



Role of Mechanization and Agricultural Machinery in Increasing Agricultural Production: A review

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Abstract

Agricultural production is one of the main pillars of every country in order to provide food security for its population. Therefore, the use of agricultural machinery and equipment plays a major role in significantly increasing agricultural production. The significant development of agricultural mechanization in countries around the world has contributed to the widespread use of this mechanization in the agricultural sector in all its aspects, from cultivation to harvesting and gathering. The use of agricultural mechanization has facilitated the processes of cultivation, irrigation, fertilization, harvesting, and even crop growth monitoring, which in turn improved the quality and quantity of agricultural output.

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1. Introduction

Agriculture is the backbone of the Indian economy, and it contributes 26 per cent of Gross Domestic Product (GDP) and provides employment to 65 per cent of the workforce, thus playing a vital role in India's development. Enormous advancement has taken place in Indian agriculture as evident from the increase in production, productivity and area under cultivation of different crops during the green revolution era (Alhshem and Ghader2022) ^[3]. Though, India ranks first in many crops like jute, groundnut, ginger, chickpea, pea, castor, onion and second in rice, wheat, sorghum, sugarcane, oilseeds, pulses, tea, etc., but it is still behind many countries in per hectare productivity of many crops like rice, wheat, pulses, etc. (Wang *et al.*, 2023) ^[53]. Cropping intensity or multiple cropping is lower than in other advanced countries due to socio-economic factors, climatic and agroecological conditions and inadequate infrastructure. It necessitates to identify various impediments that limit the agricultural production (Giller *et al.*2021) ^[13].

About 140 million hectares have been brought under irrigation but still nearly half of the farmers depend on rainfall for irrigation. Due to the increasing population the food requirement in the country has also increased. In order to meet the food production and to increase the productivity of crops, several steps have been taken during the past three decades. These include increased use of high yielding varieties of seeds, chemical fertilizers, pesticides, fertilizers and other production inputs, mechanization of agriculture by way of introduction of tractor-trolley sets in the existing bullock drawn implements, imported agricultural machinery and equipment and use of more advanced and sophisticated agricultural equipment by progressive farmers. Agricultural machinery is a pre-requisite for optimum and successful agricultural production. Since mechanization is capital intensive, the machinery must be scientific and economical in their usage and operation so that high productivity, production and profit can be achieved. In India major share of farm power in agriculture is provided by draught animals. (Amadi & Isaiah 2022) ^[4] (Lu *et al.*, 2022)

But the increasing livestock was not sufficient to meet the growing demand for farm power. In a country of vast size with varied agro-climatic regions this is the only way to mechanize the agriculture additional Renewable Energy Resources have to be tapped. This includes wind energy, bio-gas, solar energy, mini-hydel energy etc. Yielding Rates of agricultural produce must be increased at fast pace if India wants to be self-sufficient in food grains.

But it is found that the yield rates of various crops of India have been lower than those of many other countries. Exploitation of machinery in the agriculture depends upon various factors and constraints, which are interlinked. The farm holding size and farming conditions have been, and still are, ideal for diversified traditional mixed man-animal cropping systems. Hence, these concepts still hold relevance for India (Ma *et al.*, 2023).

2. Historical Context of Agricultural Mechanization

The utilization of agricultural machinery and mechanization is as old as agriculture itself. For centuries, farmers have made efforts to improve crop cultivation. First, they made crude ploughs of wood and iron which were drawn by cattle. Twisting cultivators, rotavators, etc., were used for tilling the earth that was hard and cloddy. Animal-drawn seeddrills, planters, and harrows gradually replaced the traditional methods of sowing seeds. Then came harvesting and threshing machines, various pickers for fruits and vegetables, and machines for packing, canning, grading, etc. These all progressively replaced manual labor to the extent possible (Ma *et al.*, 2023). Agricultural machinery plays a crucial role in maintaining soil fertility. It helps to lift and change land levels, thereby aiding in the growth of new varieties of crops. Used at appropriate times, agricultural machinery can help in performing various tasks more accurately compared to manual operations and modernity of which encourages crop diversity. (Laskar *et al.* 2024)^[22] (Bielykh, 2025)^[8]

Regardless of the size, type, and extent of farm mechanization, its proper use ensures minimum land and labor input requirement for production. This implies a wider use of machinery, especially tractors with their complementary implements. Some countries favor other machines over tractors, especially where conditions may not be compatible with tractorization. However, tractorization with accessories is on the rise, but it needs to be more widespread. Even in developed countries, there are vast undermeasured areas where agriculture may not be fully mechanized (Steenwyk *et al.*, 2022)^[49].

Manual operation of machines is becoming increasingly expensive since the payment must cover the time lost by the operator, repair costs, profit on capital investment, and other managerial costs. On the other side and with the advent of industrialization, colorful and varied metals find more and more entry into the field of agriculture. As improved agricultural machinery is introduced into farming systems, it requires intensifying research efforts to adapt, customize, and extend the available machines to the local climate, soil, cropping patterns, and farming systems. (Petersen-Rockney *et al.* 2021)^[39].

3. Types of Agricultural Machinery

With the rapid growth of the population, migration to cities, stable climate, and changes in society and governance, food production has become a core societal challenge and a vital threat to political stability. There are significant challenges ahead, even meeting the already high food production expectations. Agricultural mechanization is seen as the most practicable way to boost agricultural production, alleviate the labor shortage, increase productivity, and reduce environmental pollution. Focusing on sustainable agricultural development, agriculture 4.0, precision agriculture, the circular economy, and environmental pollution reduction, agricultural mechanization is needed urgently (Ma *et al.*,

2023). The mechanization of agriculture involves using agricultural machinery to carry out various agricultural operations or processes, which can significantly improve labor productivity. Conventional tiller-mounted and tractor-powered performance enhance the mechanization and precision of different operations, including seedbed preparation and the sowing, inter-row weeding, fertilization, and harvesting of sugar beet and time-consuming inter-row hoeing (Wang *et al.*, 2023)^[53]. To provide timely cover on diverse terrains against crop loss due to wind, research was conducted on variable-rate systems considered effective for dynamic cover application. The conceptual design of a smart precision planting machine comprising a soil moisture sensor, a variable-rate fertilizer application module, and an automobile with automatic control and positioning system was proposed. Furrow irrigation has been conventional in agriculture due to high water use efficiency. A plastic pin cultivation machine with drip-irrigated furrows could enhance seedling establishment and yield benefits. Agricultural robots with vision analysis, electric motor controls, and nitrogen fixation could enhance wheat planting quality, ensure thorough weeding, and improve yields. New generative design technology of lightweight and strong structures for agricultural machinery could save significant costs and energy in their transportation. Substantial effort will ensure that the global agricultural system, agricultural machinery firms and suppliers, farming service providers, and agricultural production entities are sustainable, smart, and accessible (Rai *et al.* 2023)^[40].

3.1. Tractors

Tractor is a vehicle that has large, heavy, and powerful wheels or tracks. Tractors are most commonly used in agriculture, both in farms and on ranches. A tractor driven vehicle consists of chassis, engine, framed mounted on front or rear of the vehicle, transmission, and hydraulic systems. The most important systems required for tractor driven vehicle are: 1. Engine system 2. Transmission system 3. Chassis. Chassis is the part on which all other systems of tractor are mounted, it consists of frame, axle and wheels. There are three types of chassis systems: 1. The chassis frame 2. The front axle 3. The rear axle. The chassis frame is the foundation of a tractor. It forms the base of the tractor. The tractors are constructed of a front axle, rear axles, drive wheels on which heavy drive chains are mounted, wide tire wheels are mounted on rear axle and a generally wide block frames which simplify both steering axle and universal joints and chains. The frame rests on rubber pads and mounts. These damping pads prevent vibrations in the rear. Chain covers protect both the operator and the chain from the outside elements (Ma *et al.*, 2023). (Vorozhtsov *et al.* 2022)^[51].

3.2. Harvesters

Agricultural machinery and mechanization are efficient methods of farming by applying advanced energy sources, tools, and techniques in agriculture and farming. As a result, agriculture produces modern agricultural products. Thus, farm operations occur at a much higher level of efficiency. Additionally, agricultural machinery includes horticulture machinery, tillage machinery, harvesting machinery, planting machinery, animal husbandry machinery, pest control machinery, and agriculture, forestry, and fishery machinery. To increase the length of the working season when field

crushing and harvesting crops similar to water accumulation, adapting special combinational machines may produce interoperation flows. Prior to construction, design, or reconstruction, the draft regulators' parameters must be learned along with the specific requirements accumulated on the fields of large collective farms. The trajectory shape affects the significant changes in threshold velocity, the irregular mode of cultivation, and the wave processes' occurrence (V. Zhalnin *et al.*, 2017) ^[50]. In anticipation of harvest failures, collected information concerning the airport grading regulations should be added to correct crop settlement. The data mandatory should design devices that form the set of routing algorithms and build a database. The automatic de-icing antarctica is restricted — noise limitation must be designed to accommodate the structure reduced and subsequent technology. New subsystems should be added for making noises warning, protecting invaded ground parking positions, and receiving agrometeorological data. An adaptation of data exchange protocols presently being developed in the three-central elaboration is proposed. In Europe, legislative acts often demand a reduction in the maximum noise level and border in attempts to invalidate the legislation. During any non-destructive process, dispersion is produced and the retrieval of grain dries is difficult (Ma *et al.*, 2023).

3.3. Plows

A plow is an implement or machine used to till the soil and destroy the weeds. Plowing is the first operation of various agricultural practices to prepare seedbeds for cereals, pulses, and oilseeds, it also helps to prepare fields for other planting wants and improves drainage conditions for crops. It will also help to mold the land to the required shape for surface and sub-surface agriculture which is necessary for horticultural crops. Plows are classified into four main categories: A single moldboard plow, a double plow, a disc plow, and rotary plow. Plowing is the most important and the primary operation which improves the productive potential of the soil, increases soil moisture retention capacity in the planting bed by breaking up surface hardpan, which slows moisture loss rates. It is also very important to the farming industry, from the design of the plows, to the analysis of the mechanics of plowing, down to the construction of equipment to make it easier for farmers to plow. The usefulness of a plow and its implementation varies from farm to farm and region to region according to the geographical diversity of soils and climatic conditions. It differs from high-speed steel blades of large corn planers to finely serrated blades of hand hoes for early seedbed preparation in rocky soils of middle-level land where frost-baked dry earth clods are to be grounded. The blades differ in width from a few centimeters across to widths of one meter or more. (Romanyuk *et al.* 2023) ^[44]

The earliest plow which was used by the Sumerians and the Egyptians was made of wood containing a flat horizontal blade measuring 41.35 cm or more. This word flat blade plow was used on nearly all kinds of soil which could be cultivated by it. In India, the flat-blade plow is made of timber about 2.4 m long and 15 cm broad. The leg or share is attached on one side of the blade by fixing with iron bolts. This plow is made mainly of seasoned timbers having necessary knots and bends. The flat-blade plow is an extensive agriculture implement in Indian agriculture for all cropping seasons. The flat-shape plow performs better in soil having moisture retention (Wang *et al.*, 2023) ^[53]. It is also used in preparing

seedbeds for important kharif crops. The share shaves the soil and helps to create the desired depth and conditions for improved germination and plant establishment (Ma *et al.*, 2023). It is most efficient for flat-level soils and helps in turning the soil with a minimum of scouring attachment.

3.4. Seeders

Seeder is Mission China's 3-RD generation small tractor without any ground effect chemistry, it is different from modern tractor in many aspects. A seeder is a useful device for agriculture, cultivation, horticulture, and forestry. Traditionally seeders were hand operated but now they can be powered by tractors or small gasoline engines. Beyond design and manufacturing the seeders in the market, the lab also develops innovative techniques to save their manufacturing costs. (Shamshiri & Behjati)

A seeder driven by a small two stroke gasoline engine was designed and supplied to the user. The user reports that imported seeders are about four times expensive compared to the locally made ones. The Indian produced seeders do not have proper design and consequently the users get tired and do long gaps in planting which result in uneven crop. The lab's design was apt and it was manufactured locally. In the market, a GPS controlled automated seeder module was developed, trialled and programming was supplied to the user. (YAROPUD and DATSIUK2024).

3.5. Irrigation Equipment

Agricultural irrigation equipment, which includes machinery and irrigation tools, is significant for increasing agricultural production. In previous years, farms and field management required extensive human labor. With the arrival of mechanization and the mechanization of irrigation, irrigation is significantly impacted, as entire field surfaces are leveled, and systems are laid out to allow maximum movement in an area (Humpherys, 1966) ^[16]. Water is applied uniformly on top and on the bottom of bedded rows. Equipment that mixes water and fertilizer before injection into irrigation laterals provided both water and nutrients for many crops. Fertigation use doubled in potato sands, and the extent of automated irrigation increased. Fertigation systems became more complicated as irrigation systems grew more elaborate, and recognition grew that more accurate and uniform application of fertilizer saves money and results in a better crop. (Askaraliev *et al.* 2024) ^[5]

The most frequent automated irrigation requests focused on guiding irrigation around complex field patterns, dealing with changes in crops or crop needs and scheduling irrigation with reference to weather or soil moisture. Fixed sprinklers with computerized controllers that determine when and how long to irrigate during a run were frequently requested (Wang *et al.*, 2023) ^[53]. Automated irrigation except for placing and connecting hard tubes and pipes, is a significant change in intensive irrigation management. New developments include fixed sprinklers with the computer automatically switching watering lines and computerized systems to irrigate crops grown in rows. Several discussions regarding fertigation were held in 1962. Some growers inquired about side dressing applications of fertilizers through the irrigation system or mixing chemicals to kill weeds in the irrigation return flow. An automatic water control structure for surface irrigation on farms is needed. (Champness *et al.*, 2023) ^[10].

4. Benefits of Agricultural Mechanization

The positive impact of agricultural mechanization on agricultural development is incontrovertible. The use of mechanization reflects a farmer's decision in the development of agriculture (Wang *et al.*, 2023) ^[53], but agricultural extension providers, who interact more with farmers than any other technical extension change agents, must be aggressive in ensuring that there is mass adoption at the grass-roots level, the very base of agriculture in Nigeria. Therefore, awareness campaigns, development of extension materials, establishing demonstration sites, and providing feedback to improve agricultural machinery and servicing networks will certainly accelerate the adoption of available machines. (Lu *et al.*, 2024)

The need for agriculture in Nigeria to be mechanized cannot be over-emphasized (O. Owolabi *et al.*, 2019) ^[35], based on the relative advantages, adaptability, accessibility, social acceptance, profitability, compatibility, and testability of agricultural machines. This study has also shown that agricultural extension service providers must play prominent roles at the grass-roots level in the effective use of machines available for agricultural production. These roles have been discussed and revolve around awareness campaigns, solving problems associated with the equipment, developing extension materials, establishing demonstration sites, and providing feedback to improve agricultural machinery and servicing networks. (Oduma *et al.* 2023) ^[36].

4.1. Increased Efficiency

A comprehensive national agricultural mechanization development plan has been published, which includes the development of agricultural machinery research and promotion. As modern agricultural modernization is an essential component of agricultural modernization, agricultural mechanization is a crucial focus of agricultural modernization. Overall agricultural mechanization development is typically evaluated using the mechanization of corresponding farming and planting technologies, farm machinery and equipment, the establishment of a competent workforce, and the development of infrastructure. The widespread adoption of agricultural machinery will undoubtedly increase agricultural production. Firstly, agricultural machinery's productive role will be essential in expanding land cultivated for production as standard work hours per unit land area will increase drastically. (Reddy, 2022) ^[43]

The active response to current high energy prices, war crises, and climate change requires ensuring resilience in the agricultural supply chain. Mechanization and agricultural machinery will continue to play a critical role in securing food and product availability by increasing domestic production and taking advantage of availability in other regions. Smart agricultural technology implementation and investment helps establish improved demand forecasting and future development risk assessment mechanisms. Integrated control of a task will continue being an essential approach for automation enhancement in the agricultural machinery industry. Autonomous technologies are expected to gain more interest in global agriculture. The task's autonomous execution will ensure accurate operation and smart control of agricultural machinery, providing reliable assistance to farmers. The fusion of mechanized and ecological farming operations will be studied to improve farmland ecology while ensuring food security. Farming operations integrate

precision seeding and weeding operations, as well as fertilization and pest control, with vegetable cover cultivation, between crops, and straw-sheltering cultivation. Pervasive environmental monitoring, combined with operation parameters optimized through big data, deep learning, and multi-spectral imaging, will be used to improve farming ecological service functions while reducing environmental impacts. Energy-efficient machinery design and operation will be implemented as effective countermeasures to tackle agricultural machinery energy efficiency issues like energy-intensive and massive greenhouse gas emission. Energy harvesters and hybrid machinery based on new energy sources, such as solar panels, batteries, biomass, and hydrogen, will be considered to make agricultural machinery greener (Wang *et al.*, 2023) ^[53]. (Liao *et al.*, 2022) ^[23] (Zou & Mishra, 2024) ^[56] (Fang *et al.*, 2024) ^[11].

4.2. Labor Reduction

Disproportionate share of agricultural labor forces in East Asia as compared to other regions is a bottleneck for agricultural development and modernization. Mechanization of agricultural production, including harvesting, tillage, land preparation and crop planting, has been a potential way to raise agricultural productivity and to relieve the cropping labor shortage. Mechanization improvement, however, is focusing on harvesting for grains while small trans-regional and trans-boundary businesses of agricultural machinery is absent. Over the past two decades, agricultural mechanization in China has been rapidly developed; however, both excess and shortage in agricultural capital productivity are seen. Meanwhile, population increases, global warming and other catastrophes put tremendous pressure on stability of food supply. Large improvements in efficient utilization of both labor and capital are essential in order to secure food production as well as to reduce carbon emissions from agricultural machinery operation. To sustain such improvements, both efficiency and equity of machinery utilization are important. (Liu & Li, 2023) ^[25] (Peng *et al.*, 2022) ^[38] (Wang *et al.*, 2022) ^[52]

As agricultural mechanization reduces manual work and labor is a cost input for agriculture, a labor is expected to be displaced by a man-hour saving from mechanization (Ma *et al.*, 2023). Though a man-hour saving from mechanization is compensated by increased operation time cost, without any change in utilities of man-hours/ton (unit cost) nor production scale/area, machine-driven production systems are more favorable than traditional labor-driven ones (Steenwyk *et al.*, 2022) ^[49]. Although the man-hour saving due to mechanization in harvesting is compensated by increased man-hour for hoeing and sowing, mechanization is expected to reduce net labor input cost on harvesting-based production systems. Advance in comparing labor utilization in a mechanized-based agricultural production across scales and regions accordingly is a potential way to apply desired improvement. To avoid unnecessary return of machinery for degradation in output, size of trans-boundary machinery businesses need to be a concern. (Hamilton *et al.* 2022) ^[14].

4.3. Cost Savings

In China, agricultural mechanization is broadly defined as the process of applying machines or tools to farming activities in order to substitute manual work with non-manual work (Ma *et al.*, 2023). After decades of growth, agricultural

mechanization has become a Xianqi but not yet a well-researched discipline in China, despite major contributions to food security from the perspective of sufficiency. Agricultural machinery systems face challenges such as a poorly regulated machinery market and a non-standardized vibration interference experiment standard. The role of agricultural machinery in productivity growth is unique, complex, and multifaceted as it equally contributes to crop yield, labor efficiency, and cropland efficiency. Within the scenario of missing alternative research approaches, utilizing agricultural machinery as an essential productivity factor can be beneficial in agricultural production. Meanwhile, how to balance agricultural mechanization and ecological restoration is also a problem. (Reddy, 2022)^[43] (Liu & Li, 2023)^[25]

As farming activity directly affects food production, a large number of concerns regarding the costs of agricultural machinery are raised. Prices of machinery, oil, labor, and other operating costs need to be considered to compare farm costs with and without machinery assurance. Considering food security, the primary and regulatory roles of agricultural machinery and its costs to affect grain productivity and develop reasonable mechanisms for ground/required agricultural machinery cost are critical but rarely addressed. Agricultural machinery generally refers to tools and machines, which save time, labor, and cost, and operate more accurately (Wang *et al.*, 2023)^[53]. Draft tillage machinery, which produces soil loosening and structure malformations and lower pH values, is widely adopted in China and critical in preparing soil for crop cultivation and obtaining higher yields. Based on the distinct fashions of operations, the local farm costs of non-required and required agricultural machinery using point- and line-sourced vertical tillage in rotovating field patterns, respectively, are analyzed. (Rakhra *et al.* 2021)^[41].

4.4. Higher Yields

The term yield refers to the output of agricultural production from each unit of land or labor and is the most important factor in the success of the farm business. Developing or adopting better cropping methods or better crop varieties can increase yield. However, the limitations of Israel's size and climate must first be considered (Wang *et al.*, 2023)^[53]. Agricultural policy is thus directed to revising soil tillage practices, pest control, and marketing, simpler operations may be equally effective. Mechanization and introducing agricultural machinery into the farm business should not be treated solely as an end in itself. The effect of these inputs on the various factors of production in agriculture should also be problem-oriented, considering a problem with regard to its potential impact on the final objectives of all farming enterprises (Ma *et al.*, 2023).

Two and six labels were used respectively to classify the alternative variables compared for each problem. The first model was a problem-oriented analysis of various agricultural machinery; the second model was a result-oriented analysis of Israeli farm output. Each label can have a zero or one value. These models are expressed as a linear program suitable for computer maximization and can be solved with the aid of general-purpose software. Results obtained indicate that the productive efficiency of farm products is an important limiting factor. Allocative behavior of Israeli farm produce and the adoption of computerized farm management services are vital for increasing output. Improvements in some inputs such as tractors and seeders

would reduce entire farm output according to their estimated productivity. According to tests that distribute this machinery input among the farms on an equal basis, thus complying with the available resources, outputs would be greatly increased. Although the other postulated changes appear feasible, their implementation on a wide-scale basis may be constrained and the payoffs thus speculative. (Jensen *et al.*, 2025)^[17].

5. Challenges of Agricultural Mechanization

Although crop production technology has made great advances, the mechanization of farming is an ongoing problem in improving the productivity of global agriculture. There are many economic, institutional, and social factors to be considered in agricultural mechanization. Technology availability and appropriateness have been seen, in addition to other factors, as significant constraints to greater mechanization in developing countries. There is, at present, great interest in developing a broader understanding of agricultural machinery, its use, and management in crop production all over the world. Agricultural machinery is a comprehensive term that includes stationary and mobile equipment and implements that are manufactured for agricultural production and processing. Over the last few decades, the increase in the scale of agricultural production has initiated a strong movement toward centralization of farm machinery management in many countries. The machinery distribution and purchasing power of larger farms and producers has typically increased their investment in machinery but at the same time increased their demands for machinery performance. On the one side, large farms and producers require more sophisticated machinery to increase their work performance. Yield and quality improvement has also influenced the demand for more high-tech agricultural equipment (O. Owolabi *et al.*, 2019)^[35]. At the other extreme, constraints to economic growth, availability of spare parts, fuel shortages, high demand for labor in agriculture, and the long-standing communist collectivization attempts have restricted and underdeveloped agricultural management practices and machinery in many other countries. Further investigation of machinery in agriculture requires the development and validation of performance measures. For the improvement of agricultural machinery use and management, the development of a stock steady approach that is capable of assessment over time best suits such countries with an incomplete inventory of agricultural machinery. However, due to the absence of local studies, difficulty in collecting survey data, and the lack of detailed agricultural machinery models, it has been so far too challenging to quantify (Wang *et al.*, 2023)^[53]. (Reddy, 2022)^[43]

5.1. High Initial Costs

The principal disadvantage of mechanization is the high initial cost of agricultural machinery and equipment, which is often higher than other cost of production such as labor. High costs also result from the importation costs of agriculture machinery and are not available with agricultural finance or loans, thereby earning less than smallholder farmers. High cost is the reason why farms in Asia have low agricultural mechanization levels. High initial costs also restrict entry into some technology-intensive production systems even in developed countries. As machinery size increases, lower per-unit costs may be expected, in part because of savings in labor costs. Adoption costs may be large for farm operators

considering adding new machinery options or types. Also, adoption costs are typically higher in considering machinery alternatives than in considering alternatives between alternative practices using machinery in similar manufacturer's product lines. Survey evidence indicates that relative to its cost, machinery is frequently reported as a barrier to adopting particular production practices. It is noted that too few operators in a lower mechanization farm region generate concern over whether surrounding operators can penetrate a thicker machinery supply network. A crucial determinant of capital costs is the type of production practices adopted and the choice of equipment required (O. Heady & D. Krenz, 2017) ^[34]. At an aggregate level, smaller-sized alternative crops may dominate because of high entry costs or that some practice alternatives may impose high special owner risks. Also, there are some variable costs for new machinery options that are equal to an established one, such as transmission risk in marketing hybrid seed rather than hybrid parent seed. The latter is an arrangement used in hybrid corn production in some regions. Once farmers are converted to a new practice standard, such as contour tillage, it may be difficult to switch back early in the season to another practice standard. Also, switching to no tillage may eliminate several conventional tillage machinery options used in crops with minimum tillage adoption. Labor played an important role in developing world agriculture. Conservation practices may call for substantial increases in labor inputs rather than a corresponding reduction in mastication. Conservation tillage reduces soil erosion. Increases in either costs may convert an environmentally benign operation in terms of eroding potential to one that is environmentally damaging (Wang *et al.*, 2023) ^[53]. (Aharoni and Hirsch 2024) ^[1] (Avenyo & Tregenna, 2022) ^[6].

5.2. Maintenance and Repair Issues

The rapid turnover of agricultural machinery caused a serious contradiction between demand and supply in farming machinery in China. Facing the shortage of agricultural machinery, many agricultural machinery manufacturers turned their eyes to the emerging markets in less-developed countries in Asia, Africa, and Latin America. However, the willingness to export and types of the products varied considerably among different countries. Exportable agricultural machinery types covered plow, drill, harrow, fertilizer applicator, sprayer, etc. It is suggested that manufacturers should observe the latest development in target countries, before deciding the types of machines to export. (Liu & Wang, 2022) ^[24]

After the completion of a sale and advertisement of agricultural machinery, maintenance and repair issues come on board. Agricultural machines and equipment need to be kept properly maintained to perform their best. Repairs need to be made as conditions change. It is essential to have some plan for ensuring that the agricultural machines are properly maintained and cared for. Systematic maintenance requires standards for care and records of care. It is also possible that machines can be obtained used, and if so, procedures for estimating their condition might be useful. Manufacturers' specifications on maintenance need to be carefully examined. This may be a separate booklet similar in size to the booklet on safety. The owner's manual very likely contains some information pertaining to maintenance requirements, but the owner's manual may not get into detailed standards of grease, oil, or filter change intervals. (Mishra and Satapathy 2023) ^[31]

(Scolaro *et al.* 2021) ^[46]

Broken or malfunctioning equipment must be repaired before it can operate again. If the equipment is under warranty, it is important that repairs are done according to the warranty requirements. These requirements may specify that only authorized dealers may service the machine or that particular oils or parts must be used. In these cases, it may also be advisable to have parts or services used for repairs saved in order to develop a history of repairs for the dealer or manufacturer. When locating firms or individuals to make repairs, it is essential to consider not only the cost of labor but also the timeliness of the service (Wang *et al.*, 2023) ^[53]. Geographical concerns could also warrant consideration in this context, as individuals or firms that are closer may be able to get to the equipment and affect repairs faster than those who are further away. (Cavestro, 2024) ^[9].

5.3. Skill Requirements

As well recognized, the fluctuation of grain prices heavily depends on climate, policies, and population. As climate change intensifies globally, building a modernized, efficient, and sustainable agricultural machinery system has become crucial for maintaining food security (Ma *et al.*, 2023). However, the supply-side problem of agricultural production has been underlined by frequent policy adjustment, poor planning, and flawed subsidies, leading to an increasing production gap. Meanwhile, inefficient operation, lack of land transfer, and declining profitability have highlighted the urgent demand for large-scale and specialized operations. Soil and water loss as well as biodiversity loss induced by intensified intensive tillage under mechanized farming has resulted in a decline in soil fertility and output. With the increasing pressure for food security and environmental conservation, emerging the trans-regional operation of agricultural machinery and building a low-carbon agricultural machinery system based on renewable energy have become pressing challenges for sustainable grain production. However, knowledge in this area remains limited. This paper is intended to serve as a basis for discussion on the operational mechanisms and implementable suggestions for the trans-regional operation of agricultural machinery as well as the low-carbon agricultural machinery system. Key approaches for increasing green productivity and environmental conservation through agricultural machinery are also analyzed. Despite the increasing concerns over the green transition of agricultural machinery, knowledge remains limited regarding the mechanisms by which agricultural machinery impacts green productivity or the green transition process. Therefore, it is critical to reveal the role of agricultural machinery in green productivity as well as improve the understanding of the demands, necessities, and regulations for the green transition of agricultural machinery systems. (Reddy, 2022) ^[43] (Bielykh, 2025) ^[8] (Khan *et al.* 2021) ^[18]

In the context of China's thirteenth "Five-Year Plan", a green, robust, and efficient agricultural machinery system is urgently needed. This green transition process is currently characterized by an increase in operational efficiency through enhanced mechanization levels and human capital cultivation, decreasing environmental impact through low-carbon operation and renewable energy utilization, and improved governance for sustainable food production. A proper understanding of the role of agricultural machinery in the green transition is needed to ensure reasonable resource

use and thus better performance of the agricultural production system. As agricultural engineers move from being concerned primarily with field-created new methods for improving agriculture to being concerned with design, research, and development with the engineering disciplines, a gap has developed between the skilled crafts of farming and the agricultural engineer. With the rapid mechanization of agriculture, this gap will widen until it becomes a chasm. Filling that gap is the Agricultural Mechanization graduate. What then is an Agricultural Mechanization graduate? The agricultural engineer is competent to design a system, based upon an understanding of the application. The agricultural mechanization major is competent in the application of the system, based upon an understanding of its design. What is it about agricultural mechanization? It is in a one-word name, "PRIME". The general goals of these two curricula can be stated in the three words of "PRIME Production", "PRIME Prices", and "PRIME Man". These general goals must be accomplished by means of producing two classes of graduates: Managers and Skilled Workers (L. Field, 1985). A "Manager" is a person engaged in the scientific management of decision processes pertaining to situations or actions which are highly technical, and in which the technical aspects are extremely important. A "Skilled Worker" is a person proficient in some craft or trade who has acquired technical abilities and duties in excess of those typical of normal farm operations. In fact, the production of "Managers" and "Skilled Workers" is the general goal of departments offering Agricultural Mechanization curricula. Results of follow-up studies of Agricultural Mechanization graduates indicate that the vast majority of these graduates are working as either Managers or Skilled Workers, or in some combination of the two. (Bielykh, 2025)^[8] (Zhang & Li, 2023)^[55] (He *et al.*, 2021).

5.4. Environmental Concerns

The mechanization of agriculture offers new and diverse opportunities for improving food production intensification and will consequently affect greenhouse gas emissions resulting from crop production. Agricultural machinery is a significant source of air pollution and thus increasing the pressure on agriculture production. The growth in agricultural machinery is a very important factor influencing grain growth. At present, in developing countries, especially China, understanding the role of agricultural machinery in production efficiency increase is significant for constructing sustainable and efficient agricultural systems. Empirical evidence from 2004 to 2020 was presented based on the solver model. New tangible solutions to increase production efficiency through directing and controlling agricultural machinery development in China were provided through efficiency improvement pathways. Observed excessive machineries increasing scale factor was estimated as about 1.072. Moreover, controlling this development to just below this would still achieve the untouched growth rate over 8.5 t/hm². For overpotential agricultural machinery, it was better to control the development to some extent due to limit growth and fast dirty transformation with unchanged poverty groups, but the path to continually develop it from too few would gradually improve all factors benefit. In terms of production increase maintenance, the agricultural machinery growth should mainly focus on tractor and planting machinery preservation and growth adaptation with an attention more on some low efficiency growth basic machines. It was believed

still variables exogenous could inflate growth or potential related intractable yield development amount as an strategy suggestion for instating/external situations after monitoring accordingly and making judgment (Ma *et al.*, 2023). The role of agricultural machinery in improving production and cropping system level sustainability was reviewed. It highlighted the fact that machinery has been a key factor in the intensification and expansion of sustainable production processes. Nevertheless, it was emphasized the importance of practical advances in cropping and machinery systems, more rigorous application and development of existing and new approaches to the development of machines, machinery systems and agricultural engineering as a whole. It was concluded that agricultural engineering must shape its own future in balancing the need for more intensified use of existing resources against the need to adjust and innovate technical processes to improve nature resource preservation. (Liu & Li, 2023)^[25] (Ma *et al.*, 2023) (Luo, 2025)^[28].

6. Technological Innovations in Agriculture

Technological innovations in agriculture relate to the development and adaptation of tools, machinery, and other mechanized technologies to enhance agricultural productivity and protect natural resources (Wang *et al.*, 2023)^[53]. With the rise in mechanization in agriculture, various innovations have occurred in farm implements and equipment, leading to the rise of agricultural machinery industry globally, promoting mechanization of agriculture. (Feng *et al.*, 2023)^[12]

Implements having a very sharp cutter, such as sickle and axe, uproot the plants by cutting them from below or by root, machinery for super-phosphate production, or machinery for fertilizers for better yield of crops, and few more than those, which fits into the local milieu will be the appropriate nature of innovation (Ma *et al.*, 2023). In addition to traditional farm implements, the irrigation kit, which is an innovation of pump set, size of pipes, traveling discs for irrigation, drum for irrigation pipes, and sprinkler nozzle of irrigation pipes to create sprays are other innovations towards better irrigation/fertility of land, yield records, economy of time, space, money, and labor in the local context need to be highlighted for their adaptation. Publications with illustrations of design of certain traditional/innovative implements, photographs of advanced farm machinery, improvement in farm machinery, field operation of farm implements with explanation of operational mechanism, functions, advantages/benefits, and limitations will effectively help in exposing/introducing technological innovations on a wider scale. (Ray & Majumder, 2024)^[42]

Social science aspects in terms of farmers' aspirations regarding various models of farm machinery, types of attachments/desirable features, and use of farm machinery for various purposes for designing prototypes of moving and stationery electrical powered agricultural machinery and its limitations will help convince farmers/growers on wider use of power machinery. The existing resources, user/practices-type factors/conditions regarding machinery with foreign/indigenous manufacturers and craftsmen and the constraints/past experiences in operation, resulting yield of crop and water requirement in returned system regarding such technological innovations with long life, will be made known to improve investment decisions. The print media on economic viability in relation to the fixed/capital and operational costs, skill of the operators, price yield ratio and

marketable surplus of produce/harvest along with information on where/how local farm machinery can be made available, its marketing aspect, and even on its insurance to take care of damage against unauthorized operation, theft, cyclone, etc. need be focused. (Rakhra *et al.* 2021)^[41].

6.1. Smart Farming Technologies

Agricultural 4.0 is a crucial aspect of modern agriculture, allowing farmers to optimize crop yields and help reduce resource usage. The proposed framework proposes a system that will integrate weather, temperature, soil humidity, and humidity sensors to improve farm management and sustainability. The weather sensors will provide real-time data, allowing the farmers to make informed decisions about planting, harvesting, irrigation, pest and disease management, and climate control. The temperature sensors will aid in the optimization of planting times, monitor pest and disease conditions, and provide fertilization recommendations. The tempo automatically records the soil humidity and can remind farmers of the proper irrigation times to reduce crop losses. The soil humidity sensor detects soil humidity levels to prevent overwatering. The humidity sensor allows farmers to make recommendations about planting capsulation and avoiding disastrous flooding. (Koshariya *et al.* 2024)^[20]

Agricultural 4.0 is a crucial aspect of the Smart Farming sector, which seeks to utilize advanced technologies to optimize farming efficiency (Kojo Gyamfi *et al.*, 2024)^[19]. The framework aimed to modernize farms by integrating smart farming technologies that would allow farmers to gather information on their farms and make observations rapidly. This information includes cultivation via weather sensors, humidity sensors, temperature sensors, and moisture sensors backed by a cloud-based system containing AI models that would conduct predictive analysis based on the gathered data. The aim of this framework is to empower farmers to monitor their activity along the farm on the cloud using the available sensors, which would gather information about the soil humidity, temperature, and humidity of the surrounding area. (Patil *et al.* 2024)^[37].

6.2. Data Analytics in Agriculture

Big data holds great promise in creating the basis for improved, increased, and more sustainable production in agriculture around the world. The benefits of these opportunities are still mainly in the future. Adopting and collating the data flow is challenging. Establishing sharing interfaces providing access to data is complicated (Roscher *et al.*, 2023)^[45]. This research investigates the possible actions to improve the implementation of data analysis tools, combine this with knowledge of farming, and increase the tempo of “smart farming” in agriculture. (Bhat & Huang, 2021)^[7]

New farming systems equipment will generate a new, vast amount of production improvement crop and area management data on large-scale production. Therefore, agriculture appears as a suitable and particularly challenging area for big data approaches. Until now, big data has not been embraced. Many relevant new possibilities are not yet used, or there is a possibility of improvement, at least within agriculture. Therefore, the first step is to collect available knowledge sources on and within agriculture regarding the handling of data (Morimoto, 2017)^[33]. Possibly, at the same time, new methods should be developed to blend these input

sources. Basic technologies should be exploited to interlink numerical data sources for a particular farm. The interplay between diverse data would help create an agricultural environmental feed, and strategies should be developed to increase data-based assessment tools. (Sharma *et al.*, 2022)^[48]. Within agriculture research, the toolbox of big data will be analyzed in detail. The next step will be to focus on particular methods that can handle and exploit a vast set of diverse movable, persistent, or changing data sources. It will be analyzed in which way this toolbox can be incorporated in a larger farming context to increase water, chemical, energy, nutrient, and crop production efficiency while maintaining, or possibly enhancing, soil, area, and environmental quality. There are many knock on the doors, but they would need to be established or improved, as well as adapted to agriculture in diverse regions. The action is needed to increase proper awareness of big data and improvement of successful farming efficiency opportunities. (Alahmad *et al.*, 2023)^[2].

7. Conclusion

Although still in its infancy, the mechanization of agriculture has not been able to satisfy the production requirements of crop farming’s current scale. It is nevertheless an undeniable reality that its impact has already been felt as evidenced by its incorporation to some degree in practically every farming regime worldwide, from subsistence farming where it has and continues to help produce food in challenging environments not amenable to fertilization or irrigation to intensive capital and labour cost-incentive systems that include contract farming and vertical integration spread over enormous tracts of agricultural land. From tractors and harvesters to planting and weed control machines, agricultural machinery continues to evolve from their hulking forebears in an effort to improve productivity and efficiency. Simple electric switches are gradually being replaced by sensors, controllers and multi-channel output systems that can sense not just the prized crop but also their size and weight; the consequence is a trimmer more noggling yet more sophisticated and demanding machine.

Technology is not only responsible for this evolution of agriculture machinery. In fact other cross-cutting, complementary technologies from welding, additive or laser manufacturing through metal slicing and shaping can jointly hold the key to realizing the desired outcome of improved productivity by increased mechanization. This calls for approaches, technologies and paradigms that sometimes only dimly follow yet other times have ceased to exist in the human psyche. In an effort to forge a common path forward and harmonize the current multi-dimensional confrontation that spans technology, society and the environment, opportunities arising from the convergence of mechanical systems with technology, chemical systems fuelled by bio-energy sources, raw material preparation systems cost-effectively producing renewable industrial chemicals, agri-industry cooperation at local municipalities in place of global conglomerates and even the natural evolution from ecosystem-based to bioetermed production systems are presented as next steps to enhance mechanization and agri-food production while reducing waste and pollution.

8. References

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