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REVIEW ARTICLE

Mechanization of garlic cultivation: An overview

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Abstract

The mechanization of garlic production has been developed to solve labour shortages and improve the planting, harvesting and processing operations. Various methods and machines have been designed and optimized for garlic production, including manually operated, animal-drawn, tractor-mounted and self-propelled planters. Advances in technology have significantly improved field capacity, reduced labour requirements and increased planting precision. For instance, tractor-operated planters have achieved field capacities ranging from 0.18 to 0.5 ha h^{-1}, with miss indices as low as 2.67%. Self-propelled planters have demonstrated an 87% reduction in labour demand, thereby proving their economic viability over traditional manual planting methods. Innovations such as garlic bulb breakers and precision seeders have further optimized planting activities. Additionally, the integration of automation, robotics and machine vision technologies has contributed to improvements in clove orientation and planting accuracy. Despite these advancements, challenges remain in adapting machines to diverse field conditions and accommodating a wide range of garlic varieties. Continued refinement in precision planting, enhanced adaptability to field variability and the incorporation of advanced smart technologies are essential for the full optimization of garlic production processes.

Keywords: agricultural machinery; clove orientation; harvester; metering mechanism planter; precision planting

Introduction

Garlic (*Allium sativum L.*) is a globally significant vegetable crop, recognized for its production volume and economic importance (1). It ranks as the second most widely cultivated bulb crop after onion (2) and is extensively used worldwide due to its sulphur-containing compounds, which impart a strong odour, distinctive flavour and characteristic pungency (Fig. 1). Garlic is renowned for its health benefits, including the prevention of cardiovascular diseases, hypertension, cancer, common colds and the treatment of cryptosporidiosis in AIDS patients (3).

Global garlic production is estimated at 28.2 million t, cultivated on 1.7 million ha with an average productivity of 17 t ha^{-1}. The leading producers are China, India, Bangladesh, the Republic of Korea and Egypt. China accounts for over 75% of global production (4). As per the National Horticultural Research and Development Foundation (NHRDF), India ranks second place in terms of garlic production after China (5), with an area of 358000 ha, a production of 2920.30 thousand mt and a productivity of 8.16 t ha^{-1} in 2019-2020 (6). Tamil Nadu is among the leading garlic-producing states in India, while the highest per-ha yields are reported in Punjab, followed by Maharashtra, West Bengal, Haryana and Gujarat.

Garlic varieties in India lack significant distinction and are categorized based on bulb characteristics. Local varieties are either white, characterized by larger bulbs with better storage and higher yield, or red, known for their pungency. Tamil Nadu Agricultural University introduced improved clonal selections, including Ooty 1 Garlic (1991) and Ooty 2 Garlic (2019). Ooty 1 is a high-yielding variety (17 t ha^{-1}) with a short maturity period of 120-130 days. It produces large bulbs weighing 20-30 g with 22-25 cloves per bulb, suitable for hilly regions during the June-July and October-November seasons (7).

The NHRDF has also developed notable varieties such as Agrifound White, Yamuna Safed and Agrifound Parvati, with Agrifound White and Yamuna Safed being officially notified by the Government of India. However, short-day garlic varieties grown in the northern and western Indian plains, as well as the Nilgiri hills, are prone to degeneration effects, smaller clove size, increased disease and pest susceptibility and lower yields (8). Mechanized cultivation integrated with modern agronomic practices provides significant potential to enhance garlic productivity in India. Research indicates that early sowing, longer photoperiods, higher temperatures and advanced plant age positively influence key morphological traits, such as plant height, bulb diameter, bulb weight, bulb height and bulbing index (9).

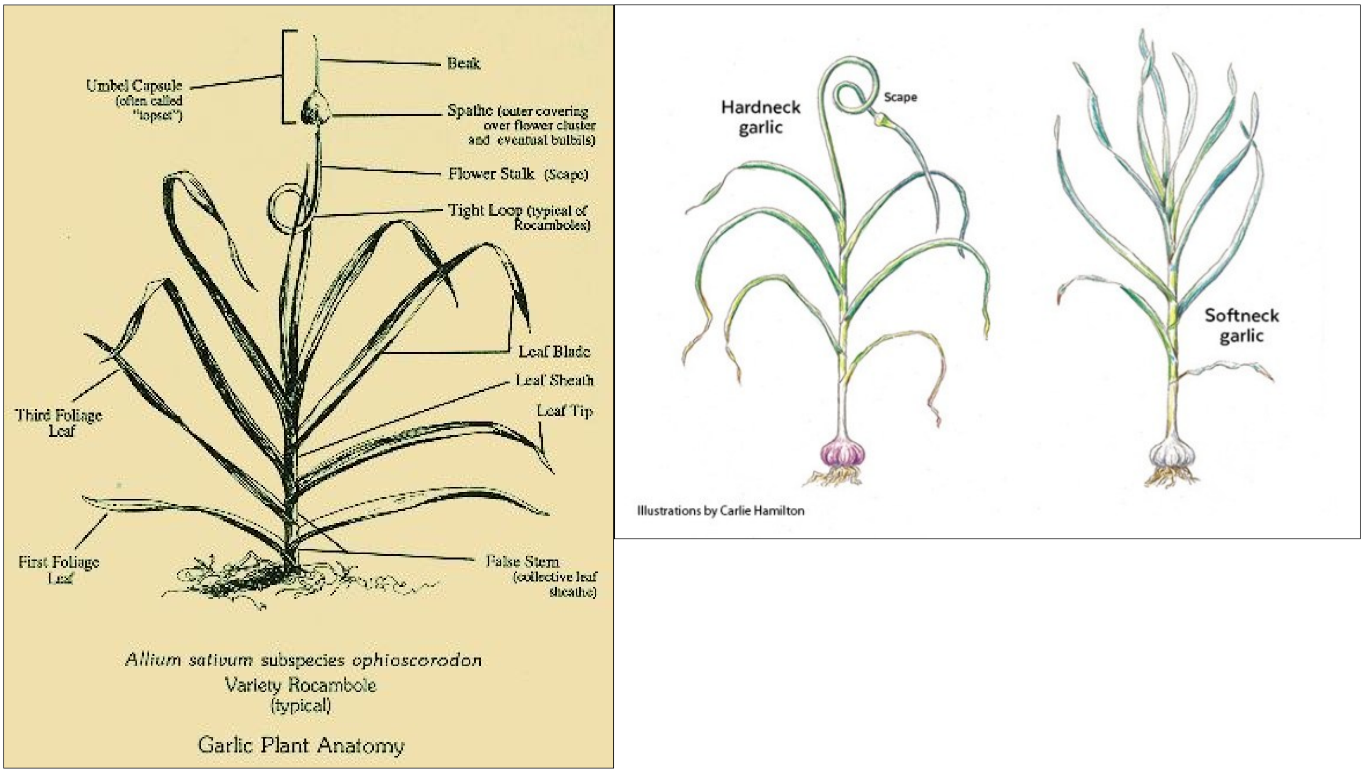

Fig. 1. Garlic plant.

Garlic cultivation faces several mechanization challenges, primarily due to labour-intensive processes and technological limitations. Traditional methods of planting and harvesting remain time-consuming and costly and the adoption of mechanization is still limited in certain regions (10). In India, for example, vegetable farming mechanization, including garlic, significantly lags behind cereal crops, increasing production inefficiencies. However, challenges persist in ensuring proper bulb orientation during planting, as incorrect placement leads to weak stems and poor bulb formation, an area where current sowing machines still struggle to guarantee uniform positioning (11). However, recent integration of AI and computer vision in precision agriculture has shown promise in enhancing seed placement accuracy and optimizing soil conditions for improved growth (12).

Mechanical harvesting, while essential for reducing labour dependency, still faces efficiency concerns due to soil variations, improper blade angles and the risk of bulb damage. Studies suggest that a 150^0 rake angle and a soil moisture level of 12.23% (d.b) optimize yield while minimizing losses (13). Recent research on garlic's physical properties has further contributed to the optimizing machinery design, ensuring appropriate harvesting techniques that minimize crop damage and maintain product quality (14). This review addresses these mechanization challenges by integrating recent technological advancements in precision agriculture, identifying best practices for planting and harvesting and highlighting areas for further research, such as automation improvements and environmental adaptability, to enhance garlic production efficiency.

Types of garlic planting methods

Garlic planting methods can be categorized based on their degree of mechanization and operational efficiency. These methods play a crucial role in determining labour intensity, crop yield and overall produce quality. The primary categories include:

Traditional planting methods

In China, garlic planting continues to rely predominantly on manual labour, making the process highly labour-intensive and inefficient (15). In India, the farmers often use a labour-intensive and time-consuming manual method to sow garlic. One ha of land needs to be sown in 60 to 82 man-days, with a 15 x 10 cm spacing for optimal plant density. Farmers are gradually deterred from growing garlic because of the labour-intensive nature of the activity and the higher pay rates. Although manually operated machinery is available, its adoption remains limited due to low field capacity and reduced efficiency (16).

Mechanized planting methods

Promoting mechanical garlic planting is crucial for long-term viability as it will raise profits and planting efficiency. The types of machinery used for planting garlic are discussed here.

Manually operated garlic planters

Punjab Agricultural University, Ludhiana, designed and developed a single-row manually operated planter for sowing garlic (17). The planter featured vertical discs, a spoon-type metering mechanism and a hoe-type furrow opener. Field evaluations indicated that the capacity of machine ranged from 0.03 to 0.04 ha h^{-1}, offering a significant cost advantage over traditional planting methods. Notably, the cost of planting using this manually operated planter was only 15% of the cost incurred through conventional manual planting techniques.

A study carried out a field test of a manually operated garlic planter (18). The device weighs 12 kg without the cloves. The planter needs to be operated by two people. It takes one person to draw the tool forward and another to manage the direction. The planter was tested in the laboratory and the field to determine the field performance regarding missed hill percentages and field efficiency. The planter's operational costs, clove placement depth, missed hill percentage and ground wheel slippage were all evaluated. The results demonstrated a field efficiency of 84.79% (Fig. 2).

Subsequently, a push-type manually operated garlic planter was developed and tested under field conditions (19). Key performance parameters were recorded, including planting depth (4.98 cm), hill-to-hill spacing (7.36 cm), number of seeds per hill (1.1), soil cover over the seed (4.96 cm), missing hills (13.46%), operating speed (3.31 km h^{-1}) and field capacity (0.0367 ha h^{-1}).

Animal-drawn garlic planter

The ICAR-Central Institute of Agricultural Engineering (CIAE), Bhopal, has made a significant contribution to small-scale agricultural mechanization by developing and evaluating an innovative animal-drawn, three-row garlic (*Allium sativum*) planter (Fig. 3) tailored for small and marginal farming systems. In this efforts, CIAE systematically assessed three distinct metering mechanisms: cell type (MM1), spoon type (MM2) and cup type mechanism (MM3) (20). Through comprehensive laboratory and field experiments, they rigorously evaluated the performance of these mechanisms based on critical parameters.

The findings revealed the superiority of the cup-type metering mechanism (MM3), which achieved a seed spacing of 102.1 mm (SD= ± 47.8 mm) under controlled conditions at a speed of 2.5 km h^{-1} and 108.7 mm (SD ± 40.10 mm) in field trials. The animal-drawn planter, ingeniously designed with the cup-type mechanism comprising eight cups mounted on a 217 mm diameter roller, maintained an optimal row spacing of 450 mm and an operational depth of 30 mm. Notably, the incorporation of a fluted roller enabled simultaneous fertilizer application and a minimized seed drop height of 300 mm ensured uniform seed distribution.

Field evaluations yielded promising results, with a miss index of 10.23%, multiple index of 7.45%, quality of feed index of 82.32%, precision index of 22.04% and seed damage ranging from 2-4%. The planter exhibited a field capacity of 0.07 ha h^{-1}, a field efficiency of 70% and required a draft force of 450 N, well within the capability of commonly used draft animals in small-scale farming. Notably, labour requirements were substantially reduced to 14 man-h ha^{-1}, compared to the labour-intensive 200 man-h ha^{-1} for manual planting. From an economic standpoint, the planter's initial cost of Rs 10000 and operational cost of Rs 1432 ha^{-1} represented an 80% cost savings compared to manual planting, which incurs costs of approximately Rs 7500 ha^{-1}.

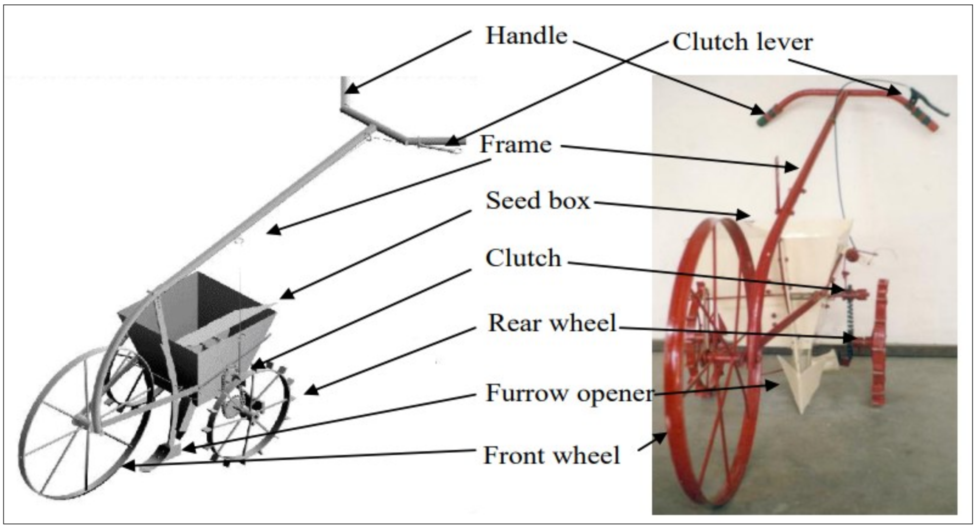

Fig. 2. CAD model and fabricated garlic planter(Kushwaha et al. 2020).

Fig. 3. Animal drawn garlic planter (Kumar et al., 2015).

Tractor mounted garlic planter

Tractor-powered garlic seed drills/planters have been developed by several manufacturers throughout India. These garlic planters often use plastic or PVC rollers equipped with grooved metering mechanisms. However, such mechanisms often fail to ensure uniform spacing between cloves. As a result, several agricultural universities have conducted research and development of tractor-operated garlic planters, as outlined below.

The Maharana Pratap University of Agriculture and Technology (MPUAT), Udaipur, has developed a 12-row garlic planter featuring a star-wheel clove and fertilizer metering system. This device is capable of planting garlic at a rate of 500-700 kg ha^{-1}, maintaining a row spacing of 150 mm and achieving a field capacity of 0.35 ha h^{-1} (21). The planter delivers a clove spacing of 50-100 mm, with a reported field efficiency of 70%.

Furthermore, MPUAT, in partnership with M/s R.K. Agro Industries, Rajkot, designed a 13/15-row garlic planter (Fig. 4a) equipped with a six-bladed plastic roller for seed metering (22). This model delivers a spacing configuration of 150 x 100 mm, a hopper capacity of 250-300 kg and a field capacity ranging from 0.4 to 0.5 ha h^{-1}. Additionally, the device features furrow openers with seed tube dimensions of 50 mm for local garlic varieties and 75 mm for the Ooty variety.

The Indian Agricultural Research Institute (IARI), New Delhi, developed a 9-row garlic planter (Fig. 4b) featuring a vertical cup-type metering mechanism (23). This planter offers a row-to-row spacing of 150 mm and a plant-to-plant spacing of 75 mm, with feed, miss and multiple indices of 88%, 2% and 10%, respectively. Laboratory testing revealed no detectable clove damage. The actual field capacity and field efficiency of the planter, operating at a speed of 2 km h^{-1}, were 0.2 ha h^{-1} and 74%, respectively (24).

A tractor-operated six-row garlic planter (Fig. 5a) with an actuating spoon-type metering mechanism (23 mm diameter and 2.5 mm depth) has been developed by Punjab Agricultural University (PAU), Ludhiana, for planting garlic at a row spacing of 150 mm (25). This planter includes a seed covering device, agitator, hopper and seed metering plate, all driven by the ground wheel through a chain and sprocket system. It is designed for planting the Punjab Garlic 1 variety on 1.0 m wide beds. The planter achieves an effective field capacity of 0.18-0.21 ha h^{-1} at a forward speed of 2.00-2.25 km h^{-1}. The average proportion of missed and multiple seed placements are 9.13% and 26.70%, respectively. Compared to manual planting, the machine reduces labour requirements by 82% and operating costs by 57%. The estimated cost of the planter is Rs. 150000, with an operational costs of Rs. 6200 ha^{-1}.

In 2020, a tractor-operated garlic clove planter (Fig. 5b) was developed and evaluated by Junagadh Agricultural University (26). This planter demonstrated a miss index of 4.21%, a multiple index of 6.20%, a quality of feed index of 89.59% and a mechanical clove damage rate of 5.70%. Its theoretical and effective field capacities were recorded as 0.41 ha h^{-1} and 0.32 ha h^{-1}, respectively, with a field efficiency of 79.02%. The effective field capacity was 4.92 times greater than that of a self-propelled planter, 21 times greater than a manual planter and 168 times higher than manual dibbling. The operational cost was Rs. 1677.67 ha^{-1}, representing a reduction of 1.5 times compared to a self-propelled planter, 2 times compared to a manual planter

Fig. 4. Tractor mounted garlic planter (a) 12-row planter (Singh, 2010) (b) 9-rows planter, IARI Annual Report, 2014.

Fig. 5. Tractor operated garlic planter (a) 6-row planter (Mehta, 2015) (b) Tractor operated garlic planter (Zilpilwar et al., 2019).

and 3 times compared to manual dibbling. The payback period was calculated as 5.05 years, with a benefit-cost ratio of 1.98. Overall, the tractor-operated planter demonstrated significantly better performance than both manual and self-propelled garlic planting methods.

Self-propelled garlic planter

A self-propelled garlic planter was developed at the Indian Agricultural Research Institute (IARI), New Delhi (27). Evaluation of the planter revealed a field capacity of 0.09 ha h^{-1} at a forward speed of 1.5 km h^{-1}. The planter exhibited a field efficiency of approximately 78% and achieved an average planting depth of 2.6 cm. The estimated cost of the machine was ₹50550, with an hourly operational cost of ₹213. The cost of operation per ha was ₹2370, significantly lower than manual hand planting, which costs ₹22500 per ha. Thus, the use of the developed garlic planter resulted in a cost saving of 87.1% per ha . Furthermore, the breakeven point for the garlic planter was found to be 79 h per year, with a payback period of 3 years. These economic analyses indicate the potential cost-effectiveness and financial viability of the developed garlic planter in comparison to traditional manual planting methods.

A research study focuses on the development of a self-propelled garlic clove planter (Fig. 6a) aimed at mechanizing the planting process and reducing the labour-intensive nature of traditional methods (16). Powered by a 3 hp diesel engine, the machine is designed to plant three rows of garlic cloves at precise intervals of 10 × 15 cm. It achieved a theoretical field capacity of 0.081 ha h^{-1} and an actual field capacity of 0.065 ha h^{-1},with a field efficiency of 79.84%. The planter demonstrated high precision, with uniform clove placement depths ranging from 4.2 to 5.2 cm, minimal seed damage (1.46%) and low miss and multiple indices of 2.67% and 8%, respectively. Cost analysis revealed a significant reduction in planting costs to Rs. 2321.50 per ha, yielding a 55.35% saving over manual methods. This innovation not only improves operational efficiency but also significantly addresses the high labour demands in garlic cultivation.

The Indian Agricultural Research Institute (IARI), New Delhi, also developed another self-propelled garlic planter (Fig. 6b) powered by a 2.65 kW petrol engine. This planter utilizes an inclined plate metering mechanism and recorded an average seed spacing of 94.2 mm. Key performance parameters included a miss index of 6.8%, a multiple index of 12.72%, a quality of feed index of 80.48%, a precision of 22.67% and a seed damage rate of 8.26%. The planter achieved a field capacity of 0.09 ha h^{-1} and a field efficiency of 77.7% at an operational speed of 1.5 km h^{-1}, with an average clove placement depth of 26 mm (28).

Precision garlic planter

An innovative precision planter for garlic cultivation (Fig. 7) was designed, fabricated and evaluated (29). This tractor-mounted, ground-wheel-driven implement comprised three planting units capable of depositing 3 rows of garlic cloves on each raised bed formed by an integrated lister & bedder assembly. Key components included a chassis with transport wheels, a hopper, metering drums driven by a chain system synchronized with the ground wheels, sweepers and knockers to dislodge cloves from the metering drums, seed tubes to conveying cloves to the furrow openers and seed coverers. Initial laboratory tests revealed satisfactory metering uniformity and minimal clove damage. However, modifications such as the incorporation of rotating rubber-finned sweepers and reduction in metering drum speed were necessary prior to field trials.

Subsequent field evaluations demonstrated that the planter achieved a plant population of 220000 per ha, with average seeding depths and in-row spacing of 12.3 cm and

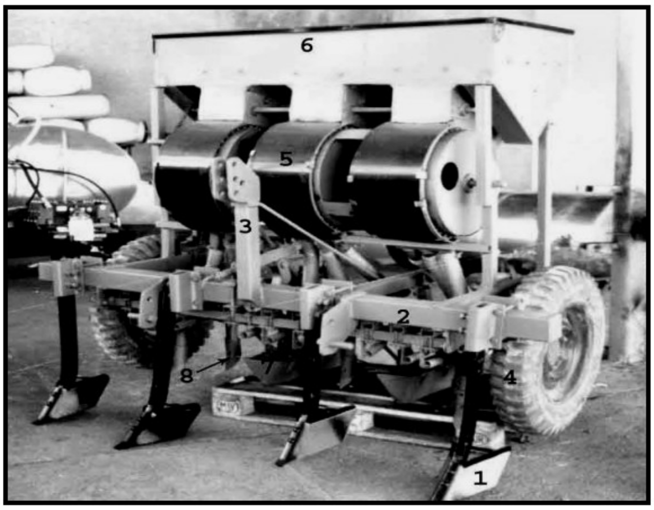

Fig. 7. Precision planter for garlic (Bakhtiari et al. (2009)).

Fig. 6. Self-propelled garlic planter (a) JNKVV, Jabalpur, (b) IARI, New Delhi.

22.7 cm, respectively. The planter recorded a missing index of 12.23%, a multiple index of 2.43% and a clove damage rate of 1.41%. While the overall performance was deemed acceptable, the achieved plant population was below the recommended range. To attain the preferred population was below the recommended range. To attain the preferred population density of 330000 to 740000 plants per ha, suggested improvements included reducing the forward travel speed while maintaining metering drum velocity and incorporating straight vertical seed tubes with water jets to improve flow of the adhesive garlic cloves.

Precision agriculture and smart planting systems

The orientation of garlic cloves during planting is important for the proper growth and development of the garlic crop. For optimal growth, the scale buds of garlic need to be facing vertically upwards when planted in the soil. To address this requirement, an adjustment device based on machine vision was developed to detect and correct orientation of cloves during planting (30). Although most existing garlic planters lack the ability to adjust clove orientation, this limitation can significantly impact crop development.

To address this problem, a garlic planter uses a machine vision system was developed (31), enabling the recognition of cloves orientation before planting. This system allows it to position the cloves with the scale buds facing up before dropping them into the furrow to promote better germination and growth. Subsequently, a spoon-clamping type garlic precision seeding device was developed (32). It has the right fittings that orient the garlic cloves in the upright position during sowing.

Upon optimization, this device demonstrated high performance, achieving a plant spacing qualification index of 90.75% and a garlic scale bud facing upward index of 94.88%. Even though the complexity of the device design increases manufacturing costs the missed index of 3.96% and the multiple index of 5.29% indicate that there is still room for the improvement in precision planting.

Automation and robotics in garlic planting

Garlic planting methods differ in labour, efficiency and cost. Manual planting, while low in initial investment, is highly labour-intensive and often results in inconsistent clove spacing and reduced yields (33). Semi-mechanized methods, like tractor-operated planters, improve planting accuracy and operational efficiency, thereby substantially reducing labour costs (34). Fully mechanized systems, while incorporate automation and digital control technologies, further improve planting precision and yield; however, they require a higher initial investment (35). Manual methods are generally more suited for small-scale farms, whereas mechanization proves to be more cost-effective for larger operations (36).

In light of the growing garlic industry and worsening labour shortages, the development of an automatic garlic planter has become increasingly essential (37). In China, an automatic garlic seed orientation device was developed to ensure the correct positioning of garlic cloves, achieving a scaly bud upward rate of up to 96.6%. This device comprises a seed placement funnel, an orientation correction mechanism (including a rotating hopper and cylinders) and an automatic control system equipped with infrared sensors and pneumatic components (38). Simulations using 3D modeling software were employed to examine the effects of funnel taper and notch diameter on the extension length of the garlic bud and root. Optimal parameters were identified as a funnel taper of 60° and a notch diameter of 10 mm. Despite these optimizations, the system remained complex and slow, leading to the development of a new approach based on capacitive sensing technology to determine clove orientation (39). Ansys Maxwell, an electromagnetic field simulation software, was utilized to model the clove's falling process and analyze changes in capacitance within a spatial capacitor.

In some cultivation systems, garlic cloves are first grown in seedling boxes-referred to as garlic boxes-within nurseries and are later transplanted into fields using a semi-automated test bed equipped with an inclined belt garlic transplanting machine (40). This method promotes better germination and ensures improved plant spacing and row alignment. Experimental results indicated that both the belt angle and the operational speed of the test bed influence the spacing of garlic boxes placed end-to-end. The optimal configuration was determined to be a belt angle of 30° and a speed of 0.75 km h^{-1}. These test-bed experiments validated the feasibility of this approach and confirmed the optimal parameters for efficient transplantation.

Nevertheless, the successful development of robust, cost-effective robotic garlic planting systems necessitates interdisciplinary collaboration among agricultural engineers, roboticists, computer scientists and agronomists. Overcoming challenges related to clove recognition, handling and soil-machine interaction will be critical for the widespread adoption and practical implementation of these advanced planting technologies.

Challenges and future research directions

The widespread adoption of garlic planters among small-scale farmers in India is limited by multiple factors, primarily high initial costs, limited adaptability to diverse field conditions and maintenance challenges. The capital investment required for mechanized planters is substantial, posing a significant affordability barrier for smallholder farmers who already face high production costs (41). Additionally, while tractor-operated garlic planters offer efficiency, they often encounter difficulties in adapting to varying soil types. These machines demand precise depth control and well- prepared field, requirements that may not be feasible for farmers lacking access to advanced mechanization infrastructure (34). Maintenance and repair pose further challenges, as spare parts and technical expertise for these machines are often inaccessible in rural areas, increasing downtime and operational costs (42). Limited knowledge and training on mechanized planting methods also hinder adoption, as many small-scale farmers continue to rely on traditional manual techniques due to familiarity and lower perception of risk (43). To overcome these obstacles, targeted government subsidies, widespread training initiatives and the development of cost-effective, adaptable and easy-to-maintain planting technologies tailored to smallholder conditions are essential.

The major challenges in garlic planter technology include labour availability, clove orientation, plant-to-plant spacing and the efficiency of the metering mechanism, all of which significantly impact the yield of the Garlic plants. Manual dibbling of garlic cloves remains extremely labour-intensive operation, resulting in remarkably low actual field capacities of 0.0019 ha h^{-1} and 0.015 ha h^{-1} for manual planters. The precision planter developed by (29), it achieved a plant population of 220000 per ha, which is lower than the preferred 330000-740000 plants per ha range. The tractor-operated six-row garlic planter developed at Punjab Agricultural University had a mean index of missing and multiples are 9.13% and 26.70%, respectively. The self-propelled garlic planter developed by (16) had a miss index of 2.67%, multiple index of 8.0% and seed damage of 1.46%. The spoon-clamping type garlic precision seeding device developed by (34) had a missed index of 3.96% and a multiple index of 5.29%, indicating room for improvement in precision planting. The garlic seed directing device developed by (38) for adjusting the orientation of garlic seeds achieved a high upward rate of the scaly bud up to 96.6%, but the method was complex and slow.

These finding underscore the urgent need for the development of cost-effective and high precision garlic planting systems that can accurately handle, orient and place garlic cloves at optimal spacing and depth while minimizing missed cloves, multiple indexes and seed damage through interdisciplinary research by integrating robotics, machine vision, sensor technologies and advanced metering mechanisms is crucial for improving garlic cultivation efficiently.

Table. 1 shows the overall comparison of the planters and Fig. 8 visualizes the efficiency gaps between each method.

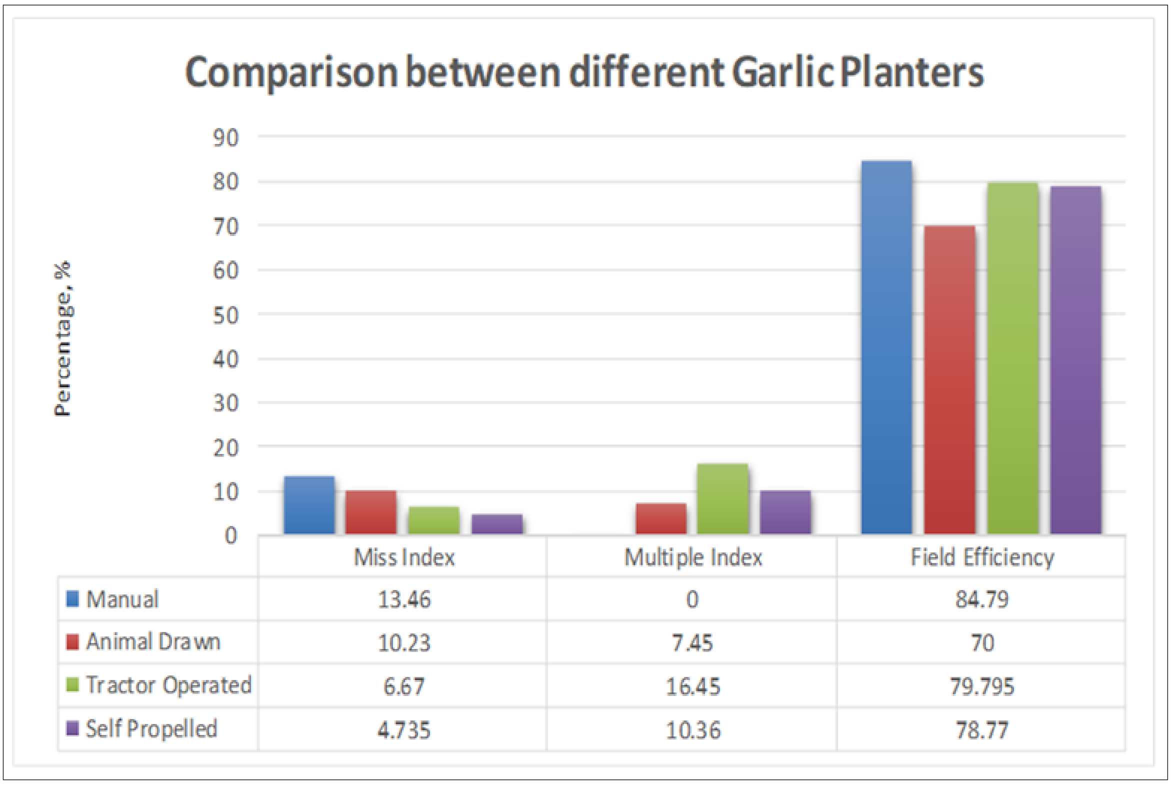

Fig. 8. Comparison between different garlic planters.

Table 1. Comparative performance of different garlic planters is presented below

Parameters	Power source			
	Manual operated	**Animal drawn**	**Tractor operated**	**Self-propelled**
No of rows	1	3	6-15	3
Row spacing, mm	150-200	450	150	100-150
No of labour required	1-2	1	-	-
Labour requirement man-h/ha	200	14	0	0
Field capacity ha/h	0.03-0.04	0.07	0.18-0.5	0.065-0.09
Metering mechanism	Spoon, Vertical discs	Cup type	Star wheel, Plastic roller, Inclined plate	Elliptical spoons, Inclined plate
Depth of clove placement, mm	-	30	-	26-52
Plant spacing, mm	100-150	-	50-100	100-150
Miss index %	13.46	10.23	4.21-9.13	2.67-6.8
Multiple index %	-	7.45	6.2-26.7	8.0-12.72
Field efficiency %	84.79	70	70-89.59	77.7-79.84

Harvesting methods

The inadequate efficiency and limited mechanization of garlic harvesting remain critical areas of the investigation. A self-propelled harvester developed by (44) (Fig. 9) with features such as material guidance and collection, limit cutting, digging, dust removal, clamping, conveying and holding. This model achieved a production efficiency of 453.33 m^3 h^{-1} and a garlic damage rate of only 0.43%. . The analysis indicates that the design meets manufacturing requirements and significantly increases garlic harvesting efficiency; as a result, it was a significant step toward single-row garlic harvesting mechanization.

Fig. 9. Self-propelled Garlic Harvester (Sun et al. 2018).

In order to increase the efficiency of harvesting garlic in some complicated locations, such as mountainous places, (45) designed and tested a handheld harvester that combined single-row harvesting and cutting capabilities. Efficient garlic harvesting can be obtained by setting the conveyance speed to 0.6 m s^{-1}, the digging angle to 19.2° and the tool rotation speed to 125.6 rpm, as determined by a series of tests and simulations. Compared to conventional methods, the new harvester was able to decrease leakage rates by 25%, increase the net harvesting rate by 4.0% and reduce the garlic injury rate by 57.1%. These enhancements increase effectiveness, decrease waste, reduce labour intensity and meet the requirements for harvesting garlic in various soil types. The performance of harvester under different geomorphologies can be analysed by Finite Element Method (FEM). In FEM, the studies like modal analysis, load simulations and mesh convergence studies are performed. The findings showed that the harvester could withstand the anticipated weights with a safety factor of 3.38 when the suggested modifications were made, mostly to the scarifier point structure (46). It is also used to find the crucial vibration frequencies that ought to be avoided when operating the harvester.

The design and experimental validation of a 4S-6 garlic combine harvester to improve harvesting quality and efficiency was reported by (47). A three-dimensional model was created, key components were analyzed and theoretical optimization was performed. A prototype was then constructed, followed by field trials using an orthogonal test method to evaluate performance under varying conditions. Statistical analysis identified the optimal combination of digging shovel angle, machine speed and clamping belt speed. The prototype demonstrated a garlic loss rate of 3.57%, damage rate of 1.22%, impurity rate of 3.95 and a bulb separation success rate of 89.34%-all meeting or exceeding standard performance thresholds. These findings suggest that the self-propelled garlic combine harvester exhibits high reliability and adaptability.

The characteristics of garlic digging shovels were optimized using a quadratic regression orthogonal rotation combination design along with EDEM simulations. The objective was to minimize resistance during digging by analyzing factors such as shovel width, length, angle and operational speed. Based on the simulation results, (48) developed a regression model to determine the primary and secondary factors affecting resistance. Shovel width, length and angle emerged as the key contributors, with operational speed having negligible impact. Strong interactions were observed between width and length and width and angle. These findings helped determine the ideal structural parameters for the digging shovel, which can be applied to enhance harvesting equipment productivity.

A floating root-cutting mechanism was developed to improve garlic root clearance efficiency while minimizing bulb damage. Dynamic simulations and force analysis conducted by (49) identified critical parameters including clamping chain speed, cutter angle, cutter group rotation and protective grid pitch. The optimal configuration included a clamping chain speed of 0.8 m s^{-1}, cutter rotational speed of 1450 rpm, a 30° cutter angle and a protective grid pitch of 35 mm. Feedback from force sensors enabled the realization of the root-cutting mechanism, leading to the proposal of a novel slotted round blade design for improved cutting efficiency (50). The blade specifications-110 mm diameter, 1 mm thickness and 1200 rpm speed-produced the required thrust force for effective root cutting. Slotted blades with inclined edges proved superior, offering cleaner and more precise cuts.

The study conducted by (51) proposed a mechanical solution to improve the harvesting of fallen garlic plants caused by stem moisture loss during maturation. A rotating rubber bar mechanism lifts and repositions the plants onto a conveyor for processing. Key operational factors, such as reel speed, forward speed and reel height, were analyzed through virtual simulations and field testing. Optimal parameters resulted in a feeding success rate of 98.73%. The study demonstrates the system's efficacy in minimizing harvest losses and improving mechanization, particularly for lodged garlic plants.

A specially designed prototype for narrow-row garlic planting systems was investigated to improve harvesting efficiency (52). The study systematically examined the effects of working speed, divider angle and lifter tooth length. Results showed that the working speed of 0.72 km h^{-1}, a divider angle of 20° and a lifter tooth length of 343.5 mm were the most critical for achieving a feeding success rate of 98.18%. Other parameters, such as lifter speed ratio and divider tooth height, showed minimal influence. The study concluded that enhanced mechanization significantly reduces labor costs and improves efficiency, particularly in densely planted systems, highlighting the role of parameter optimization in agricultural machinery design.

Root cutting remains one of the key challenges in fully mechanized garlic production. Previous study addressed this by developing a new floating root-cutting system using kinematic analysis and computer simulations (53). The study optimized variables such as spring stiffness, conveying speed and spring preload force using single-factor and virtual orthogonal tests. The optimal settings included a spring preload force of 16 N, conveying speed of 0.8 m s^{-1} and spring stiffness of 215 N m^{-1}, resulting in a high root excision rate of 92.72%. These findings provide a strong foundation for further technological advancements in garlic harvesting.

For raised beds, a tractor-drawn garlic harvester featuring an inverted triangular blade was developed to enhance cutting efficiency and minimize bulb damage. Response Surface Methodology (RSM) was employed to optimize operational parameters including forward speed, conveying speed and dropping height. The best performance was recorded at 1.53 km h^{-1} forward speed, 0.65 m s^{-1} conveying speed and 0.47 m dropping height, resulting in 96.4% digging efficiency and only 0.1% bulb damage. This mechanized solution significantly reduces labor demands and harvesting costs, proving particularly effective for raised bed cultivation (54).

Previous study introduced a vision-based automatic digging depth control system (Fig. 10) for garlic combine harvesters, addressing the shortcomings of manual depth adjustment such as slow response and inaccuracy (55). The system employs an improved YOLOv5 algorithm to detect garlic root length in real time, feeding data to a control unit that adjusts digging depth via an electric actuator. Key components include a color industrial camera, STM32F103VET6 microcontroller and a displacement sensor. The system achieved a detection time of 30.4 ms with an accuracy of 99.1%, effectively reducing energy consumption and enhancing harvest quality. While promising, the study suggests that further improvements in image processing and control algorithms are required for optimal performance in complex and multi-row field conditions.

To estimate garlic yield, the study proposed integrating machine learning algorithms with UAV-based multispectral imaging (56). The research focused on identifying key vegetation indices and texture features across three growing seasons (2021-2023). The study utilized the Random Forest (RF) algorithm to test two estimation methods: (1) direct yield prediction and (2) indirect prediction via above-ground biomass (AGB). While texture features slightly improved model performance, their overall impact remained minimal. The results affirm UAV-based remote sensing as a reliable, non-invasive approach for monitoring garlic yield, although accurately measuring certain phenological stages and biophysical parameters remains challenging.

Conclusion

Therefore, mechanization has made significant progress in addressing all the important challenges associated with the planting, harvesting and processing operations related to garlic cultivation. Innovations in planter design have led to substantial improvements, with tractor-mounted and self-propelled units able to demonstrate field capacities of 0.18-0.5 ha h^{-1} and 0.065-0.09 ha h^{-1}, respectively, compared to 0.03-0.04 ha h^{-1} for manual planters. These mechanized systems have reduced labour requirements from 200 man-h ha^{-1} to as low as 14 man-h ha^{-1} for animal-drawn planters and have virtually eliminated labour in tractor-operated and self-propelled units. Precision has also improved, with miss indices as low as 2.67% and multiple indices ranging from 6.2% to 12.72% in some advanced planters models.

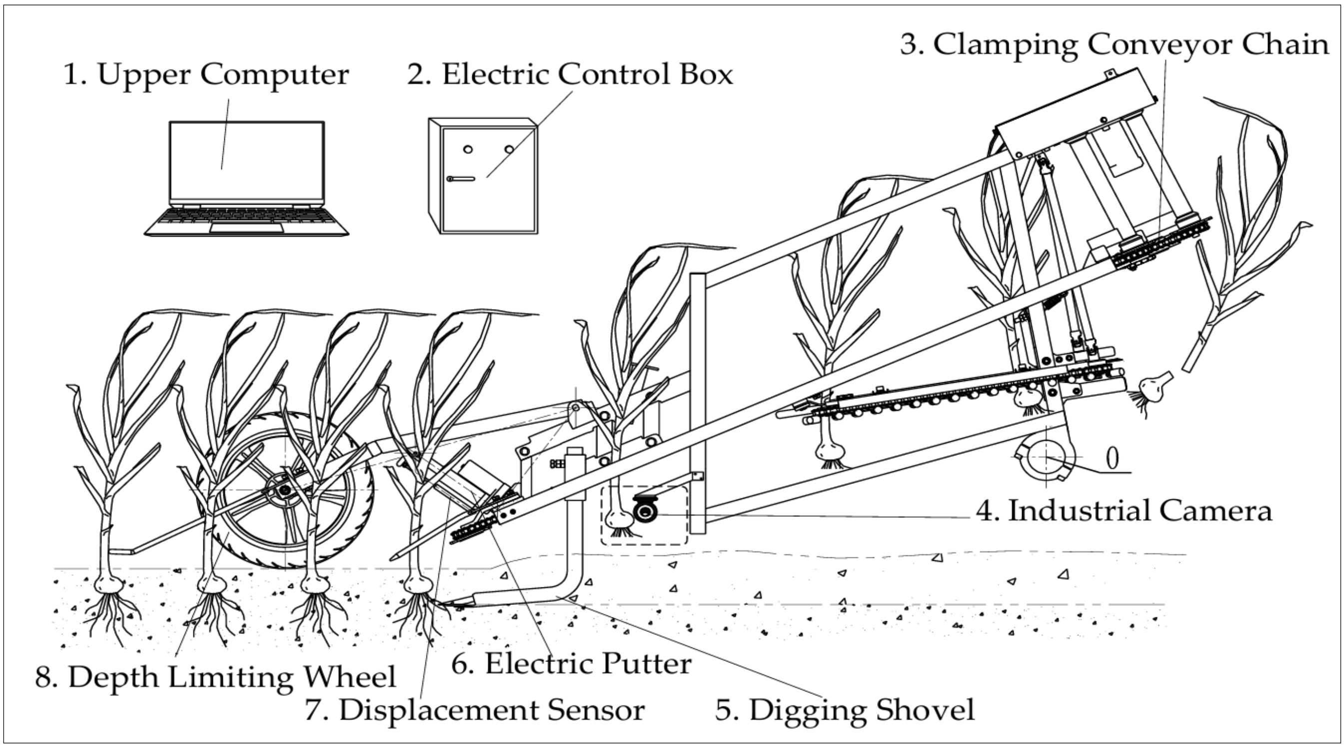

Fig. 10. Structural diagram of machine vision-based automatic depth control machine (Ding et al. 2022).

In terms of harvesting, new mechanisms have achieved digging efficiencies of up to 96.4%, with bulb damage rates as low as 0.1%. These advancements have been further enhanced through the inclusion of machine vision and smart control systems, achieving detection accuracies of up to 99.1% and response time as low as 30.4 ms for digging depth control. However, adaptation to different field conditions and variety types poses challenges.

Future research should focus on refining smart planting systems, enhancing harvester adaptability and developing integrated solutions that optimize the whole production cycle. As labour scarcity continues to affect agriculture, further research and dissemination of mechanized systems will be crucial for ensuring sustainable garlic production. These systems have already realized cost savings of up to 80% compared to manual methods, making them essential for the expansion of garlic farming worldwide.

Interdisciplinary collaboration is still essential to overcome the remaining technical barriers; mechanization should meet agronomical best practices and effective economic viability for garlic producers in the end. To further enhance the efficiency and scalability of garlic production, future advancements should focus on AI-driven planting systems that optimize seed placement, depth control and spacing for improved yield consistency. The integration of automation in planting and harvesting processes can significantly reduce labour dependency while ensuring precision in field operations. Additionally, IoT-based monitoring systems can enable real-time tracking of soil conditions, moisture levels and crop health, facilitating data-driven decision-making and resource optimization.

By adopting these innovative technologies, garlic farming can achieve greater efficiency, sustainability and resilience, ensuring long-term profitability and global expansion.

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Authors' contributions

BA and PKP participated in literature collection and drafted the manuscript. RK and ST participated in revisions and discussions. RC participated in the design of manuscript and final draft preparation. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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