategies—enabling stakeholders to prioritize control of the most critical variables when addressing all factors simultaneously is not feasible.

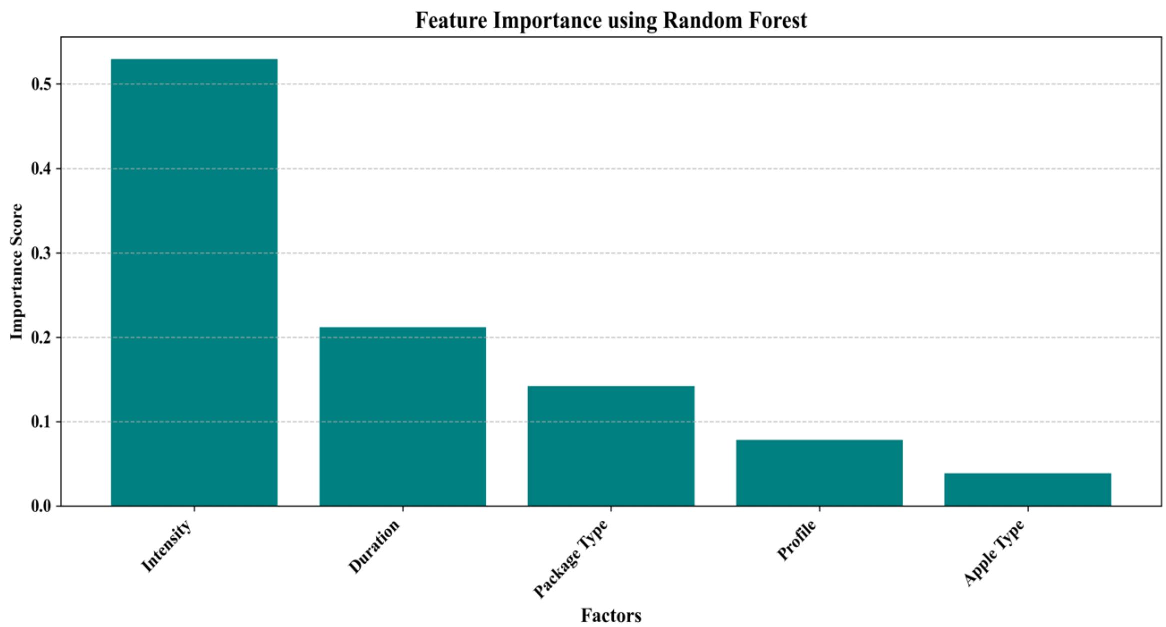


Figure 14. Feature importance analysis using Random Forest Regression to determine the relative impact of different factors on apple

4-4 Additional Test 1: Multilayer packaging design

To further investigate the influence of packaging design on how damage varies across different layers of stacked apples, an additional experiment was conducted using Jonagold apples stacked in a three-layer packaging configuration instead of the single-layer setup used in previous tests. This experiment aimed to assess whether apples in the top, middle, or bottom layers experienced different levels of mechanical damage under simulated transportation conditions.

This research did not aim to comprehensively study the impact of multilayer package design on apple bruising; rather, a preliminary experiment was conducted to explore its potential effects and provide initial insights for future studies on multilayer packaging configurations.

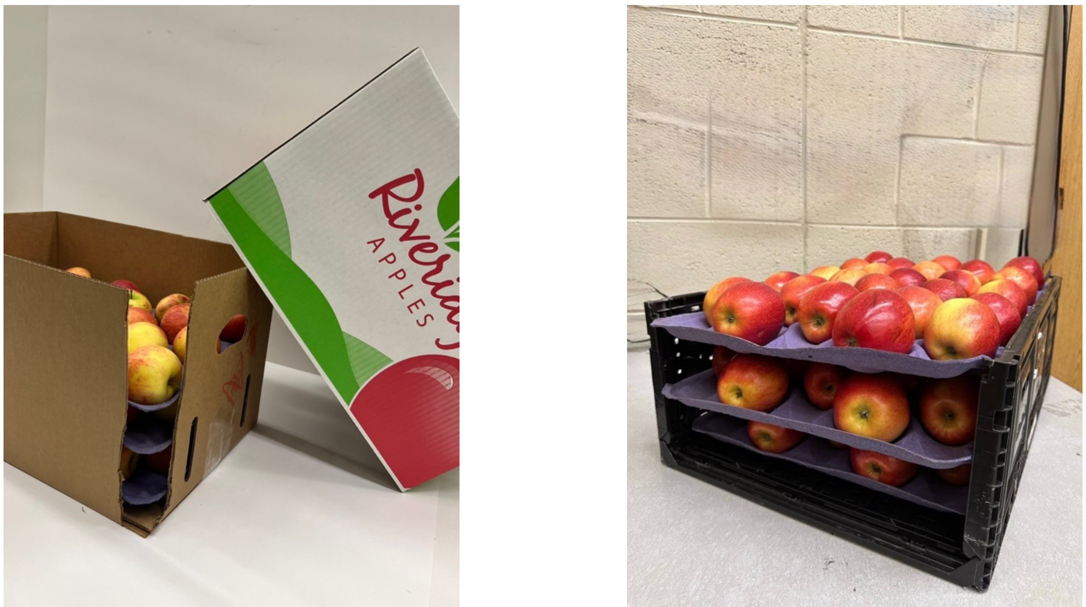
Therefore, one set of test parameters were considered; over-the-road transportation and air-ride simulated vibration at 0.5 Grms for a duration of 5 hours. Two packaging types (Figure 15), Reusable Plastic Containers (RPCs) and Corrugated Board Boxes, were compared to assess the extent of apple damage in each layer.

The results revealed significant difference in damage levels between packaging types and across different layers within the multi-layer packaging. Under over-the-road conditions, Reusable Plastic Containers (RPCs) showed damage rates of 93% in the top layer (Layer 1), 60% in the middle layer (Layer 2), and 35% in the bottom layer (Layer 3). In comparison, the corrugated board (CB) box exhibited higher damage percentages across all layers, with 100% in Layer 1, 70% in Layer 2, and 45% in Layer 3. These results suggest that the top layer experienced the highest level of damage due to direct exposure to vibration and impact forces, while damage progressively decreased in the lower layers due to energy dissipation and load distribution throughout the stack.

A similar pattern emerged during the air-ride simulated vibration test, although the overall extent of damage was notably lower compared to the over-the-road scenario. For RPCs, damage rates were 89% in Layer 1, 53% in Layer 2, and 20% in Layer 3. Conversely, the CB box, despite showing slightly lower damage in the top layer at 95%, continued to exhibit higher damage rates in the lower layers, with 70% in Layer 2 and 25% in Layer 3.

These results highlight two key observations regarding the effect of layer position on apple damage. First, the topmost layer (Layer 1) consistently sustained the highest damage across all test conditions and packaging types. This is primarily due to the direct exposure to dynamic vertical forces, which result in greater compression and impact stresses on the bouncing apples in the top layer. Similar findings have been reported in studies examining mechanical damage distribution in multi-layer packaging, where the upper layers act as the primary load-bearing point and absorb most of the vibrational energy (S. P. Singh et al., 1992; Van Zeebroeck et al., 2007).

The performance of the packaging systems was also influenced by the suspension type. The results showed a noticeable reduction in damage under air-ride suspension compared to over-the-road conditions. This is consistent with studies by Garcia-Romeu-Martinez et al. (2008), which demonstrated that air-ride systems dampen vibrational energy more effectively than leaf-spring suspensions, thereby reducing mechanical damage. The ability of air-ride systems to provide smoother vibration profiles likely enhanced the load stability within RPCs, further mitigating damage, particularly in the lower layers.



(a) (b)

Figure 15. Packaging Design Featuring Multi-layer (a) Corrugated board, and (b) Reusable Plastic Container (RPC)

Overall, the results underscore the importance of both layer position and packaging type in determining damage severity during transportation. Apples in the top layer remain the most vulnerable to mechanical stresses, while lower layers benefit from load distribution and dampening effects. The superior performance of RPCs, particularly under air-ride conditions, suggests that the combination of rigid packaging and controlled vibration environments can significantly reduce apple damage during transit for layered packages. These findings provide a foundation for further optimization of multi-layer packaging designs, such as integrating shock-absorbing materials or tray-based load distribution systems, to further enhance protection across all layers.

4-5 Additional Test 2: Sustainable packaging design

To reduce mechanical damage while addressing sustainability, Hexcel wrap a paper-based honeycomb cushioning material, was integrated into the packaging design to evaluate its effectiveness in fresh produce protection during transportation. Hexcel wrap, measuring 25 inches by 10 inches, is designed to absorb shocks and vibrations while offering enhanced environmental benefits due to its recyclable nature. Functionally, Hexcel wrap acts as a paper-based alternative to bubble wrap, providing comparable protection but with a significantly reduced environmental footprint.

The performance of Hexcel wrap (Figure 16) was evaluated under a transportation condition using Jonagold apples subjected to 5-hour vibration tests at 0.5 Grms. Similar to the multilayered design test in Section 4-4, this research did not initially aim to analyze the impact of Hexcel layer on the apple bruising. Rather, it provides a preliminary insight into the extent of bruising reduction achieved with Hexcel wrap under real transportation conditions and how its effectiveness varies across different packaging configurations. Therefore, a limited set of test parameter were selected. Two packaging configurations were tested: a corrugated board box with a tray and a reusable plastic container (RPC) with a tray. Without Hexcel wrap, bruising rates were 65% in the corrugated board system and 77% in the RPC system. When Hexcel wrap was incorporated as a cushioning material, damage was significant bruising rates, reduced to 15% in the corrugated board configuration and 13.3% in the RPC configuration.

The honeycomb structure of Hexcel wrap plays a critical role in absorbing and redistributing impact forces across a larger surface area. This is particularly important during transit, where apples experience both vertical compression and dynamic impacts. The results align with previous studies by U. L. Opara and Pathare (2014), which demonstrated the effectiveness of cushioning materials in minimizing mechanical damage through improved load distribution and impact absorption.

While Hexcel wrap significantly improves apple protection, it introduces an additional cost compared to conventional single-material packaging systems such as bubble wrap or molded trays. In this study, the cost of using Hexcel wraps was approximately 40 cents per box, and this should be more precisely evaluated in future studies. However, the trade-off between cost and performance is offset by the long-term benefits, including reduced product loss, enhanced produce quality, and alignment with industry sustainability goals. As consumer demand for eco-friendly solutions continues to grow, the adoption of recyclable materials like Hexcel wrap presents an opportunity to improve both environmental and economic outcomes in fresh produce transportation.

(a)

(b)

Figure 16. Packaging Design Featuring Hexcel Wrap (a) Corrugated board, and (b) Reusable Plastic Container (RPC)

CHAPTER 5 – SUGGESTION ON APPLE PACKAGE DESIGN AND DISTRIBUTION

To optimize the transportation of apples and minimize potential mechanical damage, shippers are advised to:

1. Utilize packaging solutions that effectively restrict apple movement within the container. These strategies include using:

   a. Volume pack: Use volume packing techniques, where apples are packed inside a plastic bag without individual trays or separators, allowing them to move freely within the package. This method ensures that apples fill the available space, making solid contact with lid to minimize excessive movement. This method minimizes gaps between apples, reducing fruit-to-fruit contact and internal movement that can cause bruising.

   b. Top Lid: Ensure the use of a secure top lid that fits tightly over the apples, making direct contact to prevent vertical movement of apples during transportation. A well-sealed lid helps avoid bouncing and limits the risk of damage caused by sudden jolts or vibrations during transit.

   c. Molded pulp trays: Use molded pulp trays to separate and stabilize each apple, reducing contact and movement within the packaging. This is especially effective for reducing bruising caused by fruit-to-fruit collisions.

   d. Foam inserts: Utilize foam inserts-preferably biodegradable-for sustainability purposes, to provide additional cushioning for particularly sensitive apple varieties or during longer transportation durations.

2. Enhance existing cushioning strategies by optimizing the selection and placement of materials between the apples and the packaging to further absorb shock and vibrations.

a. Bubble wrap: A conventional cushioning material that offers effective shock absorption, particularly useful for delicate apples during extended transit times.
b. Hexcel wrap: Incorporate Hexcel wrap as a cushioning layer between the apples and the container. This paper-based, recyclable material features a honeycomb structure that effectively absorbs shocks and vibrations, reducing the risk of bruising while promoting sustainability.
c. Additional corrugated paperboard layers: Adding extra layers of corrugated paperboard between apple layers enhances protection against vertical compression forces during stacking.
d. Molded pulp trays: Use molded pulp trays to separate and stabilize each apple, minimizing contact and movement within the packaging. This is especially effective for reducing bruising caused by fruit-to-fruit collisions.
e. Paper padding: This recyclable material helps fill empty spaces in packaging, preventing internal movement that can lead to bruising.

3. Opt for the shortest possible routes to the destination: Minimizing the time apples spend in transit is essential to reducing their exposure to mechanical stress and vibration, which can lead to bruising and other forms of damage. Shippers should use route optimization tools, such as GPS navigation systems and route planning software, to identify the most efficient paths to the destination. Conducting trial trips beforehand can also help determine the most practical routes, taking into account factors like traffic patterns, road conditions, and potential delays. Shorter routes not only reduce the risk of mechanical damage but also help preserve apple freshness and extend shelf life by minimizing the time spent outside of controlled storage environments.

4. Choose roads with superior pavement quality: The condition of the road surface plays a significant role in the level of mechanical stress experienced by apples during transportation. Rough or poorly maintained roads can increase vibrations and shocks, leading to higher rates of bruising and damage. Whenever possible, shippers should select routes that feature well-maintained roads with smooth pavement, as these reduce vibrations and provide a more stable transit environment. Conducting pre-trip assessments or using mapping tools such as Google Maps, Waze, or commercial fleet agreement systems (e.g., Verizon Connect) that provide real-time traffic and road condition updates can help identify the best routes. Investing in better road choices can lead to significant long-term savings by reducing product losses due to damage during transit.

5. Favor highways over urban or rural roads when possible: Highways generally offer smoother surfaces and more consistent driving conditions compared to urban streets or rural roads, which often feature potholes, sharp turns, and frequent stops. These sudden stops and uneven surfaces increase the risk of horizontal movement and vibrations, leading to higher bruising rates for apples. Using highways also minimizes the number of stops and starts, further reducing mechanical stresses on the fruit. In addition to offering a smoother journey, highways usually allow for faster transit times, helping to maintain apple quality by reducing the duration of transportation. Prioritizing highway routes, when feasible, is an effective strategy for preserving apple integrity and minimizing postharvest losses.

By adhering to these recommendations, shippers can significantly reduce the risk of mechanical damage to apples during transit. These advancements not only ensure the delivery of high-quality produce to the market but also contribute to broader goals of food waste reduction and environmental sustainability.

CHAPTER 6 – CONCLUSIONS

The main objective of this study was to analyze how various factors, such as vibration intensity, duration, truck suspension, apple cultivars, and packaging configurations, affect the extent of bruising damage to apple fruit produce during postharvest transit. Our findings demonstrated that apples are considerably vulnerable to vibrational energies, with the Leaf Spring truck suspension system leading to more significant bruising than Air-Ride suspensions. It was particularly evident that the tendency of apples to sustain bruising intensified with increased vibrational intensity, which represents road conditions, and longer vibration durations.

Statistical analysis using Analysis of Variance (ANOVA) and Tukey's Honest Significant Difference (HSD) test confirmed that vibration intensity, duration, and packaging type significantly impact apple bruising at a 95% confidence level. The results showed that bruising increased with higher vibration intensities and longer durations, reinforcing the importance of road conditions and transit times in packaging performance. Additionally, Tukey's HSD test confirmed that Package B (corrugated box with plastic volume pack) provided significantly better protection than Package C (reusable plastic container with tray), highlighting the role of packaging design in minimizing apple bruising.

To further quantify the influence of these factors, a Random Forest feature importance analysis was conducted, which confirmed that vibration intensity was the most significant factor affecting bruising, followed by transportation duration. While packaging type and apple cultivars also contributed to damage levels, their impact was comparatively lower. This machine-learning-based approach provided a data-driven perspective on how different parameters contribute to mechanical damage, reinforcing the need for targeted packaging designs based on transportation conditions.

As an additional test, this study examined the integration of Hexcel wrap as a cushioning material to assess its effectiveness in reducing apple bruising. The results confirmed that Hexcel wrap significantly minimized mechanical damage, supporting its potential as a viable alternative to conventional packaging materials. Its honeycomb structure effectively disperses mechanical forces, reducing vibration-induced damage while also offering a recyclable and sustainable solution. These findings reinforce the importance of optimizing cushioning strategies to enhance both produce protection and environmental responsibility in fresh produce transportation.

Additionally, this study tested two specific multi-layer packaging configurations, confirming that damage decreases with depth in the packaging. Apples in Layer 1 consistently experienced the most damage due to direct exposure to dynamic forces, while Layers 2 and 3 exhibited reduced bruising. The combination of Hexcel wrap with rigid containers, such as RPCs, demonstrated greater efficiency in stabilizing the load and minimizing apple movement across layers.

Learning from the results of this study, Chapter 5 provided actionable suggestions for optimizing apple packaging and distribution practices, including recommendations on packaging materials, cushioning solutions, and transportation strategies to minimize bruising and mechanical damage during transit.

This study enhances the existing body of knowledge in produce distribution by emphasizing the vital role of incorporating distribution factors such as truck suspension type, vibration intensity and duration, and packaging configurations. The noticeable variation in bruising observed in this study at different vibrational parameters across transport conditions highlights the opportunity for customized packaging and handling approaches to lessen apple damage. The insights from this study suggest that considering key factors such as packaging type, cushioning materials (e.g., trays, bags, or wraps), and volume packing can significantly reduce mechanical damage in apples during transportation. Strategic modifications to packaging design based on these factors could help lower bruising, maintain fruit quality, and reduce product losses during distribution.

CHAPTER 7 – LIMITATIONS AND FUTURE STUDIES

This study underscores the significance of understanding distribution vibrations and packaging in reducing bruise damage to two varieties of apple fruits and improving packaging performance. However, the research focused exclusively on external damage assessments and did not account for variability among different apple varieties or the influence of environmental factors, such as temperature and humidity, on apple bruising. Future studies should broaden the scope to include a wider range of apple cultivars, incorporate additional shelf-life assessments like apple respiration rate, and examine the effects of environmental conditions on produce damage to provide a more comprehensive evaluation of packaging solutions. Additionally, machine learning models can be developed to predict bruising outcomes based on transportation and packaging parameters, enabling more data-driven decision-making for packaging optimization.

While this study explored single-axis vibration simulations based on the commonly applied ASTM D4169 standard, the complex nature of real-world transportation involves multi-axis vibrations that occur simultaneously in six-degree-of-freedom (6-DoF), including three translational directions—vertical, horizontal (e.g., during braking or acceleration), and lateral—and three rotational directions—pitch (e.g., when passing over a speed bump), roll, and yaw. Current test standards are limited to single-axis vertical vibration. Although there have been recent organized efforts by institutes like ISTA to develop multi-axis vibration test standards, no such standard had been officially approved by the time this thesis was completed. Future research should therefore incorporate multi-axis vibration testing to better simulate real transportation conditions. In particular, three-degree-of-freedom (3-DoF) systems, which include vibrations along three translational axes (vertical, longitudinal, and lateral movements), can provide a more realistic approximation of real-world transport conditions compared to single-axis testing.

Machine learning algorithms, such as Random Forest or deep learning-based predictive models, can be leveraged to analyze complex vibration patterns and their effects on apple damage, helping to refine packaging strategies more effectively. Additionally, testing these multi-axis vibrations across different packaging designs, including sustainable cushioning materials and multi-layer configurations, will provide deeper insights into their protective performance. The recent installation of a 3-DoF shaker table at the School of Packaging at MSU presents a valuable opportunity to advance this research.

Beyond the lack of multi-axis simulation, current ASTM and ISTA vibration test standards are designed for a broad range of package types. However, fresh produce such as apples exhibits unique characteristics—such as the tendency to bounce within packaging and to undergo apple-to-apple impacts—that may not be accurately represented by these general test protocols. Therefore, more specialized vibration tests should be developed by these institutes to better simulate the transportation conditions specific to fresh produce.

Further investigations into internal damage assessment are also necessary. Techniques such as computed tomography (CT) scanning or magnetic resonance imaging (MRI) should be employed to visualize and quantify internal bruising without compromising the integrity of the fruit.

By addressing these gaps, future research can contribute to the development of cost-effective, sustainable, and optimized packaging solutions that mitigate produce damage under realistic transportation conditions. The integration of machine learning with experimental vibration studies can facilitate predictive modeling, improve damage forecasting, and support more efficient packaging innovations. These advancements will not only reduce food waste but also ensure the delivery of high-quality produce, supporting broader environmental and economic sustainability goals.

REFERENCES

Ahmadi, E. (2012). *Bruise susceptibilities of kiwifruit as affected by impact and fruit properties.*

Al-Dairi, M., Pathare, P. B., Al-Yahyai, R., & Opara, U. L. (2022). Mechanical damage of fresh produce in postharvest transportation: Current status and future prospects. In *Trends in Food Science and Technology* (Vol. 124, pp. 195–207). Elsevier Ltd. https://doi.org/10.1016/j.tifs.2022.04.018

Barchi, G. L., Berardinelli, A., Guarnieri, A., Ragni, L., & Fila, C. T. (2002). PH—postharvest technology: damage to loquats by vibration-simulating intra-state transport. *Biosystems Engineering*, *82*(3), 305–312.

Breiman, L. (2001). Random forests. *Machine Learning*, *45*, 5–32.

Chaiwong, S., Saengrayap, R., Rattanakaran, J., Chaithanarueang, A., Arwatchananukul, S., Aunsri, N., Tontiwattanakul, K., Jitkokkruad, K., Kitazawa, H., & Trongsatitkul, T. (2023a). Natural rubber latex cushioning packaging to reduce vibration damage in guava during simulated transportation. *Postharvest Biology and Technology*, *199*, 112273.

Chaiwong, S., Saengrayap, R., Rattanakaran, J., Chaithanarueang, A., Arwatchananukul, S., Aunsri, N., Tontiwattanakul, K., Jitkokkruad, K., Kitazawa, H., & Trongsatitkul, T. (2023b). Natural rubber latex cushioning packaging to reduce vibration damage in guava during simulated transportation. *Postharvest Biology and Technology*, *199*, 112273.

Chonhenchob, V., Sittipod, S., Swasdee, D., Rachtanapun, P., Singh, S. P., & Singh, J. A. (2009). Effect of truck vibration during transport on damage to fresh produce shipments in Thailand. *Journal of Applied Packaging Research*, *3*(1), 27.

Dagdelen, C., & Aday, M. S. (2021). The effect of simulated vibration frequency on the physico-mechanical and physicochemical properties of peach during transportation. *LWT*, *137*, 110497.

Eissa, A., Gamaa, G. R., Gomaa, F. R., & Azam, M. M. (2012). Comparison of package cushioning materials to protect vibration damage to golden delicious apples. *International Journal of Latest Trends in Agriculture and Food Sciences*, *2*(1), 36–57.

Fadiji, T., Coetzee, C., Chen, L., Chukwu, O., & Opara, U. L. (2016). Susceptibility of apples to bruising inside ventilated corrugated paperboard packages during simulated transport damage. *Postharvest Biology and Technology*, *118*, 111–119.

Fadiji, T., Kaseke, T., Lufu, R., Li, Z., Opara, U. L., & Fawole, O. A. (2023). Impact of Packaging on Bruise Damage of Fresh Produce. In *Mechanical Damage in Fresh Horticultural Produce* (pp. 311–336). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-7096-4_15

Fadiji, T., Kaseke, T., Lufu, R., Li, Z., Opara, U. L., & Fawole, O. A. (2024). Impact of Packaging on Bruise Damage of Fresh Produce. In *Mechanical Damage in Fresh Horticultural Produce: Measurement, Analysis and Control* (pp. 311–336). Springer.

Fernando, I., Fei, J., Stanley, R., & Enshaei, H. (2018). Measurement and evaluation of the effect of vibration on fruits in transit. *Packaging Technology and Science*, *31*(11), 723–738.

Fernando, I., Fei, J., Stanley, R., & Rouillard, V. (2020). Evaluating packaging performance for bananas under simulated vibration. *Food Packaging and Shelf Life*, *23*, 100428.

Garcia-Romeu-Martinez, M., Singh, S. P., & Cloquell-Ballester, V. (2008). Measurement and analysis of vibration levels for truck transport in Spain as a function of payload, suspension and speed. *Packaging Technology and Science: An International Journal*, *21*(8), 439–451.

Hussein, Z., Fawole, O. A., & Opara, U. L. (2020). Harvest and postharvest factors affecting bruise damage of fresh fruits. *Horticultural Plant Journal*, *6*(1), 1–13.

Jiang, Q., Jin, W., Zhang, W., Zhang, Z., You, L., Bi, Y., & Yuan, L. (2021). Analysis of vibration acceleration levels and quality deterioration of Chinese bayberry fruit in semi-vacuum package by express delivery. *Journal of Food Process Engineering*, *44*(12), e13899.

Kays, S. J. (1991). *Postharvest physiology and handling of perishable plant products.*

Keyhan, S., Shirzad, K., Almenar, E., & Joodaky, A. (2024). Transportation Vibration Effects on Apple Bruising. *Packaging Technology and Science*, *37*(11), 1065–1071.

Lin, M., Fawole, O. A., Saeys, W., Wu, D., Wang, J., Opara, U. L., Nicolai, B., & Chen, K. (2023). Mechanical damages and packaging methods along the fresh fruit supply chain: A review. *Critical Reviews in Food Science and Nutrition*, *63*(30), 10283–10302.

Moore, D. S., McCabe, G. P., & Craig, B. A. (2009). *Introduction to the Practice of Statistics* (Vol. 4). WH Freeman New York.

Mukama, M., Ambaw, A., & Opara, U. L. (2020a). A virtual prototyping approach for redesigning the vent-holes of packaging for handling pomegranate fruit–A short communication. *Journal of Food Engineering*, *270*, 109762.

Mukama, M., Ambaw, A., & Opara, U. L. (2020b). Advances in design and performance evaluation of fresh fruit ventilated distribution packaging: A review. *Food Packaging and Shelf Life*, *24*, 100472.

Mureșan, A. E., Sestras, A. F., Militaru, M., Păucean, A., Tanislav, A. E., Pușcaș, A., Mateescu, M., Mureșan, V., Marc, R. A., & Sestras, R. E. (2022). Chemometric comparison and classification of 22 apple genotypes based on texture analysis and physico-chemical quality attributes. *Horticulturae*, *8*(1), 64.

Opara, L. U. (2007). Bruise susceptibilities of 'Gala'apples as affected by orchard management practices and harvest date. *Postharvest Biology and Technology*, *43*(1), 47–54.

Opara, U. L., & Fadiji, T. (2018). Compression damage susceptibility of apple fruit packed inside ventilated corrugated paperboard package. *Scientia Horticulturae*, *227*, 154–161.

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.

Pathare, P. B., & Al-Dairi, M. (2021). Bruise susceptibility and impact on quality parameters of pears during storage. *Frontiers in Sustainable Food Systems*, *5*, 658132.

Rehkugler, G. E., & Throop, J. A. (1986). Apple sorting with machine vision. *Transactions of the ASAE*, *29*(5), 1388–1397.

Schulte, N. L., Brown, G. K., & Timm, E. J. (1992). Apple impact damage thresholds. *Applied Engineering in Agriculture*, *8*(1), 55–60.

Singh, J., Singh, S. P., & Joneson, E. (2006). Measurement and analysis of US truck vibration for leaf spring and air ride suspensions, and development of tests to simulate these conditions. *Packaging Technology and Science: An International Journal*, *19*(6), 309–323.

Singh, S. P., Burgess, G., & Xu, M. (1992). Bruising of apples in four different packages using simulated truck vibration. *Packaging Technology and Science*, *5*(3), 145–150.

Soleimani, B., & Ahmadi, E. (2015). Evaluation and analysis of vibration during fruit transport as a function of road conditions, suspension system and travel speeds. *Engineering in Agriculture, Environment and Food*, *8*(1), 26–32.

St, L., & Wold, S. (1989). Analysis of variance (ANOVA). *Chemometrics and Intelligent Laboratory Systems*, *6*(4), 259–272.

Van Zeebroeck, M., Ramon, H., De Baerdemaeker, J., Nicolaï, B. M., & Tijskens, E. (2007). Impact damage of apples during transport and handling. *Postharvest Biology and Technology*, *45*(2), 157–167.

Vursavuş, K., & Özgüven, F. (2004). Mechanical behaviour of apricot pit under compression loading. *Journal of Food Engineering*, *65*(2), 255–261.

Wang, D., Bai, Z., & Liao, Q. (2018). 3D energy absorption diagram construction of paper honeycomb sandwich panel. *Shock and Vibration*, *2018*(1), 4067062.

Wongsuriyasak, S., & Srichandr, P. (2012). Novel packaging material for mango transportation. *Advanced Materials Research*, *472*, 2805–2809.

Yu, J., Wang, M., Li, Z., Tchuenbou-Magaia, F., Wani, A. A., Zhu, P., Fadiji, T., & Liu, Y. (2024). Preserving freshness: Innovations for fresh-eating fruit distribution and damage prevention–A review. *Food Packaging and Shelf Life*, *44*, 101323.

Zheng, D., Chen, J., Lin, M., Wang, D., Lin, Q., Cao, J., Yang, X., Duan, Y., Ye, X., & Sun, C. (2022). Packaging design to protect Hongmeiren orange fruit from mechanical damage during simulated and road transportation. *Horticulturae*, *8*(3), 258.

Zhou, R., Su, S., Yan, L., & Li, Y. (2007). Effect of transport vibration levels on mechanical damage and physiological responses of Huanghua pears (Pyrus pyrifolia Nakai, cv. Huanghua). *Postharvest Biology and Technology*, *46*(1), 20–28.