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Ergonomic, energy, and field performance evaluation of self-propelled multipurpose agricultural machines: A review

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Abstract

Self-propelled multipurpose machines have become an important mechanization option for smallholder agriculture, offering planting, interculturing, spraying, and harvesting on a compact and fuel-efficient platform. This review consolidates ergonomic, energy, and field performance aspects of a 9 hp Self-Propelled Multipurpose Machine and compares them with global research trends. Studies consistently show that hand–arm vibration, heart rate response, BPDS, and ODR are influenced significantly by hand grip, forward speed, and machine-induced vibration. Field evaluation reports indicate that planting uniformity, weeding efficiency, and soybean harvesting performance of such machines match the results published for precision planters, rotary weeders, and mini-reapers. Energy analysis further shows substantial reduction in CO_2 emissions compared to tractor-operated equipment. This merged review highlights that low-horsepower self-propelled platforms offer high ergonomic safety, improved energy efficiency, and sustainable operation for small farms.

Keywords: Self-propelled multipurpose machine, ergonomics, hand–arm vibration, soybean harvesting, carbon emissions, field performance, RSM modelling

1. Introduction

Mechanization for small and fragmented farms demands machines that are affordable, fuel-efficient, lightweight, and ergonomically safe. Traditional tractor systems often consume excess fuel, incur high operational costs, and are unsuitable for narrow or irregular farm plots. Self-propelled multipurpose machines have therefore emerged as an effective alternative by integrating multiple field operations into a single low-hp platform.

The performance evaluation of the developed machine for bed making, sowing, and harvesting operations is equally important to establish its operational reliability, efficiency, and field adaptability under real conditions. Assessing its suitability also includes evaluating the reduction in drudgery for the operator and labour's, which directly contributes to improving occupational safety and working comfort in the agricultural sector.

Presently farmers are using different types of implements for different farm operations such as Seed bed preparation, Bed making, sowing, inter-culturing, spraying and harvesting etc. In Kharif season due to short window it becomes quite difficult to undertake all the operation in time and thus increases in cost of labour, time of operation. Effects on proper utilization of input and the results i.e. yield. Looking to need of climate change and increased area under soybean it has been decided to design and develop a machine that had a simple mechanism, multipurpose, suitable to small marginal farmers, easy in repair and maintenance could be manufactured locally at a cost affordable to farmers. It is costly and difficult for small and marginal farmers to maintain number of implements.

2. Design and Functional Elements of Self-Propelled Multipurpose Machines

The structural and functional design of self-propelled multipurpose machines must ensure adequate strength against bending, torsional loads, and dynamic vibrations generated during field operations. A lightweight yet rigid frame is essential to achieve better manoeuvrability, reduced power losses, and stable performance across planting, interculturing, spraying, and harvesting operations. Previous studies on small harvesters and mini-reapers confirm that higher structural rigidity reduces cutter-bar oscillations, improves cutting uniformity, and minimizes grain loss during harvesting.

2.1 Structural Design

Lal and Dutta (1995) [11] emphasized that the structural frame of agricultural machinery should be designed considering expected static and dynamic loads, load distribution patterns, and vibration behaviour under field conditions. Their work highlighted that improper frame design often leads to stress concentration, excessive vibration, and premature failure. They recommended the use of appropriately sized mild-steel sections with adequate safety factors, proper joint design, and controlled welding practices to maintain dimensional stability and durability during multipurpose field operations.

Mehetre *et al*. (2014) [13] reported that lightweight but rigid steel frame structures are critical for mini-reapers operating in soybean and similar crops. Their study showed that reducing overall frame weight improved machine manoeuvrability and ease of handling without compromising structural strength. They further observed that a rigid frame contributes to smoother power transmission to the cutter-bar and conveying mechanisms, resulting in improved cutting efficiency and reduced operator fatigue.

Gajakos *et al*. (2013) [6] highlighted that high frame rigidity plays a vital role in minimizing vibration-induced grain losses in small harvesting machinery. Their experimental evaluation demonstrated that machines with inadequate frame stiffness experienced higher cutter-bar vibrations, leading to increased uncut plants and shattered grain losses. The authors concluded that a structurally robust frame ensures uniform cutter-bar motion, stable machine operation, and improved harvesting performance under variable field conditions.

2.2 Power Transmission and Mechanisms

Power transmission systems in self-propelled multipurpose machines must provide reliable torque transfer, smooth operation, and minimal power loss under varying load conditions. Chain and sprocket mechanisms are commonly preferred due to their simplicity, durability, and ease of maintenance.

Krutz *et al*. (1984) [10] provided foundational design guidelines for selecting chain and sprocket drives in agricultural machinery. Their work emphasized the importance of selecting appropriate speed ratios, pitch, and chain type based on transmitted power and operating conditions. They demonstrated that incorrect sprocket sizing or chain selection leads to excessive wear, slippage, and reduced transmission efficiency, ultimately affecting machine performance.

Shah and Jadvani (1990) [24] outlined practical procedures for determining chain length, sprocket size, and centre distance to ensure smooth and slip-free power transmission. Their study showed that proper chain tension and alignment significantly reduce vibration, noise, and mechanical wear in agricultural machines. These design principles are particularly relevant for multipurpose machines where power is distributed to multiple attachments.

Sharma and Mukesh (2008) [25] described the advantages of "D-hole" coupling in seed metering rotors. They reported that the flat-sided interface between the rotor and shaft prevents rotational slippage under fluctuating loads, ensuring consistent seed delivery. Their results showed that such couplings improve metering accuracy, maintain uniform seed spacing, and enhance planting performance, especially at varying operating speeds.

2.3 Spraying and Harvesting Attachments

Mathews *et al*. (1992) [12] established standard design principles for estimating boom width in agricultural sprayers based on desired field capacity, operating speed, and spray overlap requirements. Their methodology ensures uniform spray distribution across the field and minimizes variation in application rate. They also emphasized that improper boom width selection leads to uneven coverage, chemical wastage, and reduced spraying efficiency.

More (1917) [14] provided one of the earliest engineering guidelines for determining nozzle spacing in hollow-cone spray systems. He recommended nozzle spacing equal to approximately 1.75 times the cone radius to achieve proper overlap between adjacent spray patterns. This principle remains widely adopted in modern sprayer design and continues to ensure uniform droplet distribution and effective crop coverage.

The harvesting unit design aligns closely with findings from mini-reaper and soybean harvesting studies.

Tanti *et al*. (2019) [26] evaluated the performance of mini-reapers and reported that cutter-bar speed, forward speed, and crop stand conditions significantly influence cutting efficiency and total harvesting losses. Their results indicated that improper speed synchronization increases uncut plants and shattering losses, particularly in lodged soybean crops. They emphasized the importance of maintaining optimal forward speed for minimizing losses.

Musoni *et al*. (2013) [17] analysed mechanical soybean harvesting systems and observed that uneven crop height, lodging, and fluctuations in feed rate substantially affect harvesting performance. Their study showed that optimized cutter-bar geometry and stable machine kinematics reduce cutting losses and improve overall harvesting efficiency. They concluded that crop–knife interaction and smooth crop flow are critical for effective soybean harvesting.

Both studies emphasize that cutting speed, crop density, and crop–knife interaction are major determinants of cutting efficiency and harvesting losses.

3. Ergonomic Performance of Self-Propelled Machines

3.1 Hand–Arm Vibration (HAV)

Munde *et al*. (2020) [16] demonstrated that hand–arm vibration levels in power weeders increase significantly when operators apply grip forces beyond the optimal range. Their experimental results showed that excessive grip pressure amplifies vibration transmission to the hands and arms, resulting in higher fatigue and reduced operational comfort. The authors emphasized the need for controlling grip force and improving handle design to limit HAV exposure during prolonged operation.

Roggio *et al*. (2022) [21] investigated the influence of handle geometry and material on vibration transmission and reported that poorly designed handles substantially increase HAV exposure and muscular strain. Their findings showed that ergonomic handle profiles and suitable materials reduce vibration transmission to the operator's hands and improve overall comfort and safety.

Dewangan and Tewari (2010) [4] evaluated different handle grip materials and found that softer materials such as rubber and foam composites significantly reduce hand-transmitted vibration in hand tractors. Their study concluded that integrating vibration-damping materials in handle design is an effective approach to minimize HAV-related health risks.

3.2 Heart Rate Response

Rodahl (1989) [22] established that heart rate increases almost linearly with physical workload, making it a reliable indicator of physiological stress during agricultural operations. His work laid the foundation for using heart rate as a primary measure of operator workload in mechanized tasks.

Bridger (1995) [2] reported that higher forward speeds increase physiological load, reflected by elevated heart rate and metabolic effort. He demonstrated that even small increases in operating speed can significantly raise operator strain, particularly during prolonged field operations.

Varun (2016) [27] observed that heart rate rises sharply during high-speed weeding operations, confirming that machine speed is a major contributor to physiological workload. The study highlighted the need to balance field capacity with ergonomic safety.

Gagandeep (2016) [5] found that increased hand grip force directly elevates cardiovascular stress due to higher muscular effort. His results emphasized grip intensity as a critical ergonomic variable affecting operator health and fatigue.

3.3 Body Part Discomfort Score (BPDS) and Overall Discomfort Rating (ODR)

Khandai *et al*. (2018) [9] reported that operators of conventional power weeders experience high musculoskeletal load due to excessive vibration transmitted through the handle and frame. Their results showed increased discomfort in the hands, arms, shoulders, and lower back during prolonged operation.

Chaturvedi *et al*. (2012) [3] demonstrated that ergonomic interventions such as improved handle grips, vibration-damping materials, and optimized operating posture significantly reduce operator fatigue. Their study showed measurable reductions in vibration transmission, BPDS, and overall discomfort, confirming the importance of ergonomic design improvements.

4. Field Performance Review

4.1 Planting Performance

Karayel and Ozmerzi (2002) [8] emphasized that precision planters must maintain uniform intra-row seed spacing to achieve optimal crop stand and yield potential. Their study showed that increased variability in seed spacing directly reduces plant uniformity and overall field performance.

Griepentrog (1998) [7] demonstrated that consistent seed placement depth is essential for uniform germination and early crop establishment. He reported that depth variations delay emergence and adversely affect plant vigor and stand uniformity.

4.2 Interculturing Performance

Mohapatra *et al*. (2013) [15] reported that weeding efficiency is strongly influenced by soil moisture content, tool geometry, and field surface conditions. Their results showed that maintaining stable working depth and uniform field conditions improves weed removal efficiency and reduces energy consumption.

Ragesh *et al*. (2018) [20] found that rotary and inter-row weeders perform best under moderate soil moisture and low soil compaction. Their study showed that unfavourable field conditions increase draft, fuel consumption, and vibration levels, thereby affecting both performance and operator comfort.

4.3 Harvesting Performance

Tanti *et al*. (2019) [26] demonstrated that crop lodging, plant density, and field variability significantly influence total harvesting losses in small-scale reapers. Their findings showed that maintaining uniform crop stands and optimal forward speed reduces cutter-bar and shattering losses.

Nadeem *et al*. (2015) [18] reported that cutter-bar dynamics—particularly knife speed, crop–knife interaction angle, and feed rate—play a major role in determining cutting efficiency. They emphasized that improper synchronization between cutter-bar motion and crop flow leads to higher uncut plants and grain losses.

5. Critical Discussion

Ergonomic analysis is often the weakest component in small machinery research. Few studies use RSM-based modelling, indicating a gap that the Self-Propelled Multipurpose Machine dataset successfully addresses. Comparisons show that ergonomic risks HAV, HR, and BPDS are most severe at high speeds and high grip forces, consistent with global findings.

Soil and crop variability significantly affect performance; studies by Mohapatra *et al*. (2013) [15] and Tanti *et al*. (2019) [26] align with the Self-Propelled Multipurpose Machine results. Carbon analysis also shows Self-Propelled Multipurpose Machines outperform tractors in emissions, a major sustainability advantage.

6. Future Research Directions

- Develop AI-enabled ergonomic monitoring systems (vibration + HR + BPDS).
- Use composite lightweight materials to reduce vibration.
- Expand studies across multiple crops and soil types.
- Standardize carbon footprint and cost assessment frameworks.
- Design women-friendly and elderly-friendly machine components.
- Integrate IoT for real-time performance monitoring.

7. Overall Significance

This integrated review confirms that self-propelled multipurpose machines provide a practical solution to mechanization challenges in smallholder agriculture. They improve ergonomic safety, reduce energy use, and maintain acceptable performance levels for planting, interculturing, spraying, and harvesting. The strong alignment between machine results and global literature supports their wider adoption as a sustainable mechanization pathway.

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