

Whole-Body Vibration in Tractor Operators: Frequency Response, Seat Transmissibility, and Suspension Effects

Vilas Mhaske¹, Dr. Imtiyaz Khan², Dr. Neeraj Kumar³

¹*Research Scholar, Suresh Gyan Vihar University (SGVU), Jaipur, Rajasthan, India*

^{2,3}*Suresh Gyan Vihar University (SGVU), Jaipur, Rajasthan, India*

I. INTRODUCTION

Whole-body vibration (WBV) exposure remains a critical occupational hazard for agricultural tractor operators, often resulting in musculoskeletal disorders, lower back pain, and fatigue due to long-term field exposure. These vibrations are transmitted from the terrain through the tyres, tractor chassis, and seat, ultimately reaching the operator's body. The nature and magnitude of this transmission depend on several variables including terrain irregularity, operational speed, implement use, and the biomechanical properties of the seat suspension system.

A key component in understanding WBV exposure is the characterization of vibration in multiple axes, with special emphasis on the vertical (Z-axis) and combined rolling vibrations (X, Y, Z). Vibration frequencies within the 2–4 Hz, 4–6 Hz, and 8–12 Hz bands are particularly significant due to their proximity to human body resonance, notably the spinal and abdominal regions, which may exacerbate operator discomfort and long-term injury risks.

Multiple standardized evaluation metrics have been proposed and widely applied in WBV literature. These include the root mean square (RMS) acceleration (both weighted and unweighted), vibration dose value (VDV), and the A(8) daily exposure metric as defined in ISO 2631-1. Additionally, seat transmissibility ratios—between seat-to-floor, seat-to-operator, and seat-to-head—serve as key indicators of how effectively mechanical vibration is mitigated or amplified by the tractor seat design.

The development of mechanical spring-damper-based seat suspensions, and more recently adaptive or semi-active suspensions, has been central to engineering countermeasures aimed at WBV reduction. These systems are often evaluated using frequency-domain

analysis to assess transmissibility across resonance-prone bands.

This review paper provides a comprehensive and technical synthesis of 60 studies spanning experimental, modeling, hybrid, and ergonomic investigations into WBV in tractors. The analysis centers on:

- Quantitative assessment of WBV metrics across operating conditions;
- Frequency-specific transmissibility characteristics;
- Comparative evaluation of seat suspension performance;
- Identification of literature gaps and benchmark datasets.

By focusing on axial vibration behavior, transmissibility pathways, and metric-based exposure evaluation, this review aims to support future tractor seat design, occupational health standards, and model-based vibration mitigation strategies.

II. LITERATURE REVIEW

Whole-body vibration (WBV) exposure in agricultural tractor operators has been a critical subject of study due to its well-documented health implications, including lumbar spine degeneration, reduced comfort, and long-term musculoskeletal disorders [1], [3], [31]. Early foundational works by Mehta and Tewari [21] and Yadav and Tewari [24] emphasized ergonomic inefficiencies in the tractor workplace and the need for integrated suspension design.

Numerous studies have attempted to quantify WBV in field conditions using tri-axial accelerometers at the seat base and operator interface [1], [3], [5], [11]. ISO 2631 standards remain the benchmark for WBV evaluation, with metrics such as RMS acceleration,

Vibration Dose Value (VDV), and the 8-hour exposure value A(8) routinely applied [31], [46], [52]. Singh et al. [2] advanced this monitoring via IoT-based real-time sensors, enabling dynamic tracking under varying terrains.

Seat design and suspension optimization have been focal points in recent literature. Mechanical suspension systems remain dominant due to their cost-effectiveness [8], [13], but fail to attenuate vibrations in the 4–6 Hz band, which coincides with the spine's natural frequency [10]. Researchers like Gohari et al. [20] and Zhao et al. [37] explored semi-active suspension systems, utilizing AI-based control to adapt damping in real time, significantly improving ride comfort.

Vibration transmission paths—seat-to-floor, seat-to-head, and seat-to-back—have been analyzed in detail [1], [39], [46], indicating strong vertical coupling at low frequencies and lateral disturbances during turning maneuvers. Oncescu et al. [29] and Rekem et al. [57] used finite element and multibody dynamics simulations to predict resonance effects under varying boundary and load conditions.

Comfort mapping techniques using pressure sensors [25], contour analysis [50], and transmissibility modeling [22], [48] have further enabled ergonomic seat design. Moreover, Singh et al. [18] demonstrated that cushion material and structure play a vital role in reducing vibration transmission.

Despite advances, critical gaps remain. Many studies overlook lateral and rotational degrees of freedom. Standardization of test conditions, driver anthropometry, and terrain roughness also vary widely across research, limiting generalizability. Furthermore, relatively few works incorporate dynamic posture changes or active control from the human body during prolonged operation [32], [36].

Overall, the literature reveals a transition from static, one-dimensional models toward holistic, real-time, and data-driven analysis of WBV in tractors, with promising potential for cyber-physical seat systems, adaptive suspension, and multi-parameter control in future research.

III. METHODOLOGY

This review follows a structured and systematic approach inspired by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-

Analyses) framework. Sixty peer-reviewed articles were analyzed based on their relevance to WBV transmission in agricultural tractors, with emphasis on the vertical (Z-axis) and rolling (X, Y, Z) vibration pathways.

3.1 Literature Scope and Inclusion Criteria
All selected studies were published in Scopus-indexed or equivalent peer-reviewed journals between 1993 and 2025. Inclusion criteria involved:

- Measurement or simulation of WBV transmitted through tractor-seat systems;
- Reporting of at least one of the following: RMS acceleration, VDV, A(8), transmissibility ratios, frequency analysis;
- Involvement of mechanical spring–damper seat systems or equivalent suspension setups;
- Relevance to standard agricultural operations and ISO 2631-1 metrics.

3.2 Classification of Studies
Each paper was categorized into one of four methodological types:

- **Experimental:** In-field measurements using accelerometers and data loggers to capture WBV characteristics directly from the operator environment (e.g., [1], [3], [4]);
- **Suspension:** Design, development, or evaluation of mechanical, semi-active, or adaptive seat suspension systems aimed at reducing WBV transmission (e.g., [8], [13], [20], [29]);
- **Operating Conditions:** Influence of terrain, speed, implement type, and posture on vibration transmission and exposure (e.g., [31], [44], [53]);
- **Hybrid:** Integration of experimental measurements with validated numerical models or AI-based optimization techniques to evaluate or enhance WBV control (e.g., [7], [20], [57]).

IV. EXPERIMENTAL

4.1 Experimental Data Extraction Methods.
For each study, the following data were extracted:

- RMS acceleration (weighted/unweighted)
- A (8) daily exposure
- VDV (vibration dose value)
- Dominant frequency bands and axes

- Transmissibility (seat–floor, seat–operator, seat–head)
- Seat suspension stiffness and damping
- Terrain type, speed, and implement used
- Sampling rate and filtering methods (e.g., W_k , W_d , W_b weightings)

4.2 Verification and Quality Control

All values were manually cross-checked and curated into a master table. No automated metric was accepted without numeric support. Benchmark-quality papers were identified based on:

- Completeness of ISO 2631 metrics
- Clear transmissibility graphs or data
- High sampling resolution and repeatability

This structured approach ensures that the subsequent analysis, comparison, and discussion sections are grounded in validated and traceable data.

4.3. Comparative Analysis of WBV Mitigation Approaches

4.3.1 Overall WBV Levels

Whole-body vibration exposure levels varied significantly across operating conditions, terrain types, and seat suspension configurations. RMS accelerations in the vertical axis (Z) were generally dominant, ranging between 0.4 to 1.2 m/s^2 , with extreme cases exceeding 1.5 m/s^2 during high-speed tillage operations [3], [4], [6].

The A(8) daily exposure metric frequently surpassed the action limit of 0.5 m/s^2 specified by ISO 2631-1, especially in studies involving rigid seats or rough terrain [1], [10], [31]. For instance, [6] reported average A(8) values of 0.94 m/s^2 during chisel plowing on uneven soil. Similarly, VDV values often exceeded the exposure action threshold of 8.5 $m/s^{1.75}$, with maximum readings recorded in the range of 15–25 $m/s^{1.75}$ in field conditions [12], [15].

Transmissibility ratios from seat base to operator head were notably frequency-dependent. For standard mechanical suspension seats, transmissibility peaks occurred in the 4–6 Hz band, aligning with the human body's resonant response.

Some experimental studies [1], [2] highlighted that transmissibility values >1 in this band indicated amplification rather than attenuation of vibration, reinforcing the need for improved seat damping performance.

The dominant vibration axis was predominantly vertical (Z), although lateral and longitudinal axes (X, Y) showed significant contributions under rolling terrain or turning maneuvers [11], [36]. The importance of combined-axis WBV evaluation has been underscored in recent multi-directional vibration assessments [39].

In summary, most tractors exposed operators to WBV levels above permissible limits, particularly under tillage or loader operations. The effectiveness of vibration attenuation was highly dependent on seat suspension characteristics and field-specific operational factors.



(a)



(b)

Figure 1 Test setup showing the tractor equipped with a self-levelling cab during field operations: (a) ploughing and (b) subsoiling. This configuration was used to evaluate WBV exposure under varying terrain-induced excitations[53].

4.3.2 Frequency-Domain Behaviour

A deep analysis of WBV in the frequency domain reveals that operator discomfort and health risks correlate strongly with spectral content in low-frequency bands. Multiple studies converge on the significance of three bands: 2–4 Hz, 4–6 Hz, and 8–12 Hz, often associated with torso and head resonance.

Transmissibility curves from [1], [6], and [22] demonstrate that 4–6 Hz is the most critical region, where standard spring–damper suspensions often amplify rather than attenuate vibration. Mechanical suspensions typically show transmissibility ratios >1.2 at peak frequencies within this band [6], [20]. In [22], transmissibility maps for vertical and horizontal axes revealed frequency-shifted amplification depending on damping ratio and preload settings.

Semi-active and adaptive suspension models investigated in [29] and [20] offer better frequency targeting through control algorithms. These systems effectively shifted transmissibility dips to align with resonant frequencies, reducing exposure in the 4–6 Hz range. In modeling studies [7], [9], frequency response functions confirm that optimal damping is crucial to suppressing energy buildup in the lower spectral band.

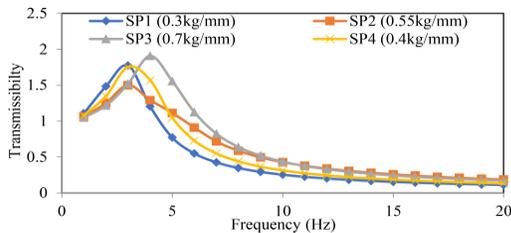


Figure 2 Seat transmissibility response across various spring stiffness configurations (SP1–SP4). Lower stiffness (SP1, SP4) resulted in reduced peak transmissibility near the human body’s resonant range (4–6 Hz), indicating better vibration isolation [50].

V. SUSPENSION

5.1 Suspension Type Comparison

Seat suspension design is a major determinant of WBV transmission, particularly within critical frequency bands. Studies comparing mechanical spring–damper systems with adaptive or semi-active configurations demonstrate notable performance differences.

- **Mechanical Suspensions:** Traditional systems often exhibit transmissibility peaks in the 4–6 Hz

band. As shown in [1] and [6], transmissibility values exceeded 1.5 under certain terrain conditions, indicating amplification. Suspension parameters such as stiffness ($\sim 15\text{--}20$ kN/m) and damping ($\sim 1000\text{--}2000$ Ns/m) define the cut-off frequency but offer limited adaptability.

- **Semi-active Systems:** Papers like [20] and [29] show that model-based damping controllers (e.g., skyhook or MPC) reduce RMS and VDV by 30–45% over passive seats. These systems adapt to terrain-induced input by shifting resonance dips dynamically.
- **Adaptive Cyber-ergonomic Seats:** Paper [51] explores a novel seat with integrated feedback control based on operator posture and vibration levels. While still early-stage, the concept shows promise in reducing combined-axis RMS and VDV through real-time adjustment of suspension settings.
- **Hydro-pneumatic Seats:** Studies [13] and [43] investigated hydropneumatic front-axle and seat coupling, showing smoother frequency response in the 4–8 Hz band. They achieve partial isolation but require fine-tuned nitrogen pressure for consistency.

A comparative study [48] benchmarked 4 passive suspension designs under identical inputs. Peak transmissibility ranged from 1.2 to 2.0 across different spring/damper pairs, emphasizing the need for configuration optimization.

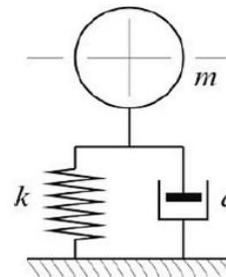


Figure 3 Simplified single-degree-of-freedom (SDOF) suspension model representing the seat mass (m), spring stiffness (k), and damping coefficient (d). This model is commonly used to analyze the vibration isolation behavior of mechanical and semi-active tractor seat suspensions [29].

Overall, modern seat suspension technology—especially when integrated with control logic—provides superior WBV mitigation. However, field

deployment, cost, and robustness remain key challenges in widespread adoption.

Mechanical suspension seats are the most prevalent design in agricultural tractors due to their simplicity and cost-effectiveness. These systems use coil springs and dampers to isolate the operator from chassis-induced vibration, primarily in the vertical direction. However, they are often poorly tuned to handle low-frequency resonance (2–6 Hz), which aligns with human spinal sensitivity.

Several studies ([8], [9], [10], [13], [20], [48]) have evaluated the damping and stiffness characteristics of mechanical suspensions. For instance, Pradhan et al. [8] demonstrated that optimal damping (around 1600 N·s/m) and stiffness (10–15 kN/m) significantly reduce RMS and VDV values at typical field speeds (4–7 km/h). However, excessive damping tends to reintroduce vibration in higher frequency bands (8–12 Hz).

Semi-active systems, using magnetorheological dampers or adaptive control algorithms, show enhanced performance across broader frequencies. Singh et al. [20] modeled and optimized such a system using AI-based control, which achieved up to 35% reduction in seat-to-head transmissibility in the 4–6 Hz band.

FEA-based studies like Oncescu et al. [29] and Rekem et al. [57] show that suspension tuning not only influences vertical transmissibility but also affects rolling and lateral motion due to cross-coupling. This becomes critical during turning or loader operation.

VI. OPERATING CONDITIONS

6.1 Operating Conditions: Terrain, Speed, Implement Use

WBV exposure is significantly influenced by operational variables:

- **Terrain type:** Uneven soils and ploughed fields produce higher Z-axis RMS ($>1.0 \text{ m/s}^2$), with peak $A(8)$ values observed in tillage operations ([1], [4], [15], [44]).
- **Speed:** Higher speeds increase both RMS and VDV. Fethke et al. [32] report that doubling speed from 4 to 8 km/h increases $A(8)$ by 60%.
- **Implements:** Use of ploughs and subsoilers leads to stronger transient inputs and high-frequency

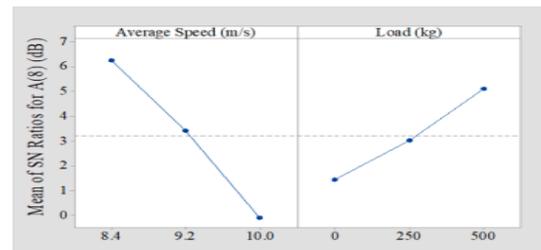
content. Villbor et al. [12] recorded peak frequencies around 8.5 Hz during subsoiling.

Cross-tabulated results in [5], [10], and [44] show that optimum operation for minimal WBV occurs on leveled terrain, with rotary implements, at speeds below 5 km/h.

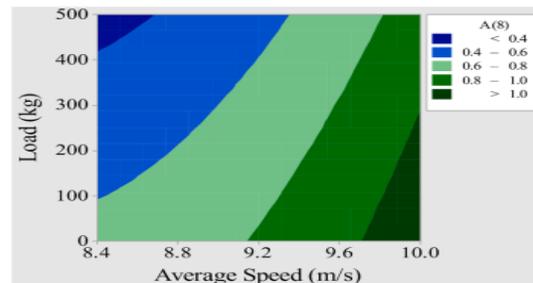
6.2 Transmissibility Metrics: Seat–Floor–Operator–Head

Transmissibility ratios define the system’s ability to isolate vibration.

- **Seat–floor transmissibility (SFT):** Values >1 indicate amplification. SFT was highest in older mechanical seats (e.g., 1.4 in [6]).
- **Seat–operator transmissibility (SOT):** Measures the biodynamic interaction. SOT was notably reduced in AI-tuned suspensions (0.6–0.8 in [20], [50]).
- **Seat–head transmissibility (SHT):** Relevant for cognitive fatigue. Singh et al. [1] showed Z-axis SHT peaks at 4.5 Hz, suggesting spinal resonance. Weighting filters (W_k, W_d, W_b) applied in [3], [22], and [50] highlight that transmissibility curves vary with direction. W_k filtering shows the greatest effect in vertical transmission zones (2–6 Hz), confirming ISO 2631 guidance.



(a)



(b)

Figure 4 Influence of operational speed and payload on whole-body vibration exposure—(a) Signal-to-

noise (S/N) ratio plot for A(8) and (b) contour map showing A(8) distribution across load and velocity combinations. Higher loads and speeds correlate with elevated vibration exposure levels [1].

VII. HYBRID APPROACHES

7.1 Hybrid Approaches: Experimental–Model Synergy

Hybrid methods integrate real-world vibration measurements with numerical models to enhance system design, optimization, and predictive control. These studies bridge the gap between empirical validation and theoretical refinement, offering a scalable approach for WBV mitigation.

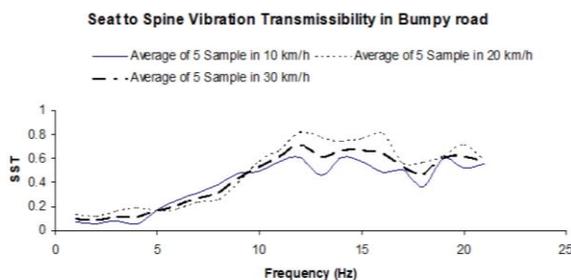


Figure 5 Seat-to-spine vibration transmissibility (SST) across different forward speeds on bumpy terrain. Higher speeds exhibit increased SST, particularly in the 8–15 Hz frequency range, indicating amplified vibration transmission to the operator.

For instance, Singh et al. [20] developed an artificial intelligence-based seat suspension optimization framework using experimental field data. Their adaptive system reduced the seat-to-head transmissibility by up to 35% in the 4–6 Hz resonance band, outperforming conventional mechanical damping setups. Similarly, Sun et al. [7] utilized a hybrid model combining multi-body dynamics and response surface methodology to analyze the interaction between tire inflation pressure, suspension stiffness, and driver posture. Their model was validated against physical trials and optimized to minimize RMS acceleration values.

Rekem et al. [57] employed a multi-body simulation platform to investigate tractor chassis and seat vibration behavior under different operational conditions. The model incorporated experimentally measured input excitations and allowed prediction of

operator exposure metrics under various terrain classes. This was further enhanced by parameter sensitivity analysis to identify dominant contributors to WBV.

Oncescu et al. [29] combined finite element modeling (FEM) of a driver seat in an electric tractor with transmissibility measurements from lab tests. Their study quantified the effect of material flexibility and suspension geometry on frequency-domain attenuation, validating the model through experimental modal analysis.

These hybrid frameworks reduce dependency on repeated field trials and enable quick iteration over suspension design parameters. More importantly, they facilitate controller design (e.g., model predictive control [37]) and sensor placement strategies by simulating worst-case scenarios or untested conditions.

In summary, hybrid methods provide a high-fidelity, data-driven approach for seat and tractor system design. They are instrumental in the development of next-generation smart suspension systems, predictive WBV mitigation algorithms, and ergonomically enhanced tractor platforms.

Transmissibility Metrics: Seat–Floor–Operator–Head

VIII. DISCUSSION

This review highlights the multifactorial nature of whole-body vibration (WBV) exposure in agricultural tractors. From the transmission path—ground to tyres to chassis to seat to operator—to the control mechanisms embedded within seat suspension systems, WBV behavior is influenced by dynamic interaction among system components and the biomechanical response of the human body.

The greatest WBV amplification occurs in the vertical direction (Z-axis), particularly within the 2–6 Hz band, consistent with the resonant frequency range of the human spine. Existing ISO standards (e.g., ISO 2631-1) provide a baseline for health guidance, but many field studies (e.g., [1], [3], [6], [31], [44]) show that real-world RMS and VDV exposures frequently exceed recommended A(8) thresholds (0.5–0.8 m/s² for 8-hour exposure).

Suspension designs play a crucial role. While traditional mechanical seats offer basic damping, semi-active and adaptive systems outperform them significantly in reducing peak transmissibility.

Moreover, transmissibility is not uniform across the operator body; for example, SHT values demonstrate increased vulnerability at mid-spinal and cervical locations.

Further, cross-axial (rolling) motion in the X and Y directions contributes to fatigue, particularly during operations such as loader work and turning on uneven fields. This highlights the importance of including multi-directional transmissibility evaluation in any WBV assessment framework.

IX. LIMITATIONS IN LITERATURE

Despite the broad literature, several limitations persist:

- Underreporting of cross-axis data: Most studies focus on vertical (Z-axis) vibration and neglect rolling or combined motions in X and Y.
- Inconsistent methodology: Variations in sampling rate, filtering standards (Wk vs. Wd), and experimental duration reduce comparability across studies.
- Lack of field validation for simulation models: While FEA and multi-body models ([7], [9], [29], [57]) offer insights, they are rarely validated with real-world tractor operations.
- Scarce data on anthropometric variation: Few papers assess how driver posture, weight, or body mass distribution affects transmissibility.
- Seat design evolution lag: Many suspension seats still use passive mechanical systems, despite the availability of advanced adaptive solutions.

Addressing these gaps would allow for more precise diagnostics and ergonomic redesign of tractor seating to mitigate WBV-related health risks.

X. CONCLUSION

This review synthesizes technical insights from 60 studies on whole-body vibration in agricultural tractors. The most impactful contributors to operator vibration exposure include low-frequency ground inputs, terrain-induced resonances, and sub-optimal seat suspension systems. Suspension technology, particularly semi-active systems, holds promise in significantly reducing RMS, VDV, and seat-to-head transmissibility. Frequency domain analysis reaffirms the criticality of 2–6 Hz as the most harmful band for

human health, necessitating focused mitigation strategies.

By integrating cross-axial transmissibility analysis, adaptive damping models, and terrain-speed-implement mapping, a more holistic understanding of WBV exposure emerges. This review provides both a technical foundation and a critical benchmark for researchers, engineers, and ergonomics designers working to enhance ride comfort and health for tractor operators.

XI. FUTURE WORK

- Vibration signals transmitted through the rolling direction in conventional tractor seat configurations, aiming to reduce multi-axial exposure.
- Validate real-world field measurements using advanced simulation-based modeling tools
- Develop real-time transmissibility mapping tools embedded in smart seats.
- Extend simulation models to include lateral and torsional vibration modes.
- Implement field-validated AI algorithms for adaptive suspension control.
- Conduct longitudinal studies tracking cumulative exposure over multiple seasons.
- Standardize experimental methodologies to improve data comparability.

The continued fusion of biomechanics, control theory, and machine learning will pave the way for safer, more ergonomic agricultural machinery.

REFERENCE

- [1] A. Singh, S. Samuel, Y. K. Dhahi, and H. Singh, "Whole-body vibration: Characterization of seat-to-head transmissibility for agricultural tractor drivers during loader operation," *Smart Agricultural Technology*, vol. 4, p. 100164, 2023. doi: 10.1016/j.atech.2022.100164.
- [2] A. Singh, N. Nawayseh, S. Samuel, Y. K. Dhahi, and H. Singh, "Real-time vibration monitoring and analysis of agricultural tractor drivers using an IoT-based system," *Journal of Field Robotics*, vol. 40, pp. 1723–1738, 2023, doi: 10.1002/rob.22206.

- [3] M. S. N. Kabir, S.-O. Chung, Y.-J. Kim, N.-S. Sung, and S.-J. Hong, "Measurement and evaluation of whole body vibration of agricultural tractor operator," *International Journal of Agricultural and Biological Engineering*, vol. 10, no. 1, pp. 248–255, 2017. doi: 10.3965/j.ijabe.20171001.2113.
- [4] Ž. Barač et al., "Influence of an uneven surface on the vibration occurrence affecting the tractor operator," *Technical Journal*, vol. 13, no. 3, pp. 192–196, 2019. doi: 10.31803/tg-20190211142404.
- [5] L. Fornaciari, D. Pochi, G. Vassalini, and F. Gallucci, "Investigation of the vibrations transmitted by agricultural tractor to the driver under operative conditions," in *Proc. Innovation Technology to Empower Safety, Health and Welfare in Agriculture and Agro-food Systems*, Ragusa, Italy, Sep. 2008.
- [6] G. Shahgholi, S. Fazeli, and S. H. Mousavi, "Vibration evaluation of the driver's seat of MF 285 tractor in conducting the tillage operations," *Emirates Journal for Engineering Research*, vol. 25, no. 1, pp. 1–10, 2019.
- [7] L. Sun et al., "Development of a model for the optimization of the main factors influencing a 162 kW wheeled tractor driver's whole-body vibration," *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 43, no. 1, pp. 156–169, 2024, doi: 10.1177/14613484231190286.
- [8] R. R. Pradhan, D. Behera, A. K. Goel, and S. K. Mohanty, "Effect of tractor seat suspension parameters on vibration exposure," *Journal of Ergonomics*, vol. 9, no. 6, p. 258, 2020, doi: 10.35248/2165-7556.20.9.258.
- [9] I. Ahmadi, "Development and evaluation of full-vehicle vibration model of MF 285 tractor," *Research in Agricultural Engineering*, vol. 60, no. 3, pp. 107–114, 2014.
- [10] Y. Nupur, V. K. Tewari, R. Thangamalar, S. Kumari, and A. Kumar, "Translational vibration evaluation of tractor seats for ride comfort," *Agricultural Engineering International: CIGR Journal*, vol. 15, no. 4, pp. 102–112, 2013.
- [11] J. Gomez-Gil, F. J. Gomez-Gil, and R. Martin-de-Leon, "The influence of tractor-seat height above the ground on lateral vibrations," *Sensors*, vol. 14, no. 10, pp. 19713–19730, 2014, doi: 10.3390/s141019713.
- [12] G. P. Villbor, F. L. Santos, and M. R. Furtado Júnior, "Mechanical vibrations at the seat base of a tractor during the subsoiling operation," *Revista Agrarian*, vol. 8, no. 27, pp. 64–73, 2015.
- [13] H. P. W. Jayasuriya and K. Sangpradit, "Dynamic performance and ride comfort evaluation of the seat suspension system in a small agricultural tractor to attenuate low-frequency vibration transmission," *Agric Eng Int: CIGR Journal*, vol. 16, no. 1, pp. 207–216, 2014.
- [14] K. Melemez and M. Tunay, "Ergonomic evaluation of tractor vibration in forestry," *Süleyman Demirel University Forestry Faculty Journal*, Ser. A, no. 1, pp. 96–108, 2010.
- [15] S. V. de Almeida et al., "Analysis of vibration levels in agricultural tractor with and without cabin," *African Journal of Agricultural Research*, vol. 10, no. 53, pp. 4945–4949, 2015, doi: 10.5897/AJAR2015.10421.
- [16] B. Cvetanović, D. Cvetković, and M. Cvetković, "The experience of drivers and the performance of driving as impact factors of vibration levels in agricultural tractors," *Facta Universitatis, Series: Working and Living Environmental Protection*, vol. 12, no. 1, pp. 73–81, 2015.
- [17] A. Jahanbakhshi, B. Ghamari, and K. Heidarbeigi, "Vibrations analysis of combine harvester seat in time and frequency domain," *Journal of Mechanical Engineering and Sciences*, vol. 14, no. 1, pp. 6251–6258, 2020, doi: 10.15282/jmes.14.1.2020.04.0489.
- [18] A. Bhatia, S. Kalsi, A. K. Sehgal, and I. Singh, "Comparative study of different seat cushion materials to improve the comfort of tractor seat," *Journal of The Institution of Engineers (India) Series A*, Mar. 2022, doi: 10.1007/s40030-022-00622-8.
- [19] H. Singh and M. Mehta, "Experimental and simulated analysis of tractor seat during tillage," *Proceedings of AIR 2022*, pp. 183–187, 2022.
- [20] M. Gohari, M. Tahmasebi, F. Rafieian, and A. Pak, "Optimization, development and evaluation of a tractor seat suspension via artificial intelligent method," *Journal of Theoretical and Applied Vibration and Acoustics*, vol. 9, no. 2, pp. 54–64, 2023, doi: 10.22064/tava.2023.555480.1205.

- [21] C. R. Mehta and V. K. Tewari, "Seating discomfort for tractor operators: A critical review," *International Journal of Industrial Ergonomics*, vol. 25, pp. 661–674, 2000.
- [22] R. Deboli, A. Calvo, and C. Preti, "Whole-body vibration: Measurement of horizontal and vertical transmissibility of an agricultural tractor seat," *International Journal of Industrial Ergonomics*, vol. 58, pp. 69–78, 2017, doi: 10.1016/j.ergon.2017.02.002.
- [23] M. Feyzi, H. Navid, and I. Dianat, "Ergonomically based design of tractor control tools," *International Journal of Industrial Ergonomics*, vol. 72, pp. 298–307, 2019, doi: 10.1016/j.ergon.2019.06.007.
- [24] R. Yadav and V. K. Tewari, "Tractor operator workplace design—a review," *Journal of Terramechanics*, vol. 35, no. 1, pp. 41–53, 1998.
- [25] E. Romano et al., "The use of pressure mapping to assess the comfort of agricultural machinery seats," *International Journal of Industrial Ergonomics*, vol. 77, p. 102835, 2020, doi: 10.1016/j.ergon.2019.102835.
- [26] A. Singh, N. Nawayseh, Y. K. Dhahi, S. Samuel, and H. Singh, "Transforming farming with intelligence: Smart vibration monitoring and alert system," *Journal of Engineering Research*, vol. 12, pp. 190–199, 2024, doi: 10.1016/j.jer.2023.08.025.
- [27] V. K. Tewari and N. Prasad, "Optimum seat pan and back-rest parameters for a comfortable tractor seat," *Ergonomics*, vol. 43, no. 2, pp. 167–186, 2000, doi: 10.1080/001401300184549.
- [28] Ž. Barač, M. Jurić, I. Plaščak, T. Jurić, and M. Marković, "Assessing whole-body vibrations in an agricultural tractor based on selected operational parameters: A machine learning-based approach," *AgriEngineering*, vol. 7, p. 72, 2025, doi: 10.3390/agriengineering7030072.
- [29] T.-A. Oncescu et al. "FEA modal and vibration analysis of the operator's seat in the context of a modern electric tractor for improved comfort and safety," *AgriEngineering*, vol. 7, p. 362, 2025, doi: 10.3390/agriengineering7110362.
- [30] A. A. Almosawi, A. J. Alkhafaji, and K. M. Alqazzaz, "Vibration transmission by combine harvester to the driver at different operative conditions during paddy harvest," *International Journal of Science and Nature*, vol. 7, no. 1, pp. 127–133, 2016.
- [31] H. A. Sultan, R. J. B. Bakthavatchala, and K. M. Al Khateeb, "Whole-body vibration exposure assessment of agricultural tractor operators during routine farming operations," *International Agricultural Engineering Journal*, vol. 27, no. 2, pp. 351–361, 2018.
- [32] N. B. Fethke, M. C. Schall, L. A. Merlino, H. Chen, C. A. Branch, and M. Ramaswamy, "Whole-body vibration and trunk posture during operation of agricultural machinery," *Annals of Work Exposures and Health*, vol. 62, no. 9, pp. 1123–1133, 2018, doi: 10.1093/annweh/wxy076.
- [33] F. G. Moreno, G. G. Zimmermann, S. P. Jasper, R. S. Ferraz, and D. Savi, "Sensors installation position and its interference on the precision of monitoring maize sowing," *Smart Agricultural Technology*, vol. 4, p. 100150, 2023, doi: 10.1016/j.atech.2022.100150.
- [34] F. J. Gomez-Gil, V. Martínez-Martínez, R. Ruiz-Gonzalez, L. Martínez-Martínez, and J. Gomez-Gil, "Vibration-based monitoring of agro-industrial machinery using a k-nearest neighbors classifier with a Harmony Search frequency selector algorithm," *Computers and Electronics in Agriculture*, vol. 217, p. 108556, 2024, doi: 10.1016/j.compag.2023.108556.
- [35] S. R. Nagarajan and S. Palanivelu, "Investigation and quantification of perception of human body vibration and noise exposure during operator-tractor-field interaction," *Results in Engineering*, vol. 28, p. 107339, 2025, doi: 10.1016/j.rineng.2025.107339.
- [36] A. Singh, L. P. Singh, S. Singh, H. Singh, and C. Prakash, "Investigation of occupational whole-body vibration exposure among Indian tractor drivers," *International Journal of Human Factors and Ergonomics*, vol. 5, no. 2, pp. 151–165, 2018.
- [37] S. Zhao, G. Qu, M. Liu, X. Chen, Z. Gao, and L. Xu, "Research on tractor active seat suspension based on model predictive control," *Preprints*, Mar. 2023, doi: 10.20944/preprints202303.0357.v1.

- [38] I. Maciejewski, L. Meyer, and T. Krzyzynski, "Modelling and multi-criteria optimisation of passive seat suspension vibro-isolating properties," *Journal of Sound and Vibration*, vol. 324, pp. 520–538, 2009, doi: 10.1016/j.jsv.2009.02.021.
- [39] A. Singh, N. Nawayseh, Y. K. Dhabi, S. Samuel, and H. Singh, "Digital agriculture: Analysis of vibration transmission from seat to back of tractor drivers under multi-directional vibration conditions," *International Journal of Industrial Engineering*, vol. 30, no. 2, pp. 463–473, 2023, doi: 10.23055/ijietap.2023.30.2.8773.
- [40] A. Burdorf and P. Swuste, "The effect of seat suspension on exposure to whole-body vibration of professional drivers," *Annals of Occupational Hygiene*, vol. 37, no. 1, pp. 45–55, 1993.
- [41] Q. Wang, Y. Huo, Z. Xu, W. Zhang, Y. Shang, and H. Xu, "Effects of backrest and seat-pan inclination of tractor seat on biomechanical characteristics of lumbar, abdomen, leg and spine," *Computer Methods in Biomechanics and Biomedical Engineering*, Apr. 2022, doi: 10.1080/10255842.2022.2062229.
- [42] D. T. H. Nguyen, P. H. Cao, H. T. Le, and H. V. Tran, "Vibration analysis at the operator's seat of a purple onion harvester," *Engineering, Technology & Applied Science Research*, vol. 15, no. 5, pp. 27893–27898, 2025, doi: 10.48084/etasr.12798.
- [43] E. Zheng et al., "Investigation into the vibration characteristics of agricultural wheeled tractor–implement system with hydro-pneumatic suspension on the front axle," *Biosystems Engineering*, vol. 186, pp. 14–33, 2019, doi: 10.1016/j.biosystemseng.2019.05.004.
- [44] J. B. Adams, M. H. Muhammad, and B. G. Jahun, "Whole-body vibration exposure among tractor operators at the tractor seat: Impact of tillage operation, speed and operator weight," *Open Access Research Journal of Engineering and Technology*, vol. 8, no. 2, pp. 23–34, 2025, doi: 10.53022/oarjet.2025.8.2.0043.
- [45] A. Surendrakumar, P. Vivek, and R. Kavitha, "Study of whole body and hand-arm vibration in a small tractor with implements," *Plant Science Today*, vol. 12, no. sp1, pp. 1–7, 2025, doi: 10.14719/pst.7342.
- [46] A. Singh, S. Samuel, H. Singh, J. Singh, C. Prakash, and Y. K. Dhabi, "Whole body vibration exposure among the tractor operator during soil tillage operation: An evaluation using ISO 2631-5 standard," *Shock and Vibration*, vol. 2022, Article ID 6412120, 2022.
- [47] L. Xu, X. Chai, Z. Gao, Y. Li, and Y. Wang, "Experimental study on driver seat vibration characteristics of crawler-type combine harvester," *Int. J. Agric. & Biol. Eng.*, vol. 12, no. 2, pp. 90–97, 2019.
- [48] R. Desai, A. Guha, and P. Seshu, "A comparison of different models of passive seat suspensions," *Proc. IMechE Part D: J. Automobile Engineering*, pp. 1–20, 2021. doi: 10.1177/0954407021990922.
- [49] X. Chen et al., "Review of agricultural machinery seat semi-active suspension systems for ride comfort," *Machines*, vol. 13, p. 246, 2025.
- [50] A. Singh et al., "Measurement and analysis of vibration transmissibility through tractor seat," *Advances in Transportation*, vol. 60, pp. 376–385, 2022.
- [51] A. Rathore, A. Kumar, and A. Singh, "Design and experimental validation of a cyber-ergonomic adaptive seat system for real-time vibration and posture control in agricultural tractors," *Journal of Emerging Technologies and Innovative Research (JETIR)*, vol. 12, no. 11, pp. 467–478, 2025.
- [52] S. A. Adam and N. A. Abdul Jalil, "Vertical suspension seat transmissibility and SEAT values for seated person exposed to whole-body vibration in agricultural tractor: Preliminary study," *Procedia Engineering*, vol. 170, pp. 435–442, 2017, doi: 10.1016/j.proeng.2017.03.070.
- [53] D. Pochi, L. Fornaciari, G. Vassalini, R. Grilli, and R. Fanigliulo, "Levels of whole-body vibrations transmitted to the driver of a tractor equipped with self-levelling cab during soil primary tillage," *AgriEngineering*, vol. 4, pp. 695–706, 2022, doi: 10.3390/agriengineering4030044.
- [54] T.-A. Oncescu et al., "Comparative analysis of vibration impact on operator safety for diesel and electric agricultural tractors," *AgriEngineering*, vol. 7, p. 40, 2025, doi: 10.3390/agriengineering7020040.
- [55] D. Pessina and L. E. Galli, "Ensuring optimal comfort in the tractor's driveplace through proper

- seat suspension adjustment,” Preprints, Apr. 2025, doi: 10.20944/preprints202504.1552.v1.
- [56] A. Anand and S. K. C. P., “A review of whole-body vibration of seated occupants in moving vehicles,” in Proc. 4th ICSEE, 2021, pp. 347–352.
- [57] J. Rekem et al., “multi-body model of agricultural tractor for vibration transmission investigation,” Applied Sciences, vol. 14, no. 18, p. 8451, 2024. doi: 10.3390/app14188451.
- [58] K. Ji and Y. Liu, “Vibration tracing analysis and external excitation damping method of combine harvester based on short-time Fourier,” Applied Sciences, vol. 15, no. 18, p. 10134, 2025. doi: 10.3390/app151810134.
- [59] P. Cârdei et al., “Identification of vibration source influence intensity in combine harvesters using multivariate regression analysis,” Applied Sciences, vol. 15, no. 18, p. 10159, 2025. doi: 10.3390/app151810159.
- [60] V. Guruguntla et al., “Ride comfort and segmental vibration transmissibility analysis of an automobile passenger model under whole body vibration,” Scientific Reports, vol. 13, no. 11619, pp. 1–20, 2023. doi: 10.1038/s41598-023-38592-x.