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Transforming Indian agriculture: Role and benefits of farm mechanization using modern machinery

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Abstract
India, currently the fourth-largest economy globally, is experiencing a rapid transformation in its agricultural sector through mechanization. The adoption of modern farm machinery including tractors, threshers, combine harvesters, rotavators, seed drills and power tillers has addressed critical challenges such as labour shortages, high cultivation costs and low operational efficiency. Mechanization enhances productivity, reduces drudgery, ensures timely farm operations and minimizes post-harvest losses, thereby improving both crop quality and farm income. Regional disparities in mechanization intensity reflect variations in tractor density, custom hiring systems and state-level manufacturing capacities. Contemporary advancements in tractors focus on ergonomics, safety, energy efficiency and sustainability, while mechanized harvesters are being optimized for crop-specific applications, including root crops, cotton and horticultural produce. Government initiatives like SMAM, KCC and PM-KISAN have facilitated accessibility and affordability of farm equipment. Overall, farm mechanization in India emerges as a critical driver for sustainable, scalable and technologically advanced agricultural practices, promoting efficiency, economic growth and rural development.

Keywords: KCC, ergonomics, farm machinery, PM Kisan, SMAM, tractors, post harvest losses

Introduction

India is currently the fourth largest economy in the world, with a Gross Domestic Product (GDP) of approximately USD 4.19 trillion (Connor. R., 2025) [8]. At the macroeconomic level, India has seen rapid growth and development to match this trend in terms of increasing rates of agricultural mechanization. Breakthrough Technologies such as Electric Powered Tractors, Unmanned Aerial Systems (UAS), Precision Farming Frameworks and Artificial Intelligence will enable automated agricultural machines to function. In terms of the overall level of agricultural mechanization in India, there has been a consistent increase and as of 2015 the percentage of agricultural mechanization in India was around 45-50 percent at the aggregate level. In addition, the percentage of agricultural mechanization for strategic crops such as wheat and rice has increased to about 60 percent (Sharma, 2016) [32]. A number of policies such as Sub-Mission on Agricultural Mechanization (SMAM), Crop Residue Management, Custom Hiring Centres (CHC), High-Tech Machinery Banks and Agriculture Infrastructure Fund along with the convergence of advanced digital platforms have now enabled many farmers to utilise and operate modern day machinery. Collectively all these institutional, technological and financial enablers have helped India reach near the convergence point of worldwide, advanced agricultural mechanisation systems. Helping agriculture be increasingly technologically intensive, environmentally sustainable and thus ultimately helping to improve production through greater efficient use of agricultural resources and maximised land-use practices.

Farm mechanization is defined as the strategic interposition of mechanical power and technological aids between human labour and the materials handled during agricultural operations. Mechanized equipment and systems in agriculture consist of soil, water, climate and environmental conditions, seeds, fertilizers, pesticides, plant growth regulators, irrigation inputs, agricultural products and associated by-products. Mechanization possibilities exist for all of agriculture from production through post-harvesting through agro-processing and so forth.

In developed economies such as the United States and China, mechanization typically refers to the automation of farming. However, in developing agrarian economies such as India, the concept of mechanization can be viewed much broader than just the use of automated farming systems. In this regard, mechanization includes any improved hand tool, implement, machine, piece of equipment, or structural innovation that has the effect of increasing labour productivity through either additional human effort or replacing manual labour. Furthermore, mechanization acts as an enabler by removing the physical burden of labour, reducing stress associated with manual labour and mitigating cognitive fatigue that can lead to poor judgement, imprecise actions and unsafe practices, which contribute to poor productivity and increased operating hazards. Additionally, when considered in this broader definition, farm mechanization also includes automated systems, environmental monitoring and control systems for the production of high-quality products, maximum operational efficiency, safety of agricultural products and lower levels of contamination from improper handling of agriculture products. Sometimes, agricultural mechanization is often confined to production agriculture alone.

Materials and Methods

In this review, a wide range of research papers, technical reports, government publications and institutional documents were examined to provide a comprehensive understanding of farm mechanization in India and its impact on agricultural productivity, labour efficiency and sustainability. Key sources included publications from the Ministry of Agriculture and Farmers Welfare, Government of India, Sub-Mission on Agricultural Mechanization (SMAM) reports, Kisan Credit Card (KCC) and PM-KISAN policy documents, research studies by the Indian Council of Agricultural Research (ICAR) and international databases such as FAO and World Bank. Peer-reviewed journal articles, conference proceedings and case studies on the use of tractors, rotavators, threshers, combine harvesters and other mechanized implements were also critically analyzed. The literature was systematically synthesized to highlight trends, regional variations, technological advancements, cost-effectiveness, labour-saving potential and environmental implications of mechanized farming in India (Sharma, 2016; Mehta *et al*., 2014) [32, 22, 23]. This methodological approach enabled a meaningful consolidation of empirical evidence and policy insights to draw conclusions on the current status, challenges and prospects of agricultural mechanization in India.

Farm mechanization

In India, the adoption of farm machinery in agricultural operations has been progressively increasing, primarily due to its demonstrated role in reducing the cost of cultivation and enhancing farmer's net returns. Although agriculture in India continues to remain highly labour-intensive, the sector is increasingly confronted with an acute shortage of farm labour, despite the country's large population base. This paradox can be attributed to rural-urban migration, diversification of employment opportunities and declining interest of younger generations in agricultural work. Consequently, reliance on human labour has become economically unsustainable, as the operational cost of human energy in farming is significantly higher when compared to machine energy.

Machines used in Agriculture Sector

Government initiatives such as the Kisan Credit Card (KCC), Pradhan Mantri Kisan Samman Nidhi (PM-KISAN) and the Sub-Mission on Agricultural Mechanization (SMAM) are critical to supporting farmers in adopting mechanization. The KCC offers farmers access to finance which allows them to purchase modern equipment on credit, while SMAM provides farmers with a subsidy up to 50 percent for the purchase of modern equipment. Through these initiatives, farmers have been able to purchase modern equipment at lower costs, allowing them to increase the number of mechanised practices within their operations. There has been a steady increase in the amount of agricultural equipment per category, including manually operated tools (e.g., sickles, hoes, weeders, hand sprayers and knapsack dusters); animal drawn equipment (e.g., country ploughs, seed drills, blade harrows and ridgers) and, equipment driven by mechanical and electrical power sources (e.g., tractors, power tillers, rotavators, threshers, combined harvesters, irrigation pumps and electrical grain cleaners). In the category of manually operated equipment, one of the largest increases in the adoption of equipment for plant protection (particularly hand-held and knapsack sprayers), has nearly doubled since liberalisation, indicating a growing recognition of the importance of crop protection and use of more efficient inputs. The liberalisation of the Indian economy during the post-liberalisation era presented an opportunity for the growth of indigenous manufacturing of agricultural machinery, with the rapid development and commercialisation of indigenous machine prototypes providing a major boost for the domestic production of agricultural machinery. Consequently, major manufacturing hubs emerged in agriculturally progressive states such as Haryana, Punjab, Rajasthan, Madhya Pradesh and Uttar Pradesh, strengthening India's capacity for large-scale production, innovation and dissemination of farm machinery.

Tractor

A tractor is one of several types of machines that can move and operate various other types of machinery. Examples of the machinery moved by tractors are construction equipment (e.g. bulldozers, backhoes, trenchers) and farming equipment (e.g. tillers, seeders, harvesters). Tractors are also used to tow other vehicles and trailers. All tractors are composed of four basic components: (1) an engine, (2) the chassis, (3) wheels or tracks and (4) a control assembly. The engine used in agricultural tractors is typically a diesel engine. The engine produces power when it combusts fuel and compresses air, creating mechanical energy, which is then transmitted through mechanical components to the tractor wheels. Some of the first tractor machines were essentially modified external combustion engines as used in locomotives that were equipped with metallic wheels. In the beginning, these tractors were primarily used to move massive mouldboard ploughing machines (a type of machine designed to till soil) and power stationary equipment via belted transmission.

The advancement of technology over the last century has allowed for many upgrades to be made to tractors to create today's advanced agricultural power sources (Hoy &

Kocher, 2020) [13]. As tractor technologies have evolved over the past century, tractor test methodologies have also improved, allowing for the incorporation of additional research priorities such as ergonomic design, operational safety and environmental impacts.

Fig 1: Tractor

Research in the modern era has increasingly focused on operator ergonomics and the reduction of noise through the use of noise-reduction systems within tractor cab structures (Fanigliulo *et al*., 2020) [12]. Investigations into the potential for, or effects of, vibration on an operator's experience of occupational comfort and safety have also gained prominence. Other safety-related investigations have centred around studying tractor stability, methods for rollover prevention and the design and implementation of active control systems for reducing accident risk under heavy operating conditions (Qin *et al*., 2021) [30]. Likewise, substantial efforts have been made to research wheelset configurations and ballast systems, which greatly affect traction, energy usage and the overall ability of machines to adapt to different soil types and terrain (Kumar *et al*., 2019) [19].

Advancements in internal combustion engine technology have also been central to tractor development. Research has explored improvements in diesel engine performance through electronic fuel injection systems, turbocharging and optimized combustion processes aimed at enhancing power output while improving fuel efficiency (Bertinatto *et al*., 2022) [6]. More recently, growing environmental concerns have driven investigations into alternative propulsion systems, including electric and hybrid tractor drives, focusing on energy optimization and sustainability (Liu *et al*., 2022) [20]. Hydraulic systems, particularly three-point linkage lift capacity and load-handling efficiency, have likewise been extensively studied to support the operation of high-and medium-horsepower tractors under demanding field conditions (Cong *et al*., 2021) [7]. Additionally, emission mitigation strategies, such as the use of alternative fuel blends, have gained prominence as regulatory pressure on off-road agricultural engines intensifies (Agarwal *et al*., 2022) [1].

State-level variations in tractor density vividly reveal pronounced regional disparities in the extent of agricultural mechanization across India. Haryana exhibits the highest tractor concentration, with approximately 84 tractors per thousand hectares of net sown area, followed by Punjab with 76 tractors, reflecting the advanced mechanization status of north-western India. Other states demonstrating relatively higher mechanization intensity include Uttar Pradesh (51 tractors), Bihar (44 tractors) and Tamil Nadu (43 tractors) per thousand hectares. In contrast, the national average tractor density remains substantially lower at 33 tractors per thousand hectares of net sown area. States such as Kerala, Assam and West Bengal display markedly lower levels of tractorization, with densities of 4, 9 and 17 tractors per thousand hectares, respectively. These disparities underscore the uneven diffusion of mechanization across India’s diverse agro-climatic and socio-economic regions (Mehta *et al*., 2014) [22, 23].

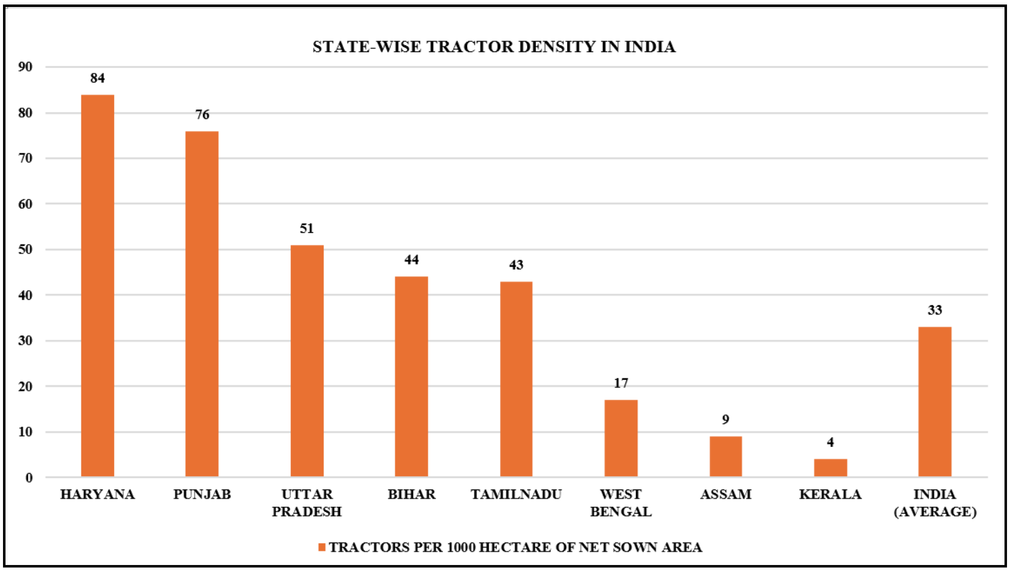

Fig 2: State-wise tractor density in India

Concurrently, the Indian agricultural machinery sector has witnessed robust and sustained growth across multiple equipment categories. Sales of rice transplanters and power weeders have expanded at an estimated compound annual growth rate (CAGR) of nearly 50 percent each, while combine harvesters, rotavators and threshers have recorded CAGRs of approximately 28 percent, 20 percent and 10 percent, respectively. This rapid expansion highlights the increasing reliance on mechanized solutions to mitigate labour shortages and improve operational efficiency in agricultural production. As a cumulative outcome of rising mechanization intensity, farm power availability and agricultural productivity in India reached approximately 2.2 kW per hectare and 2.3 tonnes per hectare, respectively, by 2020, indicating steady progress towards mechanization-led productivity enhancement (Mehta, Chandel, & Senthil Kumar, 2014) [22, 23].

Despite these technological advancements, tractor operations continue to pose occupational health risks. Prolonged exposure to elevated noise levels, whole-body vibrations, exhaust fumes and toxic gases can adversely affect operators' physical and mental well-being, while deficiencies in external safety indicators may further exacerbate accident risks (Cutini *et al*., 2022) [9]. Consequently, a substantial body of research has focused on improving operator workstations through the development of advanced seating systems, cabin suspension mechanisms and improved enclosure designs. Such interventions have been shown to significantly reduce musculoskeletal disorders and work-related pathologies among tractor operators (Mehta and Tewari, 2000) [21].

Tractor wheelsets represent a critical interface between machine power and soil, serving as the primary mechanism for converting engine torque into usable tractive force. As a result, wheelsets have been the subject of extensive investigation, particularly with respect to traction efficiency, load distribution and operational stability (Molari *et al*., 2012) [25]. Studies have also examined the carrying capacity of wheelsets and their influence on machine performance under varying load conditions. Moreover, the impact of wheel-induced stresses on soil structure has emerged as a major research concern. As tractors have increased in weight to accommodate higher power outputs and larger implements, the applied load on soil has intensified, raising serious concerns regarding soil compaction, reduced porosity and long-term degradation of soil physical properties. These challenges have reinforced the need for optimized wheelset design and load management strategies to balance productivity gains with soil conservation.

Harvester

Combine harvesters are agricultural machines that perform three significant functions of harvesting simultaneously: reaping, threshing and winnowing. By using one piece of equipment to combine all three functions into one operation, the combine harvester requires less labour, reduces the time needed to harvest crops and increases the productivity of agricultural producers. In addition, combine harvesters can be used to harvest many different types of crops such as cereals (wheat, rice, maize) and grains with little or no manual help from the farmer. The operation of combine harvesters consists of a series of mechanical processes that work together. All harvesting operations begin at the front of the machine with a crop header that is attached to the combine harvester. The header cuts the crop, moves it into the combine harvester and is designed based on the type of crop to be harvested (i.e. corn header, wheat header, etc.) Additionally, headers are designed to be used in various field situations based on the plants they cut (i.e. no-till, conventional-till, etc.). After cutting the material into the feeder house, the feeder house ensures that there is a steady flow of crop material to the threshing unit and prevents the stock pile from becoming overstocked (Editor S., 2024) [11].

A rotating threshing drum, or cylinder, is used to separate the grain from the stalks, through the use of impact and rubbing between the grain and the drum. Modern combine harvesters typically use larger, more efficient threshing cylinders that efficiently separate grain while causing minimal mechanical damage to delicate seeds. After the grain and straw are separated, the grain-straw mixture goes through concaves and sieves where size and weight separation occur. The cleaner removes chaff and lighter impurities with a controlled flow of air created by a fan. The cleaned grain is collected and conveyed into an onboard grain tank by augers. The onboard tank can hold several tonnes of grain before being unloaded. The straw and residue is expelled from the rear of the machine in a windrow or evenly spread across the field. An even distribution of residue helps retain moisture in the soil and makes farming operations easier in the future.

Fig 3: Combine Harvester

The growth in sales of combine harvesters reflects a trend towards greater use of agricultural machinery in India. An estimated number of 4,000-5,000 combine harvesters are sold in India every year, with a compound annual growth rate (CAGR) of around 28 percent since 2006. The majority of sales (60 percent) are tractor-mounted combine harvesters, which are mainly used by custom hiring services, mainly located in Southern India (Tamil Nadu, Kerala, Andhra Pradesh and Karnataka). The other 40 percent of total sales comprise self-propelled combine harvesters, generally owned and operated by professional custom-hiring contractors. The cost of a tractor-operated combine harvester is approximately 60-70 percent lower than a self-propelled harvester, meaning that they typically cater to farmers with larger holdings (greater than 4 hectares) (Singh, 2014) [33]. Punjab is the predominant region for combine harvester manufacturing in India and well-known companies such as CLAAS India Ltd., Preet Agro Industries Pvt. Ltd., Balkar Combines, Kartar Agro Industries Pvt. Ltd. and Hira Agro Industries are significant contributors to the domestic market (Mehta *et al*., 2014) [22, 23]. The trends indicated above indicate a gradual move toward increased mechanized practices as a result of labour shortages, increased prices for inputs and the increasing availability of custom hiring services.

Crop harvesting remains one of the most labour-intensive and critical operations in Indian agriculture, directly influencing productivity, cost of cultivation, timeliness and post-harvest losses. Manual harvesting is characterized by high labour demand, prolonged operational duration and considerable physical drudgery. Dependence on seasonal labour makes harvesting vulnerable to labour shortages and escalating wage rates, particularly during peak periods. Several studies have reported that rising labour costs and unavailability adversely affect the efficiency and timeliness of manual harvesting, leading to yield losses, shattering and deterioration in crop quality (Mule *et al*., 2018; Khadake *et al*., 2024) [26, 16]. In the case of root and tuber crops, manual digging often results in bruising and mechanical damage, reducing market acceptability and storage life.

Although mechanization offers a viable solution, widespread adoption of existing harvesting machinery in India is constrained by high capital costs, incompatibility with small and fragmented landholdings and limited suitability for indigenous crop varieties and agronomic practices. Large-scale combine harvesters and commercially available cotton harvesters are often beyond the financial reach of small and medium farmers and are viable mainly under custom hiring models (Mule *et al*., 2018; Khadake *et al*., 2024) [26, 16]. Similarly, harvesting operations using mini tractors face limitations due to insufficient horsepower, resulting in reduced field efficiency and operational instability (Khadake *et al*., 2024) [16]. Consequently, emphasis has shifted toward the development of affordable, compact and crop-specific harvesting solutions.

A substantial body of research has focused on mechanizing root crop harvesting, traditionally one of the most physically demanding agricultural operations. Studies have explored various digging mechanisms, including straight, crescent-shaped and inverted V-shaped blades, for crops such as ginger, turmeric, potato, onion and carrot. Optimized blade geometry and rake angle have been shown to significantly enhance digging efficiency while minimizing crop damage (Nagendra *et al*., 2023) [27]. Conveying and separation systems, particularly those incorporating vibratory mechanisms, have further improved soil separation, reduced crop loss and minimized mechanical injury in crops such as potato and peanut (Ibrahim *et al*., 2008) [14].

Power transmission in root crop harvesters is commonly achieved through tractor power take-off (PTO) systems or independent engines, employing chain-sprocket drives, gearboxes, belts and crank mechanisms (Naresh *et al*., 2018; Narender & Shrivastava, 2022; Kadam *et al*., 2023) [29, 28, 15]. Performance optimization studies highlight the influence of operational parameters such as forward speed, digging depth, blade angle and soil moisture on harvesting efficiency and crop damage, emphasizing the need for crop- and soil-specific machine adjustments (Ali, 2013; Agu, 2021) [3, 2].

Beyond root crops, research has also addressed mechanization of crops such as cotton and onion. Cotton harvester studies underscore the inadequacy of imported machines for Indian varieties, while onion harvester research has focused on efficient digging and lifting mechanisms to minimize bulb damage and facilitate collection (Singh, 2014; Mehta & Yadav, 2015; Datir *et al*., 2019) [33, 24, 10].

Across the literature, key design priorities for Indian harvesters include cost-effectiveness, compactness, reduced labour dependency, minimal crop damage and adaptability to multiple crops. Increasing attention is being directed toward low-cost, modular and farmer-friendly harvesting systems capable of improving mechanization access for small and marginal farmers while enhancing productivity and sustainability (Mule *et al*., 2018; Sharma *et al*., 2019; Balasubramani *et al*., 2020) [26, 31, 4].

Agu (2021) [2] reported that reduced tractor forward speeds significantly enhanced the performance of ginger harvesters by minimizing crop damage and improving harvesting efficiency. Basavaraj and Jayan (2020) [5] investigated the physical and frictional characteristics of turmeric rhizomes, generating essential design inputs for the development and optimization of efficient harvesting machinery. Kumar and Tripathi (2017) [18] assessed the performance of a potato digger-cum-elevator and documented substantial reductions in labour requirement and operational time. More recently, Kadam *et al*. (2023) [15] evaluated a multipurpose root crop digger for potato and ginger harvesting and demonstrated its adaptability for other crops such as garlic and onion with minor design modifications.

Benefits of Farm Mechanization

- **Time-Saving:** Use of tractors for ploughing, sowing and irrigation reduces operation time significantly compared to manual labour.
- **Labour Reduction:** Machines such as power tillers, tractors and threshers reduce dependency on manual labour, helping to overcome labour shortages during peak seasons.
- **Increased Productivity:** Combine harvesters and threshers allow faster harvesting and processing, leading to higher crop yields per unit area.
- **Cost Efficiency:** Although the initial cost of tractors, harvesters and threshers is high, mechanization lowers long-term labour costs and improves operational efficiency.
- **Reduced Post-Harvest Losses:** Using mechanical threshers and grain harvesters minimizes grain breakage, spillage and losses during harvesting.
- **Precision Farming:** Seed drills, planters and sprayers ensure accurate seed placement, fertilizer application and pest control, improving crop quality.
- **Scalability:** With tractors and harvesters, farmers can cultivate larger areas efficiently, supporting commercial-scale farming.
- **Improved Crop Quality:** Machines like fruit harvesters and mechanical reapers gently handle crops, preserving quality and reducing damage.
- **Energy Efficiency:** Tractors and combined machinery save human effort and optimize fuel use compared to manual or animal-powered methods.
- **Support for Sustainable Practices:** Zero-till seed drills, rotavators and precision sprayers reduce soil disturbance, conserve water and enable conservation agriculture practices.
- **Enhanced Economic Returns:** Mechanized farming using tractors, threshers and harvesters increases productivity, reduces losses and boosts farm income.
- **Encourages Technology Adoption:** Use of modern harvesters, sprayers and drones encourages farmers to adopt advanced technologies for efficient and data-driven farming.

Conclusion

Farm mechanization has brought about significant improvements in the efficiency, productivity and sustainability of agricultural operations in India. Marked differences were observed in the level of mechanization across regions and farm categories, largely influenced by farm size, income, awareness and access to machinery. Farmers with better economic resources and higher exposure to technological information demonstrated greater adoption of mechanized practices, while small and marginal farmers continued to face constraints related to high initial costs and machine suitability. The results further indicate that mechanization has effectively reduced labour dependency, operational drudgery and timeliness-related losses, leading to improved crop yields and farm income. Post-adoption outcomes revealed notable benefits in terms of reduced cultivation time, lower post-harvest losses and enhanced precision in farming operations.

Reference

1. Agarwal AK, Prashumn, Chandra K. Di-ethyl ether-diesel blend fuelled off-road tractor engine: Part I technical feasibility. Fuel. 2022;308:121972. doi:10.1016/j.fuel.2021.121972.
2. Agu CV. Performance evaluation of a ginger harvesting machine with four different tractor forward speeds. Niger Agric J. 2021;52(2):346-351.
3. Ali MM. Manufacture and evaluation of a local simplified potato digger. Misr J Agric Eng. 2013;30(1):139-158.
4. Balasubramani S, Ajith B, Deepak RA, Gokulakrishnan P. Design and fabrication of multipurpose harvesting machine. Int J Res Eng Sci Manag. 2020;3(6):1-8.
5. Basavaraj, Jayan PR. Studies on crop parameters of turmeric rhizome towards the development of root crop harvester. J Pharmacogn Phytochem. 2020;9(3):349-355.
6. Bertinatto R, Schlosser JF, Bertollo GM, Herzog D, Casali L, Borsatto HG. Typical performance behavior of a diesel cycle agricultural tractor engine with electronic injection management and turbocharger. Cienc Rural. 2022;52:e20200966. doi:10.1590/0103-8478cr20200966.
7. Cong Q, Yang Z, Xu J, Ma B, Chen T, Zhang X, *et al*. Design and test of load-lifting performance for hydraulic linkage of the high-medium horsepower tractor. Appl Sci. 2021;11(21):9758. doi:10.3390/app11219758.
8. Connor R. India overtakes Japan as 4th-largest economy, report says. Deutsche Welle. 2025 Jan;1-3.
9. Cutini M, Brambilla M, Pochi D, Fanigliulo R, Bisaglia C. Evaluation of key factors influencing agricultural tractor fuel consumption during heavy drawbar tasks. Agronomy. 2022;12(1):1017. doi:10.3390/agronomy1201017.
10. Datir PR, Shrivastav RK, Solanki MJ, Tarade AI. Tractor operated onion harvester: digging system. J NX. 2019;1(1):1-6.
11. Editor S. How does a combine harvester work. FMWORLDAgri. 2024;1-4.
12. Fanigliulo R, Del Duca L, Fornaciari L, Grilli R, Tomasone R, Pochi D. Efficiency of an ANC system in the tractor cabin under controlled engine workload. Noise Control Eng J. 2020;68(4):339-357. doi:10.3397/1/376733.
13. Hoy RM, Kocher MF. The Nebraska Tractor Test Laboratory: 100 years of service. In: Proc Agric Equip Technol Conf. St. Joseph (MI): ASABE; 2020. p.10-12.
14. Ibrahim MM, Amin E, Farag A. Developing a multipurpose digger for harvesting root crops. Misr J Agric Eng. 2008;25(4):1225-1239.
15. Kadam DM, Dongre R, Gupta R, Gautam R, Rajak SK. Performance evaluation of tractor-drawn root crop harvester for potato and ginger. Biol Forum Int J. 2023;15(3):564-570.
16. Khadake R, *et al*. Recent innovations and design of root crop harvester: A review. Int J Res Agron. 2024;7(8):343-348.
17. Kim WS, Kim YJ, Park SU, Kim YS. Influence of soil moisture content on traction performance of a 78-kW agricultural tractor during plow tillage. Soil Tillage Res. 2021;207:104851. doi:10.1016/j.still.2020.104851.
18. Kumar D, Tripathi A. Performance evaluation of tractor-drawn potato digger cum-elevator. Int J Agric Sci Res. 2017;7(2):433-448.
19. Kumar S, Noori T, Pandey K. Performance characteristics of ballast mode on energy efficiency indices of agricultural tyre under different terrain conditions. Energy. 2019;182:48-56. doi:10.1016/j.energy.2019.06.031.
20. Liu M, Li Y, Zhao S, Han B, Lei S, Xu L. Multi-objective optimization and test of a tractor drive motor. World Electr Veh J. 2022;13(2):43. doi:10.3390/wevj13020043.
21. Mehta CR, Tewari VK. Seating discomfort for tractor operators: a critical review. Int J Ind Ergon. 2000;25(6):661-674. doi:10.1016/S0169-8141(99)00050-9.
22. Mehta CR, Chandel NS, Senthil Kumar T. Status, challenges and strategies for farm mechanization in India. Agric Mech Asia Afr Lat Am. 2014;45(4):43-50.
23. Mehta CR, Chandel NS, Senthilkumar T, Singh KK. Trends of agricultural mechanization in India. ESCAP/CSAM Policy Brief. 2014;(2):1-13.
24. Mehta TD, Yadav R. Development and performance evaluation of tractor operated onion harvester. Agric Mech Asia Afr Lat Am. 2015;46(4):33-39.
25. Molari G, Bellentani L, Guarnieri A, Walker M, Sedoni E. Performance of an agricultural tractor fitted with rubber tracks. Biosyst Eng. 2012;111(1):57-63. doi:10.1016/j.biosystemseng.2011.10.001.
26. Mule AB, *et al*. Design and fabrication of harvesting machine. Int Res J Eng Technol. 2018;5(1):501-505.
27. Nagendra K, Ramappa KT, Anantachar M, Jholgikar P, Veerangouda M, Prakash KV. Effect of design parameters on mechanical harvesting of ginger. J Pharmacogn Phytochem. 2023;12(5):399-405.
28. Narender, Shrivastava AK. Design and development of a digging machine for turmeric and ginger crop. Indian J Eng Mater Sci. 2022;29:283-290.
29. Naresh, Rani V, Jain M, Kumar A, Narender. Design and development of tractor operated carrot digger. Agric Mech Asia Afr Lat Am. 2018;49(3):15-21.
30. Qin J, Wu A, Song Z, He Z, Suh CS, Zhu Z, *et al*. Recovering tractor stability from an intensive rollover using momentum flywheel and active steering. Comput Electron Agric. 2021;190:106458. doi:10.1016/j.compag.2021.106458.
31. Sharma R, Kumar SR, Chouhan SS, Yadav U. Design and simulation of low-cost root crop harvester. Open Agric. 2019;4:139-143.
32. Sharma VP. Marketable and marketed surplus of rice and wheat in India: distribution and determinants. Indian J Agric Econ. 2016;71(2):1-18.
33. Singh MC. Development and performance evaluation of a digger for harvesting onion (*Allium cepa* L.). Int J Agric Eng. 2014;7(2):391-394.