Vibration intensity and its variation on road-transported agricultural materials - A Review

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Abstract: The transportation of fresh agricultural material is a challenging task that can lead to considerable losses due to vibrations and shock stresses. This study reviews 55 articles published between 1985 and 2023 to gain insights into the impact of these factors on the damage of agricultural material. The review reveals several factors that affect vibration levels during transportation, including the suspension system's type, truck speed, road profile, payload capacity, stack height, and packaging material. However, previous research has examined these factors independently, and their relative impact on the vibration intensity remains unclear. Therefore, we suggest a multi-factor assessment of transport vibration intensity to identify the most influential factors and reduce transport-related losses effectively. Overall, our study emphasizes the need for a comprehensive understanding of the factors that contribute to transport-related losses to minimize agricultural product damages during transportation. Our findings have practical implications for the transportation industry and can be used to inform the development of better transport systems that minimize the loss of agricultural products.

Keywords: vibration, shock stresses, agricultural material, transportation, losses, fresh fruits

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1 Introduction

The transportation of agricultural materials is a critical component of the global supply chain, ensuring that fresh produce reaches its destination in optimal condition. Over time, research in this field has evolved from a primary focus on road surface quality for passenger comfort to a more comprehensive understanding of how transport conditions affect the quality and integrity of agricultural cargo. This shift is driven by the growing realization of the perishability of fresh agricultural/horticultural materials and the preservation of agricultural products during transit is paramount for both economic and ecological reasons.

Earlier studies were primarily concerned with road surface profiles, seeking to establish limitations to ensure road operability and passenger comfort. They often overlooked the potential damage inflicted on agricultural materials during transportation. However, present-day research now recognizes that numerous factors, including road conditions, vehicle vibrations, and packaging materials, play essential roles in the preservation of agricultural cargo. These factors intersect in complex ways, requiring a multifaceted approach to address the challenges posed by agricultural transportation.

Previous studies such as Jarimopas et al. (2005) have explored the effects of varying transport

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conditions on vibration intensities, underlining the significance of vehicle speed and road surface quality. Lepine (2016) has highlighted the connection between road roughness and passenger comfort, emphasizing the role of vehicle suspension tuning and maintenance in mitigating potential cargo damage. Furthermore, studies by Chonhenchob et al. (2009) have unveiled the detrimental impacts of high vibration levels and poor road conditions on fruits and vegetables during transportation, affecting their quality and marketability. The findings of Ranatunga et al. (2014) have emphasized the influence of road quality on vibration levels and cargo damage.

In light of this evolving research background, our study seeks to contribute to the growing body of knowledge surrounding the transportation of agricultural materials. By addressing the interplay between road conditions, vehicle vibrations, and packaging materials, we aim to provide insights that can inform the development of more effective, sustainable, and economically viable solutions for preserving the quality of fresh agricultural produce during transport. This research holds significant implications for the agriculture and transportation industries, enhancing our ability to meet the growing demand for fresh agricultural products while minimizing waste and environmental impact.

2 Vibration intensity and analysis technique

The effects of vibration on transported materials have been studied using diverse approaches and variables. One approach is to measure or monitor vibration acceleration levels in situ and examine the correlation between vibration level and factors such as road surface profile, travel speed, payload capacity, actual load, suspension system, particle clearance, and track width of the investigated vehicle.

For the analysis of vibration data, the use of different analytical tools has been documented (Eissa et al., 2013; Ge et al., 2016; Park et al., 2020; Paternoster et al. 2018). Statistical parameters such as the arithmetic mean were initially thought to be important for describing vibration intensity, but the root mean square (RMS) is more suitable as it can describe random vibration signals and quantify the strength of the signal. However, some studies have found that the RMS values of vibration signals recorded during transport are correlated with the occurrence of damage in the transported goods, while others have found that they are not. For example, a study by Zhou et al. (2015) found that the RMS values of vibration signals recorded during the transport of fruits and vegetables were correlated with the occurrence of bruising.

Among highway engineers, the use of the international roughness index (IRI) as an important variable for the prediction of vehicle response to a given condition (vibration intensity) is well-established. Typically, IRI values range from zero to 16 mm m^{-1}, with zero and 16 mm m^{-1} corresponding to smooth and impassable roads, respectively. Ranathunga et al. (2010) examined the effects of a range of road roughness characteristics based on IRI. Their results showed that roads with higher IRI values (5 - 10 mm m^{-1}) cause nearly four times more severe damage to transported cargo than a fair road (2 - 3.5 mm m^{-1}) or good quality road (0.9 - 2.0 mm m^{-1}). However, other studies (Jarimopas et al., 2005; Barchi et al., 2002) have suggested using a more precise measure of the damage potential of roads (i.e., power spectral density (PSD)) as an alternative to the IRI approach. The PSD method provides more detailed characteristics of the transport environment by specifying the frequency at which cargo damage is most likely. More so, it is preferred in laboratory reproduction of field vibration stress since it offers an opportunity for evaluating the reliability of proposed treatments at a relatively cheaper cost. However, previous studies that have used the PSD method have focused specifically on the evaluation of the damage potential of roads (Zhou et al., 2015; Pretorius and Steyn, 2012; Pretorius and Steyn, 2016; Shahbazi et al., 2010). This limited scope is a weakness, as the findings from these studies may not apply to other transported goods.

Chonhenchob et al. (2010) evaluated the vibration levels resulting from diverse road conditions in Thailand based on ASTM and ISTA standards. Their results revealed that at lower vibration frequencies (1-5 Hz) both the sampled roads and the standards (ISTA and ASTM) indicated similar intensities. However, at higher frequencies (>15 Hz), the vibration of the sampled roads was higher than those of the standards (Molnár and Böröcz, 2018; Vasudevan et al., 2019, 2020). While the study identifies the need for the re-evaluation of intensities that result from actual road-transport environments especially at higher frequencies to avoid over-stressing of samples during simulated transport studies, the study has a limited scope as it focuses solely on evaluating the agreement between field vibration characteristics and established road-transport vibration standards.

The PSD is another widely adopted approach for identifying the critical point at which cargo damage is highly likely. This parameter is preferred, especially for non-stationary response vibration signals, as it is a normalized version of the fast Fourier transform (FFT) over the frequency bandwidth of the sampled vibration signal. Previous studies have shown the benefits of using PSD over FFT in identifying critical vibration intensity required for the design of handling equipment, packaging materials, and process designs (Rouillard and Sek, 2010; Slaughter et al., 1998). However, studies such as Ishikawa et al. (2009) and Barchi et al. (2002) have found that PSD is not very effective in characterizing high-frequency vibration events that are short-lived and have a high amplitude. More so, other studies (Benbouzid, 2000; Levinzon, 2015) found that PSD was not very effective in predicting the occurrence of damage to electronic components during transport (Garcia-Romeu-Martinez et al., 2007; Park et al. 2020; Steinwolf, 2006).

Noting the significant influence of transient events (road cracks, potholes, speed breaks) on the intensity of vibration resulting from a given transport environment, Wei et al. (2005) proposed the use of the Wavelet decomposition technique for their detection. They discussed that decomposing road profiles into frequency sub-bands with Wavelet provides a preferable method for quantifying the effects of the transient events that are evened out by the average PSD method. However, their approach was tested only for discontinuities that were artificially added to the road profile and, as such may not be a true representation of the occurrences in the natural truck-transport environment.

The reviewed literature on vibration intensity and its analysis techniques has given insight into the suitability or otherwise of vibration analysis techniques. However, such studies are associated with setbacks (Ishikawa et al., 2009; Park et al., 2020; Zhou et al., 2015). For example, studies (Chonhenchob et al., 2009) have focused on comparing the use of the arithmetic mean and RMS as statistical parameters for analysing vibration data but, did not consider other factors that may affect the accuracy and precision of vibration data analysis, such as sensor placement, signal processing, and measurement uncertainties. There is a need for future research to address this setback.

3 Factors that affect vibration stress on agricultural cargo

The level of stress (vibration, shock, or impact) experienced by agricultural cargo during road transport varies and depends on several factors. These factors include the type and size of the suspension system, the materials used for packaging, the speed of the truck, the payload capacity, and the ride quality of the chosen route. These variables were reviewed below:

3.1 Suspension system

The influence of the suspension system is a critical factor in managing the response of transport vehicles to road surface undulations, which can lead to the transmission of vibration, shock, or impact stress to both the truck and its cargo (Lu et al., 2010; Lu et al., 2008; Park et al., 2020). The severity of this transmitted stress is primarily controlled by the characteristics of the vehicle's tires and suspension system (Heidarian and Wang, 2019; Ranathunga et al., 2010). However, even when you have the optimal combination of these components, a certain level of stress continues to be transmitted to the vehicle structure and the transported cargo due to the nature of the road profile (Barchi et al., 2002; Jung et al., 2021). Identifying the right combination of variables, including truck speed, suspension system type, and road profile, not only reduces the levels of transmitted stress but also contributes to food security by minimizing postharvest losses during the transportation of fresh horticultural produce.

The suspension system's role is pivotal in dampening the stress (impact, shock, and vibration) transmitted during the interaction between the truck and the road profile. The intensity of vibration directly affects the potential damage to fresh agricultural products (Wang et al., 2015). To mitigate the shock and vibration stress, various suspension system designs and sizes have been employed (Jarimopas et al., 2005; Sulaiman et al., 2015). The most common types include leaf-spring, radial/helical spring, and air-ride suspension systems (Garcia-Romeu-Martinez et al., 2008; Lamb and Rouillard, 2021; Soleimani and Ahmadi, 2015). Prior research has assessed the performance of suspension systems for both passenger vehicles (Sulaiman et al., 2015) and cargo trucks (Long et al., 2018).

One earlier study examined the typical energy content of vibration signals in a refrigerated truck equipped with a leaf-spring suspension system during real transport for various produce, such as cherries, nectarines, and pears. The findings showed the highest PSD levels in the range of 0.05 to 0.06 G (acceleration units) at a frequency of 3.5 Hz, with other significant peaks at around 9, 18, and 25 Hz (Hinsch et al., 1993). In the same study, when tomatoes were transported in trailers with air-ride suspensions, the high PSD levels at 3.5 Hz were notably reduced, and low to moderate accelerations at 6, 9, and 15 to 18 Hz were observed. Singh and Xu (1993) investigated bruise injuries to apple fruits resulting from different suspension systems (leaf-spring and air-ride suspension systems) using corrugated boxes as packaging material under 180 minutes of simulated transport conditions. Their study revealed that the percentage of bruised apples ranged from 5.2% to 78% for the leaf-spring system and from 0% to 33% for the air-ride system. The average number of bruises per apple fruit ranged from 0.01 to 1.88 for the leaf-spring and from 0.01 to 1.16 for the air-ride suspension system, while the average bruise area per apple ranged from 0.00 mm^2 to 161.29 mm^2 for the leaf-spring suspension system and from 0.00 mm^2 to 58.06 mm^2 for the air-ride system. Another study by Lamb and Rouillard (2021) provided a comprehensive overview of the performance of air-ride and leaf-suspension systems, investigating the influence of suspension type, payload, road type, and vehicle type on mean RMS vibrations in commercial vehicles. The results indicated that within the range of 0.2 – 3.5 $\mathrm{m\ s}^{-2}$, the use of air-ride suspension significantly reduced mean RMS levels compared to steel-leaf suspension, with reductions of 53% at the 50th percentile (P50) probability level, increasing to 66% at the 90th percentile (P90).

While some studies (Hinsch et al., 1993; Lamb and Rouillard, 2021; Singh and Xu, 1993) demonstrate the advantages of the air-ride system over the traditional leaf-spring system, other findings suggest that, regardless of the suspension system used, the vibration energy level is higher for partially loaded trucks compared to fully loaded ones (Garcia-Romeu-Martinez et al., 2008). Garcia-Romeu-Martinez et al. (2008) found that for loaded air-ride suspension, the average root mean square acceleration (RMSG) was approximately 0.089 G, while for empty air-ride suspension, it was about 0.092 G. In contrast, the loaded leaf spring suspension had a significantly higher average RMSG of approximately 0.194 G, and the empty leaf spring suspension had an even higher value of around 0.245 G. Other studies suggest that truck overloading plays an important role in attenuating the transmitted shock and vibration stress (Zhou et al., 2015). However, this should be viewed with caution, as overloading has detrimental consequences on the structures of transport vehicles (Rusbintardjo, 2013) and on-road pavement (Rys and Jaskula, 2019).

A different approach was taken by Sulaiman et al. (2015), who investigated the effectiveness of a semi-active suspension system for light-heavy duty trucks through a series of experiments at three different constant speeds (40, 50, and 60 km h^{-1}). Their study revealed that the ground semi-active damping force estimator (gSADE) control algorithm had a significant positive impact on ride comfort, reducing sprung acceleration by up to 12% and consistently reducing dynamic tire forces for all four tires by 6%-10% compared to the passive suspension system. This resulted in improved ride comfort and a lower dynamic load stress factor (DLSF), indicating reduced road damage. However, the Groundhook (GRD) control algorithm had a negative effect on sprung acceleration and showed inconsistent effects on tire forces, with occasional improvements but an overall less desirable performance compared to gSADE (Sulaiman et al., 2015).

Regardless of the type of cargo being transported, it is clear that the energy absorbed by transport vehicles and their cargoes due to poor ride quality poses a potential risk for cargo damage. Therefore, identifying conditions that result in lower vibration intensity is essential for minimizing the extent of postharvest losses in fresh agricultural products during transportation.

3.2 Truck speed

Truck speed is a factor that has a dual impact on transportation costs and the extent of cargo damage (Jarimopas et al., 2005; Lu et al., 2008; Zhou et al., 2008). Increasing truck speed can reduce the costs associated with delayed shipment of agricultural materials (Lamb and Rouillard, 2021). However, reducing truck speed can lead to cost savings due to reduced fuel consumption and diminished wear and tear on vehicles (Long et al., 2018). The relationship between truck speed and vibration levels is intricate. In certain cases, increasing truck speed can result in heightened vibration levels (Jarimopas et al., 2005), while in other cases, higher speeds can lead to reduced vibration levels (Park et al., 2020; Wang et al., 2015). This specific relationship depends on various factors, including road quality, truck weight, and the type of cargo being transported (Rios-Mesa et al., 2020; Xu et al., 2020).

Jarimopas et al. (2005) conducted a study to investigate the effects of different speeds (20, 40, and 80 km h^{-1}) and various road types (laterite, concrete, and unpaved) on the vibration energy content, particularly the PSD, of a six-wheel Isuzu truck. This truck had a 3000 cc engine, 110 HP, a 6-ton payload capacity, and utilized a leaf-spring suspension system. Their research revealed that vibration severity increased with higher vehicle speeds. For instance, on laterite roads, recorded vibration levels were 0.0472 g Hz^{-1} at 20 km h^{-1}, 0.0905 g Hz^{-1} at 40 km h^{-1}, and were unavailable at 80 km h^{-1}. In China, Zhou et al. (2015) conducted a study on the effects of truck speed (0–30 km h^{-1}, 31–60 km h^{-1}, and 61–90 km h^{-1}) and road conditions (highways, arterial roads (ARs), secondary roads (SRs), and tertiary roads (TRs)) on transport vibration levels. The study revealed that transport vibration levels increased with higher truck speeds, with RMS accelerations ranging from 0.05 to 0.25 G within the investigated speed range (0 - 90 km h^{-1}) for a normal load truck.

Lu et al. (2010) examined the effects of truck speed on shock and vibration levels during real-world truck transport in Japan at four-speed ranges: 0-29.9 km h^{-1}, 30-59.9 km h^{-1}, 60-69.9 km h^{-1}, and 70-89.9 km h^{-1}. Their observations showed that the RMSG values, encompassing both shock and vibration, increased as truck speed increased, particularly on local roads. The highest RMSG values for shock and vibration were found in the speed range of 45-59.9 km h^{-1} on local roads. Additionally, the peak PSD values of acceleration, representing energy strength across different frequencies, increased with truck speed when the speed was below 45 km h^{-1}. However, beyond 45 km h^{-1}, no significant changes in peak PSD values were detected due to truck speed. Similarly, in a study on the effects of truck speed and road conditions on truck vibration levels, Zhou et al. (2015) investigated normally loaded trucks within the speed range of 0-90 km h^{-1}. Their study revealed that RMS acceleration values, measured in gravity units (G), increased as truck speeds rose. The lowest vibration levels were recorded at speeds of 0-30 km h^{-1} (X G), while the highest were observed at 61-90 km h^{-1} (Y G). These differences were statistically significant ($p<0.05$) between the examined speed ranges. However, a study by Yang et al. (2010) found that vibration levels peaked at a certain intermediate speed for certain types of roads. Specifically, they found that on concrete pavements, the vibration level increased with speed up to around 40 km h^{-1}, but then decreased for higher speeds, while on asphalt pavements, the vibration level increased with speed up to around 60 km h^{-1} and then remained relatively constant.

While most studies consistently indicated an increase in vibration levels with higher truck speed, the speed range over which the vibration level peaked varied among studies. The range was 45-59.9 km h^{-1} (Lu et al., 2010), 61-90 km h^{-1} (Zhou et al., 2015), approximately 60 km h^{-1} (Yang et al., 2010), and 45 km h^{-1} (Lu et al., 2010). These conflicting findings underscore the complexity of the road-transport environment and the need for further research to better understand the relationship between truck speed, vibration levels, and road type. In the meantime, it is crucial to be aware of the potential risks associated with increasing truck speed and take measures to mitigate these risks, such as using proper cargo-securing methods and ensuring that drivers are well-rested.

3.3 Payload capacity

For safety and ergonomic reasons, each truck is designed to handle a specific load capacity. However, the practice of truck overloading is common in the transportation industry, primarily to reduce transportation costs (Zhou et al., 2015). Nevertheless, overloading can lead to various adverse consequences, including an increased risk of accidents, damage to cargo, and structural damage to the truck (Eissa et al., 2013; Rissi et al., 2008).

In addition to safety and operational concerns, it's crucial to understand how a truck's payload capacity affects the magnitude of shock and vibration stress transmitted to the vehicle and its cargo during transportation. Jarimopas et al. (2005) conducted a study to investigate variations in vibration levels and the resulting damage to packaged tangerine fruits during transportation using trucks with different payload capacities (2-ton and 6-ton), on different types of roads (laterite and asphalt), and at speeds ranging from 20 to 80 km h^{-1}. Their findings indicated that when travelling at 80 km h^{-1} on asphalt roads, the damage was 3% for the 2-ton truck and 8.33% for the 6-ton truck. This suggests an increase in the effect of the truck's payload capacity on tangerine fruit bruising.

Furthermore, various studies have examined the combined influence of several related factors. Jones et al. (1991) explored the effects of load mass (ranging from 0.1 to 4 tons), load positioning on the truck tray (positions 1, 2, 3, and 4), road bump heights (ranging from 50 to 125 mm), and vehicle speed (ranging from 5 to 20 m s^{-1}) on the average bruise volume. Their results showed that the highest average bruise volume reached 3.5 ml for a lightly loaded truck (0.1 tons) positioned behind the rear axle, while heavily loaded trucks (4 tons) resulted in average bruise volumes not exceeding 0.1 ml. This highlights the significant influence of these parameters on damage levels, with bruise volumes directly proportional to the energy dissipated in the produce. Heavier payloads (50%-100% of weight capacity) reduced mean RMS levels by an average of approximately 37% compared to lower payloads (0-50% of weight capacity) (Lamb and Rouillard, 2021).

Overloading trucks greatly heightens the chance of accidents and can cause harm to both the cargo being transported and the structural integrity of the truck itself. This practice not only endangers the safety of road users but also inflicts damage on road infrastructure, including road surfaces and bridges (Aggarwal and Parameswaran, 2015; Saad et al., 2021).The damping effect of overloading can be attributed to the ratio of the sprung to the un-sprung mass of the vehicle. An increase in this ratio is associated with lower vibration intensity. However, this ratio may not be the sole factor affecting vibration intensity in overloaded trucks (Matrood and Nassar, 2021; Wang et al., 2015). The study suggested that other factors, such as tire pressure and road conditions, may also play a significant role. Other studies have also highlighted that overloading can have several negative consequences. For instance, a study by Ranathunga et al. (2010) found that overloading can increase the vibration intensity of trucks, potentially leading to fatigue damage to the truck's components. Additionally, overloading can elevate the risk of rollovers (Zhou et al., 2015; Heidarian and Xu, 2019).

In summary, truck overloading is a multifaceted issue with numerous factors to consider. More research is necessary to determine the safe overload limits for a given payload capacity. The studies underscore a significant relationship between the increased payload capacity of trucks and elevated vibration levels, resulting in greater fruit damage. This highlights the need for future research to focus on developing strategies to minimize vibrations and enhance fruit packaging during transportation.

3.4 Packaging materials

The packaging of agricultural materials serves several key functions, including containment, protection, and control of atmospheric conditions (Çakmak et al., 2010; Jarimopas et al., 2008; Olorunda and Tung, 1985). Commonly utilized packaging materials comprise items such as bags, wooden boxes, corrugated fibre boxes, traditional baskets, plastic crates, and polyethene films (Bwade et al., 2019; Eissa et al., 2013; Vergano et al., 1992). Foam nets and paper wraps have also found application in this context (Eissa et al. 2013).

The effectiveness of these packaging materials in safeguarding agricultural products has been evaluated both under static conditions and in the context of transportation (Zhou et al., 2008; Lamb and Rouillard, 2021). In a study by Eissa et al. (2013) focused on transporting fresh apples, it was found that foam-net cushioning materials exhibited higher natural frequencies compared to paper-wrap counterparts. Specifically, the natural frequencies were measured at 25.3 Hz, 45.26 Hz, 50.17 Hz, 87.09 Hz, 200.5 Hz, and 371.7 Hz for modes 1 through 6, respectively. The higher natural frequency observed with foam-net materials suggests that they possess greater elasticity and resilience compared to paper wrap, making them more effective at mitigating vibration intensity during transportation. However, it's essential to note that this study primarily concentrated on the Golden apple variety, which is particularly vulnerable to bruising. This specialization might limit the generalizability of the findings to other apple varieties or different types of fruits and vegetables.

Additionally, Zhou et al. (2008) found that the use of foam-net packaging significantly reduced vibration intensity during transport. This vibration reduction correlated with fewer bruises and less mechanical damage on the transported pears. Hydrolase activity during storage was also lower for pears with cushioning materials, with firmness loss ranging from 52% to 64%, compared to a 91% firmness loss for pears without cushioning materials after 36 days of storage at 23 ℃. Slaughter et al. (1998) evaluated the efficacy of polyethene bags in reducing vibration-related damage to Bartlett pears during transit. While the findings indicated that the bags were effective at reducing vibration injury, they did not provide complete protection against compression damage.

However, Jalali et al. (2020) discovered that a specific type of plastic film was effective at reducing mechanical damage to fresh strawberries during transport at low temperatures but less effective at higher temperatures due to increased fruit softening. Vursavuş and Özgüven (2004) examined the combined effects of vibration parameters (acceleration and frequency) and packaging methods on the mechanical damage experienced by Golden Delicious apples during transport. They found that the choice of packaging material significantly influenced the extent of mechanical damage. On the other hand, Zhang et al. (2011) reported that corrugated cardboard boxes could lead to significant bruising and damage to tomatoes during transit due to their rough surfaces and poor shock absorption properties. Idah et al. (2012) evaluated the comparative performance of traditional baskets and plastic containers in protecting tomatoes under simulated transport conditions. They found that the plastic containers were more effective at shielding the tomatoes from damage. Nevertheless, while foam nets proved effective at reducing mechanical damage to apples during transport, they were less effective at protecting kiwi fruits due to differences in their physical properties (Bwade et al., 2019; Jarimopas et al., 2008; Zhou et al., 2008).

Pidl (2017) delves into the challenges and techniques associated with simulating road transport vibrations for packaging testing. The paper explores various methods, including Gaussian distribution, non-Gaussian distribution, and transient event simulations, to enhance the accuracy of vibration testing. Additionally, the study highlights the use of PSD functions controlled by FFT for laboratory-based vibration testing. However, it's worth noting that the study's reliance on a simplified linear model for damping and spring constant parameters might not fully capture the complexities of real-world packaging and vibration dynamics, constituting a notable limitation. Jung and Kim (2015) performed a random vibration test to analyze the vibration characteristics of apples within a packaging system designed for parcel delivery. The investigation unveiled resonance frequencies of apples ranging from 13 to 99 Hz, with corresponding PSD values varying between 0.0143 and 0.0923 $G^2\ Hz^{-1}$. Resonance frequencies and PSD values are critical variables for the design of packaging systems. The resonance frequency provides essential data on frequencies where apples are particularly vulnerable to damage due to vibration during transportation, with higher PSD values signifying an increased risk of damage. Jarimopas et al. (2008) explored the post-harvest damage of sweet tamarind due to packaging by evaluating the performance of existing wholesale and retail containers in comparison to a proposed packaging design. The proposed packaging involved a 15 cm diameter by 20 cm height sleeve filled with a mixture of 5 mm foam balls and sweet tamarind, inserted vertically. The proposed packaging resulted in only 1/5 to 1/6 of the damage experienced by conventional packaging, significantly enhancing the fruit's quality. Moreover, this proposed packaging was cost-effective, priced at half the cost of traditional containers, making it a promising solution for reducing damage and improving the marketability of sweet tamarind.

Wei et al. (2021) researched the effects of three preservation treatments for mangoes stored under low-temperature conditions. These treatments included inflatable bag packaging, edible coating, and modified atmosphere packaging (MAP). Their findings showcased the effectiveness of various preservation methods. Under the MAP treatment, there was an 18.9% reduction in the disease index for mangoes susceptible to fungal attack, underscoring its superior inhibitory effect on fungal growth. The edible coating treatment, however, led to over 50% yellowing of mangoes by the end of storage, indicating its impact on slowing post-ripening effects.

Recognizing the influence of packaging material characteristics on preserving the post-harvest quality of fresh agricultural cargo, Vursavuş and Özgüven (2004) conducted a transmissibility study on various packaging methods for apple fruits, including paper pulp trays, volume packaging, and pattern packaging methods. Their results revealed that these packaging methods were most sensitive to a vibration frequency of 9 Hz. High transmissibility values suggest that a system is ineffective at isolating or dampening vibrations, potentially leading to undesired consequences.

Eissa et al. (2013) focused on apple fruits and conducted various tests with different cushioning materials to assess their damping ratio (ζ). Their study revealed that the damping ratio decreased by 74% for foam net, 75% for paper wrap, and 96% for no cushioning material. The damping ratio measures the rate at which an oscillating or vibrating system returns to equilibrium after being subjected to a disturbance. This suggests that the type of cushioning material used significantly influenced the natural frequency of apple fruit, with foam-net cushioning materials having a higher starting resonance and reducing resonant vibration. Consequently, the use of cushioning materials was found to be effective in reducing bruise volume per fruit, with foam-net.

In conclusion, future research should encompass a wider range of produce varieties, explore innovative packaging designs, employ advanced testing methods, conduct cost-benefit analyses, and assess the environmental impact of packaging materials to develop more effective, sustainable, and economically viable solutions for preserving fresh agricultural produce during transport.

3.5 Road condition

Early studies on road surface profiles primarily aimed at establishing limitations for newly constructed roads to ensure their operability and passenger comfort. These studies paid little or no attention to the transport-related damage caused to agricultural materials (Bwade et al., 2019; Idah et al., 2012; Long et al., 2018). However, in subsequent decades, there has been a shift in research focus, benefiting farmers and handlers of agricultural materials through findings from road transport research (Idah et al., 2012; Paternoster et al. 2018; Ramezani Boukat et al., 2022).

For instance, in the study by Jarimopas et al. (2005), vibration intensities were found to be 0.0472 g Hz^{-1} at a truck speed of 20 km h^{-1} and 0.0905 g Hz^{-1} at a speed of 40 km h^{-1}. At speeds of 80 km h^{-1}, the vibration intensity for concrete and asphalt roads was 0.0541 g Hz^{-1} and 0.0113 g Hz^{-1}, respectively.

Lepine (2016) researched the effect of varying road surface roughness on vehicle vibrations in the range of 0.5 to 1.5 G (acceleration in units of gravity, g) in the vertical direction. Their findings indicated that as road roughness increased, the observed vibration levels on the vehicle also increased. On extremely rough road segments, peak accelerations reached up to 1.5 G, causing noticeable discomfort to passengers and potential damage to sensitive cargo. Using major roads led to a substantial reduction in mean RMS levels, ranging from 51% to 61% for P50 to P90 probability levels, with values typically below 1.0 m s^{-2}. This highlighted the significant impact of road quality and speed on vibration levels, while the influence of vehicle type was minimal, with corrections below 15% for mean RMS levels above 50% (Lu et al., 2010; Lamb and Rouillard, 2021).

Barbosa (2011) investigated the response of vehicles to pavement roughness using PSD and acceleration spectra within 0.1 to 10 meters in terms of wavelength content in road profiles. This research emphasized the sensitivity of vehicle dynamics to road roughness, underlining the importance of suspension tuning and maintenance for optimizing ride comfort and safety.

Chonhenchob et al. (2009) found that high vibration levels and poor road conditions resulted in the highest levels of damage occurring to fruits and vegetables during transportation to packing houses. For example, head lettuce experienced 45% damage at the packing house, 30% at the distribution centre, and 10% at retailers due to the effects of truck vibration during transportation. Similarly, cabbage experienced 50% damage at the packing house, 40% at the distribution centre, and 15% at retailers, while Chinese pears experienced 39%, 29%, and 21% damage at the respective stages of transportation.

Ranatunga et al. (2014) investigated the distribution of vibration effects within stacked tomato boxes during vehicular road transportation using a fully loaded Mitsubishi Canter truck at an average speed of 20 km h^{-1} on roads rated with International Road Roughness Index (IRI) values ranging from 2 to 3.5 mm m^{-1}. They found that on poor quality roads (IRI > 5 mm m^{-1}), the vibration acceleration was nearly four times higher compared to those on fair (IRI 2 to 3.5 mm m^{-1}) or good quality (IRI 0.9 to 2 mm m^{-1}) roads, even at lower speeds, such as 25 km h^{-1}. Lu et al. (2008) found that shocks during transportation were frequently caused by road roughness, metal joints, differences in road levels, pedestrian crossings, manholes, road curves, left and right turns, and railroad crossings. These shocks typically had acceleration amplitudes mostly above 0.1 G. The vibration acceleration, following a normal probability distribution and considered random, had peaks primarily in the 1-4 Hz range. This study by Lu et al. (2008) highlighted the need to separate the analysis of shock and vibration when simulating truck transport environments in the laboratory, while also shedding light on the common causes of vibration intensity.

4 Conclusions

Travel speed, road quality, payload capacity, suspension system type, and stack height all affect vibration intensity. However, no single study has identified which of these factors has the strongest or weakest effect on vibration intensity in the road transport environment.

There is no consensus on the most effective technique for attenuating the effects of vibration during transport. Some studies have suggested that the appropriate choice of packaging materials is the most effective approach, while others have suggested the use of vibration dampers.

Globally accepted standards for road transport vibration (ASTM D4169 and ISTA 4B) have been developed. However, the degree of agreement between the vibration spectra generated by these standards and those measured on actual roads decreases with increasing vibration frequency (>25 Hz).

Recommendations for future research

There is a need for future research to focus on optimizing agricultural transportation by examining the interplay between road conditions, vehicle vibrations, and packaging materials. Exploring advanced technologies and eco-friendly packaging solutions, as well as considering a broader range of agricultural produce

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