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REVIEW ARTICLE

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Measurement and evaluation of the effect of vibration on fruits in transit—Review

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Mechanical vibration is a prominent cause of produce damage in many postharvest fruit supply chains. Knowledge on the causes, occurrence, and mechanistic relationship of vibration to produce damage is important for systematic development of remedial actions. This review identifies and discusses the critical factors of vibration, their implications for fruit quality, and possible improvements to addressing the issue of fruit quality deterioration. Frequently reported mechanical damage types caused by vibration on fruits are scuffing, fruit rub, and skin bruising. A wide range of factors can significantly affect the vibration intensity and thus resultant mechanical damage. Critical frequencies of vibration in the range of 0 to 10 Hz, attributed to peak energy levels in the power spectrum, cause substantial damage in fruits. Greater vertical acceleration and transmission of vibration to the higher tiers in a stacked column of packages result in increased mechanical damage. Fruit packages stacked in the rear positions of trucks are also affected more by vibration. Produce transported in leaf spring trucks has a higher risk of damage when compared with air-ride suspension trucks. Additionally increased road roughness, vehicle speed, and duration of exposure to vibration proliferate fruit damage. The effects of different inner packing methods and different package types on mechanical damage are less frequently investigated. More accurate characterization of mechanical damage caused by vibration and shocks and its reproduction by enhanced simulation methods will contribute to optimizing damage prevention mechanisms and further improving the quality of fruits in transit within the postharvest supply chain.

KEYWORDS
fruits, mechanical damage, supply chain, transport, vibration

1 | INTRODUCTION

The demand for fresh produce has risen dramatically due to the growing consumer trends to eat out, to eat healthily, and to consume more ready-to-eat foods.[1] In the recent years, this has led to development of longer fresh produce supply chains with the concomitant spread of global retail chains. Development of international distribution systems requires agricultural food systems to be increasingly productive, quality centric, and safety driven.[2] However, the extension of postharvest supply chains in length and complexity can considerably escalate the exposure and susceptibility of fresh produce to damage during handling and transport.[3,4]

Postharvest losses in fresh produce can be as high as 50% amounting to a commercial realization of only half of what is grown[5] with a substantial portion of postharvest losses being attributed to fruit damage in transit. The causes of damage along the supply chain must be identified and characterized to enable systematic development of remedial measures to reduce the losses.[6] Forces of shock and vibration during handling and transport can result in significant immediately visible damage,[1,7] such as skin bruises, scuffing, skin abrasion, and puncture damage[1,3,4] in fruits. Damage due to internal transmission of forces however may result in less obvious slower physical, chemical, or biological changes in produce.[3] Physical damages can also cause fruit to be more vulnerable to further decay as a result of facilitating access and growth by microorganisms.[1,8]

The specific cause of vibration damage is stated to be fatigue due to repeated forces on the fruit resulting in cell rupture beneath the skin. Goff and Twede[9] suggested that vibration, more than the impact forces, might be the reason for most of the bruising on produce. The intensity and the duration of vibration determine the severity of damage.[10,11] As the travel distance increases, so does the percentage of fruit being bruised during transit.[12] The vibration excitations are significantly dependent on road surface, suspension characteristics, velocity, and payload. Similarly, Jones, Holt, and Schoorl[13] showed that vibration and impacts were the basic sources of produce damage in transit and that the integrated system of road-vehicle-load (RVL) interactions determines the extent of mechanical damage to produce.

Random vibration during truck transport is nondeterministic in nature. This is mostly because the vibration intensity and the frequency of oscillation of a system are dependent on a combination of variables including road characteristics and velocity levels. This results in a multidegree of freedom (MDOF) system where the magnitude of the oscillation is distributed within a range of frequencies in the frequency spectrum (Figure 1). In vehicle vibration, the frequencies with higher energy levels may transfer to the cargo or products being transported. The highest amplitude in the frequency content depicts the critical frequencies where the energy of oscillation is the greatest in the vibration system.

Several studies have analysed vibration data in time domain and frequency domain to understand its effects on produce.[14-16] Fourier analysis of the time-series data is used to understand the critical frequencies affecting the produce during transit. Most authors were interested to derive the power spectral density (PSD) profiles of the respective routes to represent the energy or power of the vibration excitations. The area under the PSD curve represents root mean square (RMS) acceleration of a given vibration system, which has been used to compare the vibration intensity levels within different variable settings (factors) such as the suspension type of a truck, vehicle speeds, or the road conditions.[8,17-20] Comparing the vibration intensities and their relationship to fruit damage contributes to determining the factors, which were critical for mechanical damage in produce.

1.1 | Objective and scope of the review

This review synthesizes the findings of past studies, categorizes the methodologies, and evaluates the approaches to identify overall limitations in past research to recommend future directions for understanding the effects of vibration on fruits. The review is centred on research papers published in the last 25 years. Five main bibliographic databases (ProQuest, Web of Science, Scopus, Springer, and Google Scholar Database) were used for the literature search. The focus was on the published peer-reviewed articles that analysed the effect of vibration on fruits, with a major emphasis on the undesirable changes caused by mechanical damage. Other papers with less detailed analysis of vibration parameters were also considered to enable some understanding of the effects of fruit vibration when otherwise only a limited number of studies would be available.

2 | INVESTIGATING THE EFFECT OF VIBRATION ON FRUIT

Vibration and shock transmitted from the truck bed cause adverse damage to fruits,[14] and prolonged exposure to harmful vibration may increase the susceptibility of fruit damage.[10,21] As summarized in Table 1, the impact of transit vibration has been evaluated for a range of fruits. However, many different experimental designs with different variable settings were used to evaluate the effects of vibration on fruits, making a comparison and understanding of some of the results challenging.

In most of the studies, the prime objective was to evaluate the damage to fresh produce caused by harmful vibration. Some studies focused solely on measuring the vibration without correlating these with produce changes or damage. The emphasis in such studies was to understand the vibration levels within a transit passage with respect to variables such as truck suspension type, truck speed, road condition, and payload.[55,69-74] Variation of power density (G^2 Hz^{-1}) was investigated in these studies to understand changes in vibration intensity on a given route. While these studies have been useful for the evaluation of vibration levels in certain territories or routes, they did not correlate vibration intensity with product damage or quality indices.

2.1 | Experimental approaches

Vibration studies on fresh produce can be broadly categorized into three experimental approaches for the purposes of comparison. They are *In-Transit* experiments, *Simulation* experiments, and a combination of these two approaches that can be termed as *Transit-Simulation* (*Trans-Sim*) type experiments. Independent variables such as different

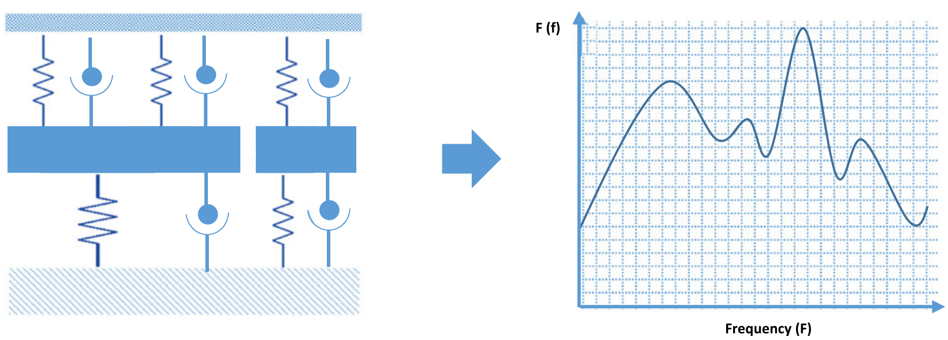

FIGURE 1 Illustration of the frequency spectrum for a MDOF vibration system

TABLE 1 Summary of studies on the effect of vibration impact to fruits[a]

Produce	Experiment Type	Conditions/ Variables in Transit	Conditions/ Variables in Simulation	Measured Variable (Y)	Test or Prominent Frequency	Reference
Apples	*Simulation*	Not applicable	Vibration treatment (ASTM)[a] Vibration treatment (F) Package type	Bruise area Bruise volume Package damage	9 Hz, 12 Hz	Fadiji et al[22]
	In-Transit	Suspension type Road condition Vehicle speed	Not applicable	Effect on the artificial fruit Acceleration levels Power density (PD)	0.1-5 Hz	Soleimani et al[20]
	In-Transit	Suspension type Package position[b] Package height[c] Fruit depth[d]	Not applicable	Effect on the artificial fruit Acceleration levels PD	0.1-5 Hz	Soleimani and Ahmadi[19]
	Simulation	Not applicable	Vibration treatment (F) Cushioning material	Apple damage	0-1.6 KHz	Eissa et al[23,24]
	Simulation	Not applicable	Vibration treatment (C) Stack height	Loading force on fruit Damage to apples	8-9 Hz	Acican et al[25]
	Simulation	Not applicable	Vibration treatment (FA) Stack height[d] Fruit size	Bruise diameter Bruise depth Bruise volume	4 Hz	Van Zeebroeck[26,27]
	Trans-Sim	Package position	Vibration treatment (FAD) Packaging method	Equivalent Severe Bruise Index (EBI) Bruise diameter Transmissibility ratio	5-15 Hz 9 Hz (peak)	Vursavus and Ozguven[10]
	Trans-Sim	Suspension type Travel distance Bin position Fruit position in the bin (middle, side) Bin type	Vibration treatment (ASTM) Vibration treatment (FA) Bin type	Bruise and abrasion rating damage diameter Resonant frequency	2.5-9 Hz and 20-70 Hz 7-15 Hz (resonance)	Timm et al[14]
	Trans-Sim	Suspension type Road condition	Vibration treatment (FA)	Package type Packing material	0-10 Hz	Singh and Xu[28]
Bananas	*Simulation*	Not applicable	Vibration treatment (C) Packaging method	Percentage of injured fruit Bruise area Weight loss	Not given	More et al[29]
	Simulation	Not applicable	Vibration treatment (C) Packing material	Visual Quality Index (VQI) Respiration rate	3.5 Hz	Wasala et al[30]
Cherries	*In-Transit*	Transport mode (air \road) Suspension type Transport route	Not applicable	Damage to cherries PD	15 Hz (air ride) 2-3 Hz (leaf spring) 80 Hz (air transport)	Ishikawa et al[31]
Cherry tomatoes	*Simulation*	Not applicable	Vibration treatment (F) Package height	Resonant frequency Acceleration levels Transmissibility ratio	36.61 Hz (bottom) 10.76 Hz (middle) 6.44 Hz (top)	Zhang et al[32]
Fig fruits	*Trans-Sim*	Road condition Packing material Travel duration	Vibration treatment (FA) Fruit cultivar	Visual quality Weight loss, fruit firmness Internal temperature	3 Hz and 16 Hz	Çakmak et al[33]
	Simulation	Not applicable	Vibration treatment (FD) Package type Orientation of fruit	Visual quality Fruit firmness, weight loss Moisture content Internal temperature Total soluble solids (TSS)	2.5 Hz and 7 Hz	Alayunt et al[34]
	Simulation	Not applicable	Vibration treatment (A)	Ethylene production Respiration rate Cellular leakage	Not given	Mao et al[35]
Grapes	*Simulation*	Not applicable	Vibration treatment (D) Package position	Cracking resistance Separate resistance Modulus elasticity	109 Hz (resonance)	Demir et al[36]
	Simulation	Not applicable	Vibration treatment (F) Package height	Grape damage Fruit firmness Respiration rate	5-10 Hz	Fischer et al[37]
Mandarin fruit	*Trans-Sim*	Fixed conditions[e]	Vibration treatment (D) Package type Packing material	Mandarin damage	60 Hz	Raghav and Gupta[38]
Kiwi fruits	*Simulation*	Not applicable	Vibration treatment (FA) Stack height Fruit size	Bruise depth	13 Hz	Tabatabaekoloor et al[39]

(Continues)

TABLE 1 (Continued)

Produce	Experiment Type	Conditions/ Variables in Transit	Conditions/ Variables in Simulation	Measured Variable (Y)	Test or Prominent Frequency	Reference
	Simulation	Not applicable	Vibration treatment (ASTM) Vibration treatment (D) Fill type (layer, bulk) Package type	Kiwi damage	Not given	Lallu et al[40]
Loquats	*In-Transit*	Truck type Road condition Package position Package height	Vibration treatment (FAD) Package height	Loquat damage	13-25 Hz 9 Hz, 16 Hz (peak)	Barchi et al[16]
Mangoes	*In-Transit*	Fixed conditions	Not applicable	Fruit firmness Respiration rate TSS	Not given	Yasunaga et al[41]
	Tran-Sim	Package type Packing material	Vibration treatment (ASTM) Vibration treatment (F) Package type Packing material	Mango damage Resonant frequency	3-17 Hz (resonance)	Chonhenchob and Singh[42]
Melon	*Trans-Sim*	Fixed conditions	Vibration treatment (FA)	Fruit softening Flesh firmness, weight loss Enzyme activity Cell wall constituents Electrical conductivity	2-10 Hz	Zhou et al[43]
Papaya	*Trans-Sim*	Package type Packing material	Vibration treatment (ISTA) Package type Packing material	Papaya damage	4 Hz	Chonhenchob and Singh[44]
Peaches	*Simulation* *Trans-Sim*	Not applicable Fixed conditions	Vibration treatment (D) Vibration treatment (F) Packing method	Enzyme activity Skin discolouration Fruit firmness	5 Hz 2-25 Hz	Dantas et al[45] Kitazawa et al[46]
Peaches	*Simulation*	Not applicable	Vibration treatment (C) Fruit cultivar Fruit maturity	Bruise damage	6 Hz	Vergano et al[47]
Peaches and nectarines	*Simulation*	Not applicable	Vibration treatment (C)	Skin discolouration	9 Hz	Crisosto et al[48]
Pears	*Simulation*	Not applicable	Vibration treatment (FAD) Package height Stack height	Pear damage	Not given	Li et al[49]
Pears	*In-Transit*	Road condition Packing material	Not applicable	Pear damage Fruit firmness Enzyme activity Cell wall constituents	2-5 Hz 15-20 Hz	Zhou et al[50]
	In-Transit	Road condition Package position	Not applicable	Skin discolouration Electrical conductivity Flesh firmness Enzyme activity Cell wall constituents	2-4.5 Hz 15-40 Hz	Zhou et al[51]
	Trans-Sim	Road condition Package position	Vibration treatment (FA) Package height	Damage to pears	10-15 Hz (in-transit) 8-40 Hz (simulation)	Berardinelli[52]
	Simulation	Not applicable	Vibration treatment (C) Anti-Browning solutions (coatings/antioxidants)	Skin discolouration	3.5-4 Hz	Feng et al[53]
	Trans-Sim	Packaging type Package position	Vibration treatment (ASTM) Vibration treatment (FA) Package weight/size Fill method (tight, loose)	Average injury score	2-30 Hz	Slaughter et al[17,54]
	Simulation	Not applicable	Vibration treatment (ASTM) Vibration treatment (FA) Fill method (tight/loose) Fill weight	Mean bruise score	3.5 Hz and 18 Hz	Slaughter et al[8]
Pears and plums	*In-Transit*	Transport route Transport distance	Not applicable	Damage to pears/plums	1-5 Hz	Chonhenchob et al[55]
Pears and avocado	*Simulation*	Not applicable	Vibration treatment (ASTM) Fruit firmness Packing material	Bruise score	Not given	Thompson et al[56]
Pineapple	*Simulation*	Not applicable	Vibration treatment (ASTM) Vibration treatment (F)	Bruise damage and decay Skin discolouration	6-8 Hz (resonance)	Chonhenchob et al[57]

(Continues)

TABLE 1 (Continued)

Produce	Experiment Type	Conditions/ Variables in Transit	Conditions/ Variables in Simulation	Measured Variable (Y)	Test or Prominent Frequency	Reference
			Package type Orientation of fruit	Fruit Firmness Titratable acidity (TA) and TSS Resonant frequency		
Strawberries	*Simulation*	Not applicable	Vibration treatment (C) Package type	Package performance	2 Hz	Konya et al[58]
	Trans-Sim	Not given	Vibration treatment (FAD) Package height	Skin discolouration Fruit firmness Microbial activity TSS and TA Volatile organic compounds	5-20 Hz	La Scalia[11,59]
	Simulation	Not applicable	Vibration treatment (FD) Package height	Bruise percentage/severity Fruit firmness Electrical conductivity TSS and TA	3-5 Hz	Chaiwong and Bishop[60]
	Simulation	Not applicable	Vibration treatment (C) Storage temperature	Sensory properties Bacterial growth	7 Hz	Nakamura et al[61]
	Simulation	Not applicable	Vibration treatment (ASTM) Pre-cooling temperature	Shelf life	Not given	Mokkila et al[62]
	Simulation	Not applicable	Vibration treatment (F) Package height	Strawberry damage Skin discolouration Fruit firmness	5-10 Hz	Fischer et al[37]
Tangerines	*In-Transit*	Truck type Road condition Travel speed Package height	Not applicable	Tangerine damage	2-5 Hz	Jarimopas et al[15]
Tomatoes	*Simulation*	Not applicable	Vibration treatment (A)	Tomato tissue damage Infrared spectroscopy of damaged tissue	Not given	Wu and Wang[63]
	Simulation	Not applicable	Vibration treatment (ASTM) Package type Stack height	Tomato damage Transmissibility	Not given	Aba et al[64]
	Simulation	Not applicable	Vibration treatment (F) Package type Ripeness stage	Modulus elasticity	3.7 Hz and 6.7 Hz	Babarinsa and Ige[65]
	Trans-Sim	Road condition Vehicle speed Package position Fruit depth	Vibration treatment (F) Package height	Tomato damage	7 Hz	Ranathunga et al[18]
Tomatoes	*Simulation*	Not applicable	Vibration treatment (F) Fruit cultivar Ripeness stage	Tomato damage Resonant frequency	9.1-17.6 Hz	Idah et al[66]
	In-Transit	Road condition Vehicle speed Stack height	Not applicable	Pressure on fruits Tomato damage	1.5 Hz and 7 Hz 10-15 Hz	Geyer et al[67]
Watermelons	*Trans-Sim*	Package position	Vibration treatment (FAD) Stack height	Percentage decay of the modulus elasticity (PDME)	7.5 Hz (flesh) and 13 Hz (hull)	Shahbazi et al[68]

[a]Vibration treatment (ASTM)/(ISTA): Standard ASTM/ISTA profile was used. Vibration treatment (F): Only vibration frequency was considered as a variable; vibration treatment (A): Only vibration acceleration was considered as a variable; vibration treatment (D): Only vibration duration was considered as a variable. Vibration treatment (FA): Vibration frequency and acceleration were considered as a variables; vibration treatment (AD): Vibration acceleration and duration were considered as variables; vibration treatment (FAD): Vibration frequency, acceleration, and duration were considered as variables. Vibration treatment (C): Constant treatment with fixed frequency, acceleration, and duration was used.

[b]Package position: Refers to the placement of the package along the truck bed.

[c]Package height: Refers to the tier in which the package is stacked along a column of a pallet.

[d]Stack height/fruit depth: Refers to the height of the fruit layer inside the package or bin.

[e]Fixed conditions: No variables or variable combinations were considered in transit.

truck types or suspension systems,[16,20,75] travel speeds,[15,18] and road conditions[18,20,51] have been examined in relation to variations in vibration levels. The resultant vibration levels were then correlated with produce damage levels or quality indices to understand the effect on produce. However, some studies measured the dependent variable as peak acceleration (a_{peak}) or RMS acceleration (G_{rms}) or transmissibility level (T) caused by transit vibration. From these studies, it has been inferred that higher acceleration and transmissibility levels result in more energy transfer to the produce and hence result in more damage.[19,20]

In many studies, the measured or the dependent variables were related to the effect on produce such as physiological changes or external damage. Frequently measured physiological changes were the effect on respiration rate, fruit weight, fruit firmness, ethylene production, cell wall permeability, enzyme activity, total soluble solids (TSS), and titratable acidity (TA).[11,50,51,57] Most of these physiological changes in fruits have been primarily caused by mechanical damage due to the experienced vibration. External damage caused by vibration stresses has been assessed visually as a percentage,[8,15,37,52] length and width of damage,[16] bruise diameter and equivalent bruise index,[10,14] bruise depth,[39] percentage decay of the modulus elasticity (PDME),[68] bruise area, bruise volume and package damage,[22] abrasion rating,[14] or a bruise score[8,33] as summarized in Table 1. This highlights that most of the studies focused on the impact on the appearance quality of the fruits subjected to vibration and shocks.

2.1.1 | In-transit experiments

In-Transit experiments were centred on studying the interaction of different variables during transit passage and directly correlating these with the resultant damage or changes in produce quality. Such studies attempted to evaluate the effects of experienced vibration on fresh produce with respect to different parameters under investigation.[15,19,20] Experiments were performed in real transit passage in a live setting while the produce was being transported in a truck or a similar carrier. The effects on the produce were examined before and after the transport experiment.[15,31,51] This approach enabled the vibration parameters to be directly related to changes in produce quality, but the investigations were mostly restricted to data collected during a single transit trip.

Many past studies used piezoelectric accelerometers coupled with charge amplifiers to record the acceleration data in the *in-transit* experiments.[16] A contemporary approach has been to use fruit-shaped accelerometer devices to measure the *in-transit* vibration levels. For instance, Soleimani and Ahmadi[20] used an electronic sphere resembling the actual fruit shape with an embedded tri-axial accelerometer to assess the vibration impact on Golden Delicious apples. Past studies either recorded three-axis acceleration or were limited to single-axis (vertical) vibration, as it has been found that the vertical vibration caused more harm to produce.[10]

2.1.2 | Transit-simulation (*Trans-Sim*) experiments

Trans-Sim type experiments measured the vibration level along the transport passage and use the derived vibration profiles as the input to drive vibration and shock simulators.[14,16,52,75] *Trans-Sim* experimental designs consist of two distinct experimental stages. The first *in-transit* data-capturing stage is performed in the actual transit passage. Accelerometers mounted inside the cargo hold in a truck record the acceleration variations, and the data are used to develop the vibration profiles for the truck passage. Three-axis or single-axis acceleration is recorded in time domain and then be converted to frequency domain using Fourier transformation. This Fourier analysis of the time-series data can be used to understand the critical frequencies affecting the produce during transit.[76] PSD profiles[15,16] that were developed for the respective routes represent the energy or power of the vibration excitations. PSD can be effectively used to measure the vibration energy in a transit passage, as the bruising injury is a result of the energy absorbed during transportation.[18] Power density (PD) of a given vibration signal within a band of frequencies could be derived through Equation (1).[15]

$$PD = \frac{1}{BW} \sum \frac{RMS\ gi^2}{N} \tag{1}$$

where *RMS gi* is the RMS acceleration measured in *g* at any instance within a bandwidth (*BW*) of frequencies and *N* is the number of samples in a given vibration signal.

In the *Trans-Sim* and *Simulation* type experiments, the variables used during simulation have mainly consisted of frequency, acceleration and duration of vibration.[11,39] The vibration treatment may be for either variable durations[10,68] or controlled fixed duration.[8,22,39] Within a vibration treatment, the frequency may also vary in the range of interest[32,37] or be an identified fixed frequency[18,22,39] as determined by the *in-transit* experiments. In these *Trans-Sim* experiments, the key-independent variable for simulation is the vibration treatment consisting of frequency, acceleration, and duration values derived from field data. Similarly to *Simulation* experiments, different vibration treatments have been used as the input variables to determine the effect on produce. Previous studies with different experimental settings have been categorized and summarized in Table 1. Studies that had not evaluated the effect on fruits with the parameters of the vibration were excluded from this table.

2.1.3 | Simulation experiments

Simulation type experiments are laboratory studies in which a known vibration intensity, based on limited frequencies of interest, or a standard vibration profile has been used to drive a shaker. The vibration frequencies and profiles were often based on set standards such as American Society of Testing and Materials (ASTM)[77] or International Safe Transit Association (ISTA).[78] For both *Trans-Sim* and *Simulation* types of experiments, a vibration table or a shaker capable of exerting vibration effects in given frequencies needs to be used. The shakers were electrohydraulic[8,37] or electrodynamic[16,22,52] in the operating mechanism. A schematic diagram of a modern vibration simulator is given in Figure 2. These simulators are usually capable of adjusting the vibration frequency or amplitude or both parameters to exert the decided effect on produce.

Most of the studies have used different vibration treatments with varied frequency or acceleration or duration or combination of these parameters as input variables to drive the simulators. However, there have been some *Simulation* type studies that subjected the produce to a constant vibration signal.[44,58,61] Constant vibration treatment has a fixed frequency, acceleration and duration to drive the simulator. The objective of this type of studies was to determine the effects on produce when subjected to a known vibration treatment, and thus, this approach does not analyse how the produce may behave in response to different vibration treatments. However, such studies have been useful for characterizing the physiological changes in fruits when subjected to a known vibration. Some studies have chosen the constant vibration approach based on previous research findings on similar produce.[30,48,64] Contrastingly, some studies had used arbitrary parameters for the vibration treatment,[58,63] which makes it difficult to realize why the particular parameters were used in simulation.

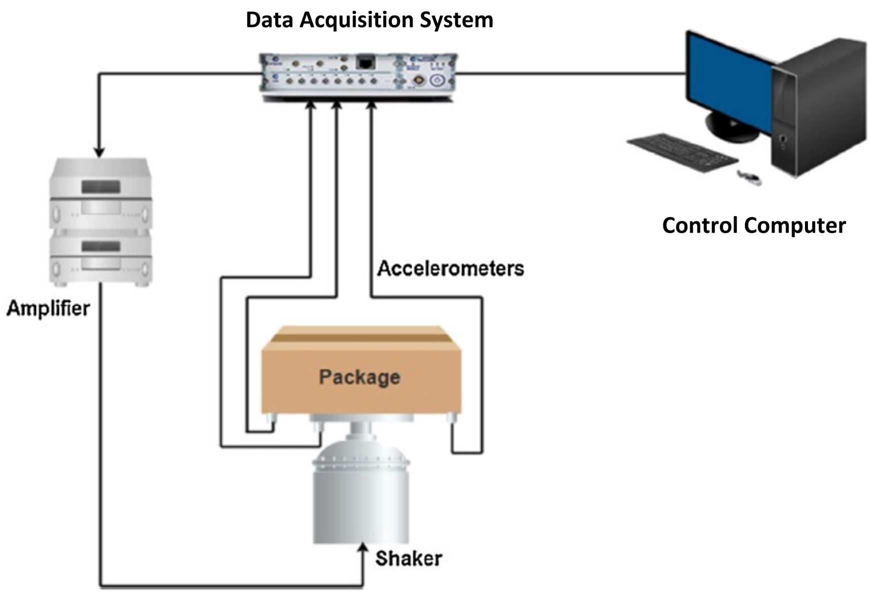

FIGURE 2 Schematic diagram of the main components of a vibration simulator[22]

3 | CRITICAL FACTORS FOR VIBRATION DAMAGE TO FRUITS

3.1 | Vibration effect on fruits

The effects of vibration on fresh produce are related to the energy available for causing mechanical damage.[10] This has been shown to be dependent on a range of factors. These factors include vibration frequency,[8,37,79] acceleration and transmissibility,[22,32,52] height and the position of the package,[15,18,19,75,79] vibration duration and travel distance,[14,68] suspension type or truck type,[18,19] road condition and vehicle speed,[20,51] and fruit depth or stack height[19,39] (as summarized in Table 1). The physical properties of the fruits, including properties of the peel and resistance to damage, have been shown to have an influence on the susceptibility to mechanical damage.[4] Additionally, the resonance frequencies of a column of boxes are dependent on the effectiveness of the tight-fill packaging, variations in fruit firmness, stacking pattern of the cartons on the pallet, and the moisture content of the fibreboard boxes.[8,79] All these factors may influence the extent of energy exerted on the fruits and, thus, the susceptibility of mechanical damage in transit.

3.2 | Critical frequencies

Previous studies have demonstrated that the critical frequencies that cause significant damage to fresh produce occur in the lower ranges.[10,71,74,80] The frequency range of 0 to 10 Hz causes the most damage to the produce.[11,18,37] The critical frequency range was further defined by some studies where PSD spectra revealed peaks in the range of 2.5 to 4 Hz.[8,51,79] Jarimopas, Singh, and Saengnil[15] concluded that the average PSD for all measurements for truck transport was in the range of 0.1 to 5 Hz and that the PSD decreased beyond this range. Escalated energy levels in the lower frequencies could be attributed to shock suspension responses of the trucks while the frequencies from 5 to 20 Hz could be attributed to the discontinuity of the road surface.[75] Fischer, Craig, Watada, Douglas, and Ashby[37] found that the frequency range of 5 to 10 Hz caused the most damage to grapes and strawberries. More than 55% of the strawberries at the top of the stack suffered severe bruising after the vibration treatment in the 5- to 10-Hz range. Similarly, Shahbazi, Rajabipour, Mohtasebi, and Rafie[68] confirmed that the flesh of watermelon was sensitive to frequency of 7.5 Hz and that the hull of the watermelon was sensitive to vibration frequencies around 13 Hz. These findings suggest that lower frequencies, mostly attributed to truck suspension or other similar causes such as package resonance, are critical for damage to the fresh produce being transported. A stack of cartons may resonate at 3 to 7 Hz with a secondary peak between 10 to 18 Hz.[13] This is in concordance with most findings from experiments relating critical frequencies with escalated energy levels.

3.3 | Acceleration and transmissibility

In the *In-transit* type experiments, the top packages on a pallet have been found to be vibrating at higher acceleration levels than the trailer floor with an increased transmissibility in the frequency range of 2 to 40 Hz.[8,79] For the frequency range of 8 to 10 Hz, the rear top boxes of fruits (pears) exhibited three times the transmissibility level compared with the bottom box on the floor of the truck.[79] The transmissibility was defined by Vursavus and Ozguven[10] using Equation (2):

$$\text{Percentage Transmissibility}\%(T) \quad = \frac{a_b}{a_t} \quad \times 100\%, \qquad (2)$$

where a_b is the vibration acceleration in the container (g) and a_t is the vibration acceleration on the table/floor (g).

Higher transmissibility levels can cause fruits in the top layers to be airborne (bounce) inside the package during transit. In a recent study, Fadiji, Coetzee, Chen, Chukwu, and Opara[22] showed that the frequency of 12 Hz exhibited the maximum transmissibility of 243% for packaged apples. Slaughter, Hinsch, and Thompson[8] reported that when the transmissibility level reached 400%, the top boxes became airborne as the vertical acceleration levels exceeded 1g. Vursavus and Ozguven[10] also found that at 9 Hz, the percentage of transmissibility was 160%, and when the vertical vibration levels approached 1*g*, the top layer of apples moved freely as they received sufficient energy to be weightless against gravity. The study further suggested that the bounce caused the apples to rotate and bump against each other, which caused surface discolouration, cell wall fatigue, and consequent bruise damage. Similarly, Shahbazi, Rajabipour, Mohtasebi, and Rafie[68] found that when the acceleration levels in the top layer of fruits approached 1.2*g*, the fruits moved freely resulting in excessive decay in the modulus elasticity of watermelons.

3.4 | Position of the package

The package position on the truck floor has been shown to influence vibration levels experienced by the produce. Hinsch, Slaughter, Craig, and Thompson[79] reported that the highest acceleration level was recorded on the floor at the rear positions, where a vibration peak was exhibited at 3.5 Hz. Berardinelli, Donati, Giunchi, Guarnieri, and Ragni[52] found that the global RMS acceleration values for the entire passage under study were 0.43 m s^{-2} (front), 0.57 m s^{-2} (middle), and 0.92 m s^{-2} (rear), signifying that the vibration energy was highest in the rear position of the truck. Many authors were in agreement with this argument that the vibration levels are several times higher in the rear position of the truck than the foreparts.[19,51,75,79] Ranathunga, Jayaweera, Suraweera, Wattage, Ruvinda, and Ariyaratne[18] found that the rear of the truck produced as high as 10 times RMS (G_{rms}) energy compared with the front of an empty truck bed, which signifies that the produce sitting at the rear of the truck is usually more affected. Barchi, Berardinelli, Guarnieri, Ragni, and Fila[16] further emphasized this as the acceleration peak in the rear position was about 14 times higher than the peak in the middle position at the peak frequency of 16 Hz and more than 20 times higher than the peak in the front position that occurred at 18 Hz. In summary, these findings suggest that the rear of the truck bed exerts the highest vibration energy, followed by the middle and then the front positions.

3.5 | Height of the package in a stack

Fruit damage levels can correlate with the height of the package in a column. This may be due to the increased peak acceleration from bottom to top. The top box of the stack can show twice the vibration of the middle box and about four times the vibration of the bottom box.[37] The highest damage in tangerines occurred in the top crate for every combination of tested variables.[15] Barchi, Berardinelli, Guarnieri, Ragni, and Fila[16] found that the acceleration on the crates increased from bottom to top in the range of 5 to 20 Hz and the resonance peak was identified at 9 Hz. Zhang, Yang, Wang, Pan, Meng, and Tong[32] used a sinusoidal vibration table within the frequency range of 3 to 100 Hz with 5 m s^{-2} of peak acceleration to measure the vibration impact on cherry tomatoes. The resonance frequencies were found to be 36.61 Hz (bottom), 10.76 Hz (middle), and 6.44 Hz (top), which implied that the resonance frequencies reduced from the bottom to top while the resonance peak acceleration was increasing from the bottom to top.

3.6 | Suspension type or truck type

Truck suspension type has been shown to have a significant influence on vibration levels. This influence might also be affected by the type of the truck as not only the shock from the road surfaces but also part of the truck engine and chassis vibration itself may transfer onto the cargo. The transmissibility of such vibration may be dependent on the damping properties of the chassis structure of the truck and how firmly the pallets and packages are stacked. Timm, Brown, and Armstrong[14] showed that the vibration damage for apples may differ according to the suspension type of the truck. It was found that air-ride suspension trucks provided reduced magnitude of vibration and cause less damage to apples compared with leaf spring trucks.[14,79] Usuda, Shiina, Ishikawa, and Satake[81] also found that 60% of the vibration peak could be reduced by changing suspension to air ride from leaf spring. Soleimani and Ahmadi[20] also revealed that the vibration levels for leaf spring suspension trucks were significantly higher than the air-ride suspension trucks. For both trucks types, the PSD peaks occurred at 3 and 1.46 Hz, which also signifies the peaks occur at lower frequencies. Ranathunga, Jayaweera, Suraweera, Wattage, Ruvinda, and Ariyaratne[18] reported that the tyre air pressure of the truck is also related to the resultant vibration. Pierce, Singh, and Burgess[82] concluded that air-ride suspension may exhibit lower vibration only when they are maintained properly and a malfunctioning air-ride suspension may produce higher vibration levels than that for leaf spring suspension at the lower frequencies.

3.7 | Road condition and vehicle speed

The road condition and the vehicle speed have been shown to be directly related to the resultant vibration and hence the produce damage. Soleimani and Ahmadi[20] concluded that the vibration levels caused by dirt roads were the highest, followed by asphalt roads and highway roads. Similarly, Jarimopas, Singh, and Saengnil[15] compared the recorded vibration levels with the standard (of ASTM) and concluded that concrete and asphalt roads produce less vibration than the recommended maximum, but unpaved laterite roads result in severe conditions at higher speed levels. Additionally, the greatest damage to tangerines was found on laterite roads followed by concrete roads. The least damage levels were recorded on asphalt roads and also the damage levels increased with velocity levels. Zhou, Su, Yan, and Li[51] found that the highest G_{rms} value was recorded for tertiary roads (2.09 m s^{-2}) and the lowest was recorded on the highways (1.78 m s^{-2}). Similarly, Ranathunga, Jayaweera, Suraweera, Wattage, Ruvinda, and Ariyaratne[18] measured the relationship between the International Roughness Index (IRI) of roads and the PSD of the recorded vibration. International Roughness Index is defined as the ratio between the accumulated suspension motions to the distance travelled by the vehicle. It was found that poor quality roads with an IRI of between 10 and 5 produce more vibration than the fair or good quality roads with an IRI in the range of 3.5 to 0.9. Fei Lu and Satake[83] analysed the vibration levels in truck transport over seven speed intervals and concluded that higher speeds were positively correlated with G_{rms} vibration in both vertical and lateral directions. This suggests that the condition of roads and vehicle speed are important parameters in transit vibration.

3.8 | Vibration duration

Vibration duration and the travel distance were correlated with produce damage, as longer durations and distances result in higher levels of vibration damage.[14] La Scalia, Aiello, Miceli, Nasca, Alfonzo, and Settanni[11] found that strawberries showed a significant reduction in appearance and structural characteristics with the increased duration of vibration. An increment in the vibration duration of 30 minutes in simulation resulted in a 1.52 times higher percentage decay score for watermelon.[68] Soleimani and Ahmadi[19] found that, although highways produced smoother road conditions, the vibration impact was more significant than that of the poor roads due to exposure to extended transportation time. Vursavus and Ozguven[10] calculated the Equivalent Severe Bruise Index (EBI) for apples subsequent to the simulation (8.2 and 12.6 Hz) with the measured acceleration levels (0.33*g* and 0.63*g*) for the durations of 10, 15, and 20 minutes. The study indicated that the EBI value could reach as high as 40% when the vibration duration increased from 10 to 20 minutes. These studies together conclude that the duration of exposure to vibration is critical to produce damage.

3.9 | Depth of fruit within a package (stack height)

A few studies have measured the effect of the depth of the fruit inside the package on fruit damage. The depth is calculated from the top of the corrugated box to the position of the produce.[18,19] The same variable has also been defined inversely as the *stack height* in some studies[39,68] where the fruit depth is measured from the top of the container, and the stack height is measured from the bottom of the container. Soleimani and Ahmadi[19] confirmed that vibration levels were higher in the top layers in the stack compared with the levels at the bottom of the crate. Shahbazi, Rajabipour, Mohtasebi, and Rafie[68] showed that the damage to watermelon hull at the three positions inside the bin (top, middle, and bottom) had a relationship with the percentage decay of the modulus elasticity of the fruit, confirming that the fruit at higher levels exhibited more damage. These studies emphasize that vibration damage increases with the stack height of the fruit inside the package.

3.10 | Other factors for vibration damage

Several other variables including fill status, package type, fruit position inside the package, and cushioning between the layers of fruit have been considered as influential for the level of vibration damage in fruits, although these parameters have been less frequently examined. Slaughter, Hinsch, and Thompson[8] showed that if packages are underfilled, the tight fill status is not achieved. Vibration damage can be reduced by tight-fill packaging where the fruits are immobilized. Timm, Brown, and Armstrong[14] showed that the damage to apples in plastic bins was lower compared with wooden or plywood bins. Differences in apple damage levels were detected for different fruit positions inside the bin such as if the fruit was placed in the middle of each bin or against a side wall of the bins. Barchi, Berardinelli, Guarnieri, Ragni, and Fila[16] confirmed that vibration-absorbent sheets reduced the damage to tangerines by 20% to 40%, as they provided cushioning effect between the layers of fruit and also between the fruit and the bottom of the crate.

4 | IMPLICATIONS ON VIBRATION MEASUREMENT AND SIMULATION

4.1 | Evaluating the effects of vibration

Several *In-Transit* experiments have only measured the vibration levels along transit routes without evaluating the effect or produce damage with respect to recorded vibration intensities. An underlying assumption of such studies was that higher energy levels or acceleration levels may cause more damage to the produce. However, the level of produce damage may not be known unless the fruits are examined before and after the *in-transit* experiment. It is important to establish a relationship with different vibration levels and their effects on various fruits to enable understanding of the response of produce to different vibration intensities. Alternatively, this relationship could be better established by collecting vibration data of the truck floor in different transit routes and by simulating the vibration profiles in laboratory conditions with a stack of fruits on top of a vibration simulator (*Trans-Sim*). This allows better characterization of the produce damage to different vibration intensities.

The *Simulation* type experiments that use a constant vibration signal (fixed vibration intensity)[30,48,53,58,61] did not examine the produce changes with respect to different vibration intensities. These experiments focused on finding the responses of fruits when exposed to a known constant vibration signal. However, it is important to carefully choose the parameters of a constant vibration treatment preferably selected after a field study, by examining the critical frequency levels and acceleration intensities experienced in transit. Alternatively, such a treatment should be selected based on the previous studies on the same type of fruits with similar transport conditions. This enables realistic simulation of the effects on fruit that is comparable with a partial or complete field experience.

4.2 | Vehicle speed in experiments

Most vibration experiments, irrespective of the experimental design, have been conducted to understand the effects of vibration parameters on the internal or external changes in fruits. However, due to constraints such as road conditions or traffic, it is not possible to travel constantly at a specified test speed for a long duration making it difficult to reach conclusions on how a specific vehicle speed may affect vibration levels and subsequent produce damage. In real *In-Transit* experiments, the speed would be an average rather than a constant. Correlating average speed with the effects on produce is not an ideal method but may work for highway roads where the speed can be kept literally constant for a longer duration. Vursavus and Ozguven[10] used this method to correlate the effect of transit speed with vibration where the speed was held constant at 50 km h^{-1} to obtain different acceleration measurements. This controlled experimental method is more suitable for examining the significance of vehicle speed on vibration, rather than averaging the speed for the entire journey to correlate with the vibration intensity. A better method would be to record the vibration levels at each speed interval, derive the PSD profile, and then replicate the signal in a controlled simulation to ascertain the damage or changes in the produce.

4.3 | Transient shocks in vibration profiles

Some researchers have argued that analysing the shock responses within the vibration profile may affect the quality of data produced in the analysis. This was emphasized in the work by Kipp[84] as the probability density function (PDF) resulting from the data mixed with shocks, and vibration cannot be considered random and therefore cannot be described accurately with the PSD alone. When the shocks are removed, the PDF can be approximated to a Gaussian distribution. Kipp[85] further suggested that improvements can be made to the single spectrum PSD approach due to the fact that there is an increased recognition of the non-stationary aspects in-transit as the shock responses cannot be superimposed on vibration. If transient shock responses are not separated from the in-transit vibration responses, the time domain acceleration data may present a misleading picture of the vibration levels of a given route. This may also affect the PSD profile in the frequency domain. Fruits may behave differently to transient shocks compared with vibration and the effect of transient shocks with a significant energy content cannot be neglected.[86] Shocks also occur within the transit passage; hence, they are an integral part of the journey, and therefore, shocks should be represented in the overall PSD profile. However, when creating the averaged PSD profiles for simulation purposes, these transient events will also be averaged and will not be significantly represented.

To resolve these issues, some researchers have split the spectra into two or three segments of different vibration intensities.[87] For instance, the spectra can be analysed with 30% of the higher acceleration levels separated from the lower 70% to create two PSD profiles for the same journey.[71] This method can be identified as split-spectra decomposition. Although it is based on logic, identifying the optimum split is a challenging. Fei Lu and Satake[83] conducted an experiment into the effects of sampling parameters on shock and vibration and concluded that a 0.7*g* threshold could be used to differentiate vibrations from shocks. Ishikawa, Kitazawa, and Shiina[31] measured vibration and shock during the truck transport passage with a 0.3*g* trigger threshold for vibration and 3*g* threshold for shock data collection. Determining the threshold, however, is a challenge without a proper understanding of the magnitude of shocks encountered in the passage, as shocks are essentially characterized by the condition of the road. Frequent bumps and potholes along the road may constitute the force characteristics on the RVL interaction, which may ultimately transfer as energy to the produce.[13] Determination of the crest factor (defined as the ratio of peak value to RMS value of the waveform) might be useful to detect transient shock events in a composite signal.[88] Whichever approach is chosen, the threshold to differentiate a shock from the rest of the broadband vibration needs to be defined.

Identifying the number of shock responses separately in each road segment in the distribution chain may also provide an overall understanding of the transport conditions. Once the shock responses in a given distribution environment are identified, a comparative shock simulation may ideally reveal how the cumulative shocks affect the produce and failure mechanisms of the packages that lead to significant damage of fruits. An approach to superimpose transit shocks on an accelerated random vibration test profile was suggested in an early study by Kipp.[84] The author argued that this method is better than increasing the intensity (G_{rms}) of the overall PSD profile with large acceleration levels to account for shocks during product simulation. However, the shocks generated from a drop test on packages may not be equivalent to transit shocks during truck transport, as the force characteristics exerted on the packages will be significantly different. If the shock responses are performed on simulated packages, it needs to be a close approximation of the shocks encountered in the field transport.

Another approach to characterize shocks from broadband vibration is to decompose the spectra into segments with different kurtosis levels that vary the sharpness of the peak of a frequency-distribution curve. For this purpose, one of the most widely used methods is wavelet-based decomposition that uses the wavelet algorithm to characterize the shocks within vibration profiles. Griffiths, Hicks, Keogh, and Shires[89] proposed a simulation method based on wavelet analysis to decompose the vibration simulation signal. Comparison of the overall RMS value, the kurtosis of the constructed PSD signal, and the PSD pertaining to field data gave a better correlation of scuffing damages on produce subjected to the simulation, when compared with the field experience. Several authors also reported that the wavelet analysis of the random vehicle vibration produced improved simulation results when compared with the damage produced in field experiments.[86,89,90] In another recent study,[91] the capability of machine learning to detect shocks in road vibration signals was investigated and reported to also have achieved successful correlation. Further research on these methods to characterize damage on different fruits may permit the development of more accurate test profiles to be used in simulation compared with the conventional-averaged PSD spectra-based simulation approach.

4.4 | Constructing the simulation profile

When there are different PSD profiles generated during the same journey for different variable settings (such as speed and road condition), the overall PSD profile to be used in the simulation experiment needs to be decided. The conventional approach is to average the PSD profiles or weight and accumulate to derive a global PSD profile for simulation purposes.[52] In an alternative method, Timm, Brown, and Armstrong[14] used the worst-case PSD input with peak accelerations as the input for simulation representing the worst-case trip scenario. Another approach has been to use fixed time intervals for vibration with the simulator operating at a mean acceleration for a given period. Shahbazi, Rajabipour, Mohtasebi, and Rafie[68] used this method to simulate the vibration effects on watermelons by using mean values within the highest distribution intervals for frequency and acceleration. However, vibration signals generated with a mean acceleration, and a fixed frequency may not ideally represent the real field transport conditions during the simulation.

Some researchers have emphasized the non-stationary and non-Gaussian nature of the road vehicle transport.[92-95] The averaged PSD, which is widely used for simulation, has a constant RMS level and disregards random fluctuations in transport routes.[96] Consequently, Sek[92] suggested that the Gaussian nature of the acceleration signal in road vehicle transport has to be determined on a case-by-case basis. This argument is valid when the route contains frequent road irregularities and an averaged PSD profile would not reasonably replicate the field experience during simulations. Rouillard and Sek[97] suggested an approach to simulate non-Gaussian transport vibration by synthesizing the signal into a series of Gaussian processes of different RMS values and durations. Bins or segments with different RMS values can be created, based on the statistical occurrence of different acceleration intensities within the signal and then collated to generate a synthesized signal.[92,96,97] This method decomposes non-stationary random vibration into a series of independent Gaussian segments with different amplitudes. In a recent study, Hosoyama[98] proposed a method based on non-Gaussian simulation, which could better characterize the accumulated fatigue on the package contents compared with the conventional simulation approaches. The study concluded that non-Gaussian input acceleration influenced the response acceleration of the package contents and the kurtosis of the vibration table affected the accumulated fatigue of the contents inside the package.

Alternate simulations based on Weighbull distribution,[99] and a method based on vehicle and road characteristics[96] when the PSD profiles of the routes are already known, have also been reported to have achieved similar success. Rouillard[100] also suggested using pavement profile data available from road maintenance authorities or agencies in the respective countries as an approach for simulating non-stationary vehicle vibration. Increasingly, this approach of non-stationary and non-Gaussian phenomena of random vehicle vibration has gained acceptance in many contemporary studies.

More realistic simulation can contribute to effectively designing optimum packaging for different fruits and may prevent designing of overpackaging or underpackaging, which leads to increased cost and wastage in fruit supply chains. In the case of ASTM or ISTA, certain test standards are specified for repetitive shock, resonance test, or random vibration testing. Simulations can be performed as single or multiaxis vibration.[101] Kipp[84] argued that the use of a standard profile in simulations could be debatable as they might not represent the actual transport conditions. In an earlier study Turczyn, Grant, Ashby, and Wheaton[102] argued that using set standards such as ASTM in simulation may exert intensified effects on produce, and therefore, a limited time simulation is more than adequate as a longer duration will result in adverse damage in produce.

4.5 | Time compressed or accelerated simulation

The duration of simulation has to be carefully determined considering the objectives of the experiment. The use of shaker simulations can be costly, and therefore, it might not be viable to simulate journeys that take many hours or days to replicate. Consequently, time-compressed simulations should be considered. A simulation could be termed as effective if it produced similar results compared with the field experience. This means if the damage in the simulation corresponds to the field, such an experiment would probably be a close approximation for a good simulation.[80] There have been studies based on conventional simulation approaches, which have resulted in outcomes similar to field experience.[14]

Jung and Park[103] simulated a standard ASTM vibration profile for a total journey duration of 331 minutes, replicating the duration of the entire journey in transit to measure the effect on apples. This is not a practical approach in many transport scenarios, such as long-duration interstate transport. Conversely, Kipp[84] implied that time-history reproduction of vibration data in simulation is of less statistical significance and limited to simulation frequencies below 50 Hz (restricted by the simulator capabilities). Furthermore, it can be argued that using a composite PSD in simulation to represent a transit passage may result in "averages" to be "averaged." This is also applicable to the vibration standards such as ASTM and ISTA, which are still widely used. A possibility to compress the simulation time is mentioned in the literature and identified as focused simulation[84] given by the Basquin model[88] in Equation (3):

$$\frac{t_j}{t_t} = \left(\frac{I_j}{I_t}\right)^k, \tag{3}$$

where t_j is simulation time, t_t is actual transit time, I_t is intensity (G_{rms}) in the original profile, I_j is intensity in the test profile, and k is constant associated with the product, for which k = 2 is generally used while rarely some studies use k = 5. The maximum compression should be 5:1 to preserve the validity.[84]

Dunno[101] conducted an important study to find out if the time-compressed profile correlates with the actual in-transit vibration outcomes for produce. The results showed that time-compressed (accelerated) simulation did not correlate with the field experience. However, the non-stationary and non-Gaussian simulation method correlated with the field experience and hence could be used to reduce the simulation time. Similarly Griffiths[104] conducted a study on apples to determine if the MDOF time-compressed simulation would produce similar scuffing damages on apples compared with actual road transport. It was concluded that the modulated RMS simulation and the single spectra PSD approach in a time compressed setting (5:1 where k = 2) produced similar levels of damage to time history replication. Furthermore, it revealed that a single degree of freedom (SDOF) Gaussian equivalent simulation gave the best approximation of the scuffing damage on apples. However, a suitable k value needs to be used if a time-compressed simulation is considered. Shires[105] concluded that a lower level of time compression was required for the simulation of air-ride suspension trucks to reduce the error sensitivity. This implies that the higher the time compression is, the more errors that will be encountered in simulation. These studies suggests that more research needs to be conducted on different fruits to find out which simulation approach may best replicate the actual field experience specially for simulation targeted on package optimization.

4.6 | Data overriding

The early *In-transit* studies used digital audio tape recorders[10,52] while modern vibration measuring devices are equipped with internal memory or data can even be stored on a memory card mounted to the device. However, due to the limitations of memory capacity, peak acceleration override methods were adopted in the past[70] with potential consequences that useful data along the track may be overridden by a new event. Overriding disables tracking events through the analysis of the timestamp. Therefore, data overriding within the same passage may not be advisable. Having global positioning system (GPS) tracking capability in the vibration and shock devices also gives an added advantage by providing a spatial meaning to data. However, the impact location was not known for earlier studies since the devices were not enabled with GPS capability. New devices developed with GPS capability must receive a signal to a device placed inside the truck to receive location coordinates. However, signal transmission can be obstructed by the metallic framework of the truck that prevent line of sight to satellites.

4.7 | Limited time sampling

Time duration has been one of the limiting factors in many *In-Transit* and *Trans-Sim* type experiments due to limited memory capacities or utilizable battery power of the available devices. This has led to capturing of data over a limited sampling time in many studies. Vibration signals that have been recorded only during a stretch of the journey or during a limited period, such as fixed interval limited sampling, randomized sampling, or signal triggered sampling have been frequently reported.[11,14-16,52,79] Some researchers used a threshold for acceleration, and below the threshold the logging was not performed.[31,101] However, having a higher acceleration threshold may only capture the shocks instead of vibration. Continuous data logging without a set threshold is limited by the power or the memory capacity of the device, and the first to run out determines the time of continuous use for a device. Therefore, it is difficult to collect high-frequency vibration data throughout transit times over days, especially in interstate supply chains. An alternative proposition is to sample and collect a fraction of the journey to represent the vibration responses in the entire passage.

Several studies have been conducted on the sampling parameters for vibration, with the objective of finding out the minimum duration of sampling required to characterize vibration in a given route. Rouillard and Lamb[106] suggested that recording data for 1/8th of the journey is sufficient for this purpose, while Fei Lu and Satake[83] found that 1/30th for highway travel and 1/15th for local roads of the journey are sufficient for the purpose. The differences in sampling parameters given in these studies show that the minimum duration of sampling is highly dependent on the variables such as the route condition, travel duration, and distance. This emphasizes that the best sampling interval may be found only after finding out which fractions of sampling time ideally represent the anomalies of vibration within each route segment.

Another approach is to sample vibration responses at different variable settings for a limited period for each road segment and sample shock responses throughout the journey. In this approach, the vibration responses could be sampled for different speed intervals and road segments to develop the respective PSD profiles while the shocks can be recorded as and when they occur throughout the journey by specifying an appropriate shock threshold. Whichever sampling approach is used, the data sampling time can be extended by applying recording thresholds for acceleration to shut down the devices while the truck is not moving or the engine is turned off. Dunno[101] used this method to capture vibration data while the truck was in motion by depicting a very low (0.1*g*) signal threshold, potentially capturing all the vibration and shock events pertaining to the journey. This is an effective approach in supply chains extending to several thousands of miles in transit as there are mandatory intermittent rest stops for truck drivers required by regulations in respective countries.

4.8 | Instrumented spheres and devices for remote quality monitoring

In contemporary studies micro-electro-mechanical (MEMS) accelerometers have been frequently used in road vibration studies due to the advantages of their miniaturized design, their ability to perform analogue-to-digital conversion within the same circuit, and the data being easily logged on an on-board memory chip.[18,68] Albarbar, Mekid, Starr, and Pietruszkiewicz[107] stated that the choice of the accelerometer depends on factors such as sensitivity, amplitude limit, shock limit, natural frequency, resolution, amplitude linearity, frequency range, and phase shift. The study concluded that two out of three tested MEMS types are fairly compatible with the conventional piezoelectric accelerometers in their study on machine condition monitoring. Thanagasundram and Schlindwein[108] found that MEMS (ADXL105) accelerometers had 16 times higher noise level when compared with piezoelectric accelerometers, although the noise level was only found to be a major limitation in very low "*g*" amplitudes. MEMS accelerometers have been found to show the same quality of data compared to piezoelectric accelerometers when the vibration level was measured up to ±2*g* at 100 Hz. Therefore, MEMS accelerometers can be considered for some of the suitable applications since the trade-off is generally between the cost, simplicity, size advantage, and portability versus the sensitivity. However, the choice of an accelerometer is largely dependent on the application, and there are still many challenges to using MEMS-based devices to capture in-transit data continuously at high sampling rates. The accelerometer sensitivity, noise levels, and mounting mechanism should be thoroughly investigated before deciding on which accelerometer device to use to record data in-transit.

Piezoelectric accelerometers need to be attached to a charge amplifier, a signal conditioner, and a data recording device to capture the data. Many studies have used piezoelectric accelerometers because of their sensitivity and resolution.[16,75] The dimensions of the components in a conventional piezoelectric system however can reduce the portability, especially when used inside cartons or packages, and present complications in wiring up. It can also be difficult to provide portable power for these systems for long truck journeys extending to days. However, piezoelectric accelerometers with miniature integrated designs are now becoming available and increasingly popular for portable applications when coupled with external-portable battery packs. With the rapid development in accelerometer technology, miniature devices can be developed with all systems embedded in a single data logging device, and these can be even presented in the form of instrumented spheres (IS) in the shape of a fruit.[109] An IS might be an ideal choice for impact studies such as capturing the shocks to fresh produce in a packaging or a sorting line.[110-113]

At present, real-time monitoring of consignments in the supply chain involves remote acquisition of information on the proximity, temperature, humidity, and some gas concentrations during transit. In the future, real-time monitoring of harmful transit conditions such as exposure of package to resonant frequencies and transit shocks may provide additional information that will be of an importance for predicting resultant fruit quality. This could result in the ability to apply concurrent changes to delivery conditions and routes. The development of an IoT (Internet of Things) based miniature transducers with the wireless-cloud support will enable this real-time monitoring of the exposure to harmful mechanical vibration and shocks. Such devices may benefit not only fruit supply chains but also any delicate product that is susceptible to damage and has quality implications due to the mechanistic effects of vibration and shocks.

5 | CONCLUSION AND FUTURE RESEARCH

Vibration in transit affects the visual quality and may cause significant mechanical damage in fruits. The extent of fruit damage may depend on the intensity of input vibration attributed to the RVL interaction, which may ultimately transfer as energy to fruit packages. Past research on vibration effects to fruits reveals that the intensity of vibration is significantly influenced by a range of factors including suspension characteristics of the vehicles, road condition, travel speed, acceleration transmissibility, and the duration of exposure to the produce being transported. Furthermore, the vibration intensity is also affected by the position of the package along the truck bed and the height of the package in a stacked column. It has been concluded that higher energy levels are transferred onto the produce in the frequency range of 0 to 10 Hz, suggesting that the critical frequencies are in the lower range of the spectrum. However, only a limited number of studies have been conducted on how mechanical damage is influenced by the size of the fruit and the depth of the fruit stacked inside the package when subjected to transit vibration.

Many researchers have repeatedly conducted experiments into the vibration effects on the same type of produce such as apples, pears, and strawberries. This has resulted in limited research into other produce susceptible to damage such as bananas, avocados, mangoes, and stone fruits in general. Some studies have been conducted without correlating the parameters under investigation with produce damage or changes, resulting in limited knowledge of how vibration or shocks had actually affected the produce. It is essential that damage or changes in fruits are correlated with the vibration dose and intensity experienced by the packages or fruits. This contributes to understanding the causes and to improving preventive mechanisms. It is also important to carefully use the parameters of a vibration treatment, rather than arbitrarily exposing the fruit to a randomly chosen frequency, acceleration, and duration. The constant vibration treatment may be selected based on the previous findings on similar fruits or ideally after a field study.

Limited research to date in the areas of packaging improvements and dampening mechanisms to minimize fruit mechanical damage emphasizes the need for further research on the effectiveness of packaging, inner packing methods, and pallet stabilization methods. Further studies on the resonance characteristics of packages and the damping properties of different packaging methods may reveal how best the acceleration transmissibility can be minimized in the upper tiers of the pallet. This will be important to reduce mechanical damage by immobilizing the fruits to prevent relative motion of the fruit in the upper tiers. There has been a tendency towards using reusable plastic crates (RPC) for fruit and vegetable packaging, mostly due to its cost advantages and environmental friendliness. However, limited research has been conducted on the use of RPCs and their vibration and resonant characteristics. Further research is suggested on the effectiveness of RPCs to prevent mechanical damage in different types of fruit during transport and to confirm cost savings of the reusable creates.

Package simulation approaches need to be used to explore the effectiveness of interventions such as the use of different inner packing material and packing methods, especially to prevent scuffing damages on fruits. Both soft fruits and hard fruits may bounce on trays when exposed to acceleration levels exceeding the gravitational acceleration (±1 g), and thus, it is important to verify mechanisms to reduce damage by minimizing the rotating and bouncing effects when exposed to vibration and shocks. In addition, there is lack of research on the effect of storage temperature and humidity to the susceptibility of mechanical damage in fruits, subjected to simulated transport. Further research into the failure mechanism of fruit packages subjected to vibration under different storage temperatures and relative humidity conditions will be also beneficial in designing optimum but robust packaging solutions to withstand dynamic atmospheric conditions during transit.

Simulation methods need to be carefully chosen for design and optimization of fruit packaging. Currently, there is a lack of a universally accepted method for vibration simulation, which can be used on all fruits. However, it is collectively implied that a reasonable simulation should be chosen by comparing the effects on produce with the field experience. Approaches based on non-Gaussian and non-stationary simulation are becoming popular as the recent studies reported to have achieved greater successes. The suitability of different simulation methods for different fruits need to be further researched as the behaviour of each fruit to a given vibration dose could be significantly different. An inaccurate simulation may result in underestimation or overestimation of the packing performance, which may not provide optimal solutions when used in the real distribution environment.

It is also important to develop mechanisms to enable improved shock and vibration data recording throughout the transit passage to understand the cumulative effects on fruits. Data capturing from the origin to destination may contribute to developing an accurate RMS distribution of the transport environment. Data capturing technologies are evolving in this area, and the design of micro-controllers and accelerometers is advancing towards less power consumption and greater memory storage. Recent advances in MEMs and piezoelectric accelerometers enable the devices to be portable and miniaturized allowing them to be used easily inside fruit packages. The addition of GPS capability in the vibration and shock recording devices adds another valuable perspective to understand when and where shocks occur in the transit passage and frequency of such shocks, which might result in cumulative mechanical damages in produce.

Instrumented sphere devices will be useful to characterize the vibration effect on individual fruits compared with the vibration of the truck floor or package. This may reveal the behaviour of different fruits to different input vibration levels, which can be used to assess the effectiveness of preventive mechanisms to reduce fruit-level movements, which has been the primary cause of scuffing damage. With the advancement of IoT-enabled devices and user application environment, integrated IS and real-time solutions to monitor vibration and shocks could be developed to compliment the current remote quality monitoring systems for fresh produce. This will increase the ability to respond in real time to improve the tractability of fruit supply chains, which may ultimately reduce produce wastage and retain the perceived value of fruits in transit.

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CONFLICT OF INTEREST

The authors would like to declare that they do not have any conflicts of interest with their work and the content of this paper.

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