



ISSN Print: 2618-060X
 ISSN Online: 2618-0618
 NAAS Rating (2026): 5.20
 IJRA 2026; 9(9): 1492-1498
www.agronomyjournals.com
 Received: 02-07-2026
 Accepted: 21-08-2026
 Published: 30-09-2026

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Strategies to mitigate challenges in mechanization of grafting system for production of horticultural nursery – A review

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i9t.6723>

ABSTRACT

Grafting is among the most common vegetative propagation methods utilized in horticulture for enhancement of plant vigour, disease resistance, stress tolerance, yield, and fruit quality by mixing favourable traits of rootstock and scion. The growing demand for grafted planting material has in turn resulted in fewer workers having the skillset needed and increased costs of production accelerating the progress in mechanised grafting systems. The goal of this paper is to provide a synthesis of the history, configuration, and mechanical utilisation of grafting systems in the production of horticultural crops. All currently existing grafting technologies have been divided into groups according to their level of automation and type of power used, crop, and cutting type. This paper makes a summary of the most important achievements in the development of grafting machines carried out by different researchers. The major factors influencing the evaluation of the quality of work and standards for their evaluation also include grafting ratio, rate of alignment, capacity, duration of grafting, damage, costs, and ergonomics of the technology. The paper lastly mentions some of the major problems related to the existing grafting systems. While, the review also presents the latest technologies in the field of robotics and machine vision, AI and IoT using different types of sensors and smart nursery tech in their applications in grafting. The technical aspects of grafting machines such as their structure and their mechanism of cutting and aligning plants and their automatic control system for making machines more effective is discussed including major research gaps and technologies that have to be addressed in the future.

Keywords: Grafting systems, Mechanization, Grafting machine, Nursery automation, Artificial intelligence, Robotics, Machine vision, Horticulture

Introduction

Horticulture contributes significantly to India's agriculture GDP, approximately 30.4 % of the total, despite utilizing only 13.1 % of the cropped area. India's horticulture production has been steadily increasing, reaching 351.92 million tonnes in 2022-23 (Fortune IAS Circle). India has emerged as a world leader in the production of a variety of fruits like mango, cashew, banana, guava, papaya, sapota, pomegranate, lime and is the second largest producer of fruits and vegetables. Productivity of horticultural crops had increased by about 38 % between 2004-05 and 2019-20 (National Horticulture Mission, 2022). Maharashtra is also leading producer of grapes, sapota, pomegranate, cashew nut and contributes over 6.6 % of mango production in country. Grafting has become an essential propagation technique in horticulture, particularly for improving crop performance, disease resistance, and uniformity in fruit and vegetable production. The increasing demand for quality saplings due to a shortage of skilled labour has created a need for efficient and consistent grafting methods. Semi-automatic grafting machines provide a practical solution by combining human control with mechanical precision to increase productivity in nurseries.

Grafting is one of the most widely used vegetative propagation techniques in horticultural crops for combining desirable characteristics of rootstock and scion such as disease resistance, stress tolerance, improved vigour, and enhanced fruit quality (Hartmann *et al.*, 2011; Goldschmidt, 2014; Rasool *et al.*, 2020) [1, 2]. Recent advances have demonstrated that grafting also worked as an important experimental system for understanding long distance molecular signalling, vascular regeneration, and graft compatibility. These findings have the applications of grafting beyond propagation to include crop improvement and stress adaptation. (Loupit *et al.*, 2023) [3]. It is extensively used in fruit crops, and vegetable crops for the production of healthy and uniform planting material. In recent years, grafting has gained significant importance due to increasing incidences of soil-borne diseases, climatic stress, and the growing demand for high-quality nursery plants (Gautier *et al.*, 2019) [4]. The rootstock-scion interaction also contributes to improved nutrient uptake, enhanced adaptability, and increased productivity in horticultural crops (Shivran *et al.*, 2022) [5].

Conventional manual grafting is highly skill-full job which requires precision for successful union formation between rootstock and scion. The quality and success rate of grafting largely depend on the expertise of the

worker, cutting accuracy, proper handling and alignment of delicate plant materials. Manual grafting operations are often associated with efficiency of skilled labour, operator fatigue, inconsistency in graft quality, and increased labour costs (Devi *et al.*, 2020) [6]. Moreover, the shortage of skilled grafters has become a major constraint for commercial nurseries and large-scale sapling production.

Several researchers have developed grafting machines for horticultural crops such as Tomato, cucumber, Watermelon, and other vegetable seedlings. However, limited research has been reported on grafting mechanization for crops such as Mango and Cashew under Indian conditions. Variability in diameter of scion and rootstock, delicate handling requirements, and high equipment costs remain major challenges in the development and adoption of grafting machines (Rasool *et al.*, 2020) [2]. Therefore, there is a need to critically review the existing grafting systems and technologies developed for horticultural applications.

To overcome these limitations, mechanization in grafting operation with different types of grafting tools, semi-automatic machines, and fully automated robotic systems have been developed to improve grafting efficiency, reduce labour dependency, and enhance precision in nursery operations (Devi *et al.*, 2020) [6]. Semi-automatic grafting machines combine human operation with mechanical assistance for cutting, alignment, and joining of plant materials, thereby improving uniformity and reducing operational time. These systems are considered suitable for small and medium-scale nurseries due to their relatively lower cost and operational simplicity compared to fully automated robotic grafting systems. Recent developments in robotics, machine learning, and artificial intelligent control systems accelerated research.

The present review paper focuses on the development, classification, working principles, performance evaluation, advantages, and limitations of different grafting systems and machines developed for horticultural crops. The review also highlights recent advancements, existing research gaps, and future scope for the development of efficient and economical grafting technologies suitable for nursery mechanization.

Grafting in horticulture

Grafting is one of the most important vegetative propagation techniques used in horticultural crop production. In this technique, the upper portion of a plant known as the scion is joined with the lower portion called the rootstock in such a way that the cambial tissues of both plant parts unite and grow as a single plant. Successful graft formation depends upon proper cambial alignment, compatibility between rootstock and scion, environmental conditions, and post-grafting care (Rasool *et al.*, 2020) [2]. Grafting is extensively practiced in horticultural crops because it enables the combination of desirable characteristics from two different plant materials into a single plant system. The grafting process mainly consists of three important components namely rootstock, scion, and graft union. According to Rasool *et al.* (2020) [2], successful graft union formation involves wound healing, callus formation, cambial bridge establishment, and vascular differentiation. Improper alignment or incompatibility between graft components may result in graft failure and poor plant growth. Recent studies further indicate that successful union of two plants depends on coordinated wound healing, cell-wall remodelling, plasmodesmata formation, and the establishment of functional xylem and phloem connections, all of which determine long term graft compatibility. (Loupit *et al.*, 2023) [3].

The rootstock generally provides resistance against soil-borne diseases, drought tolerance, salinity tolerance, and improved nutrient uptake, whereas the scion contributes desirable characteristics such as fruit quality, yield, and market acceptability (Gautier *et al.*, 2019) [4]. Grafting has gained considerable importance in modern horticulture due to its role in improving plant vigour, enhancing resistance to biotic and abiotic stresses, promoting early bearing, and ensuring uniformity in orchards and nursery production systems (Shivran *et al.*,

2022) [5]. The technique is widely adopted in fruit and vegetable crops such as Mango, Cashew, Tomato, Watermelon, brinjal, cucumber, and citrus crops. In modern horticulture, grafting has become an important climate-resilient technology because it enhances tolerance to drought, salinity, flooding, nutrient deficiencies, and soil-borne pathogens while maintaining productivity and fruit quality under changing environmental conditions. (Nie *et al.*, 2023) [7]

Types of grafting methods

Different grafting methods are adopted depending upon crop type, stem diameter, nursery conditions, and propagation objectives. Splice grafting is commonly used in vegetable seedlings due to its simplicity and suitability for mechanization. In this method, matching diagonal cuts are made on both rootstock and scion and then joined together using clips or support materials. Devi *et al.* (2020) [6] reported that splice grafting is widely preferred in vegetable nursery automation because of its higher operational speed and compatibility with semi-automatic grafting systems.

Cleft grafting is commonly used in woody perennial crops where a vertical split is made in the rootstock and the wedge-shaped scion is inserted into the split. Tongue grafting involves preparing tongue-shaped cuts on both rootstock and scion to improve graft stability and increase contact area. Veneer grafting is extensively practiced in crops such as Mango and Cashew, where a slanting cut is prepared on the rootstock and the scion is inserted and wrapped properly. Approach grafting and side grafting are also used in several horticultural crops depending upon propagation requirements and compatibility conditions. Despite substantial advances in grafting biology and the understanding of rootstock scion interactions, the commercial adoption of grafting has been constrained by the labour-intensive nature of nursery operations, creating a need for efficient grafting technologies. (Loupit *et al.*, 2023) [3]

Need for precision and mechanization in grafting

Grafting is one of the most widely used vegetative propagation techniques in horticultural crops for combining desirable characteristics of rootstock and scion such as disease resistance, stress tolerance, improved vigour, and enhanced fruit quality (Hartmann *et al.*, 2011) [1]. The increasing demand for quality planting material and large-scale nursery production has created the need for efficient and rapid grafting methods. However, traditional grafting operations are mainly performed manually and require skilled labour for precise cutting, alignment, joining, clipping, and wrapping of graft components (Lee *et al.*, 2010) [8].

Manual grafting is labour-intensive, time-consuming, and highly dependent on operator skill and consistency. Repetitive grafting activities often result in operator fatigue, lower working efficiency, inconsistent graft quality, and increased labour costs (Devi *et al.*, 2020) [6]. In commercial nurseries, shortage of skilled labour and rising labour costs have become major constraints affecting grafted seedling production efficiency (Kubota *et al.*, 2008) [9]. Among different grafting stages, rootstock and scion cutting operations are considered major challenges for mechanization because they require uniform cutting angles and accurate alignment for successful graft union formation (Rivard *et al.*, 2006) [10].

To overcome these limitations, the horticulture industry is gradually shifting towards automation and mechanization to improve operational efficiency, reduce labour dependency, and achieve uniform graft quality (Bie *et al.*, 2017) [11]. Semi-automatic and automatic grafting machines have been developed to improve cutting precision, alignment accuracy, grafting speed, and overall productivity while minimizing human error (Devi *et al.*, 2020) [6]. Mechanized grafting systems are becoming increasingly important for large-scale nursery production due to their ability to enhance productivity, maintain uniformity, and improve graft success rates. Therefore, there is a strong need for the development of efficient grafting systems capable of performing precise cutting, alignment, and joining operations with minimum human effort and higher operational efficiency.

Classification of existing grafting technologies systems

Existing grafting technologies and systems developed for horticultural nursery applications can be broadly classified based on automation level, power source, crop type, and cutting mechanism. The advancement from simple manual tools to intelligent robotic systems has mainly focused on improving grafting precision, reducing labour dependency, increasing operational efficiency, and achieving uniform graft quality (Lee *et al.*, 2010) [8]. Different grafting systems are designed according to the crop characteristics, grafting method, production scale, and level of automation required in commercial nurseries.

Manual tools

Manual grafting tools are the simplest and most commonly used systems in nurseries and small-scale propagation units. These tools include grafting knives, pruning shears, grafting clips, wrapping tapes, and manually operated grafting cutters. The entire grafting operation, including cutting, alignment, joining, and wrapping, is performed manually by skilled workers (Hartmann *et al.*, 2011) [1]. Manual systems are inexpensive, easy to use, and suitable for low-scale production; however, they are labour-intensive, time-consuming, and highly dependent on operator skill and experience. Variations in cutting angle, alignment accuracy, and handling often result in inconsistent graft quality and lower productivity (Kubota *et al.*, 2008) [9].

Manual grafting tools are generally classified as hand-operated systems powered entirely by human effort. They are widely used for fruit crops, vegetable seedlings, ornamental plants, and forest species where production volume is relatively small. Common cutting mechanisms used in manual systems include splice cuts, tongue cuts, wedge cuts, and V-shaped cuts depending on the crop and grafting technique employed (Rivard *et al.*, 2006) [10].

Semi automatic machines

Semi-automatic grafting machines were developed to reduce operator fatigue and improve grafting speed and precision while still requiring partial human involvement. In these systems, certain operations such as seedling feeding, alignment, or joining are manually performed, whereas cutting and clipping operations are mechanically assisted (Lee *et al.*, 2010) [8].

These machines are generally powered by electric motors, pneumatic systems, or compressed air mechanisms. Semi-automatic grafting machines improve uniformity in cutting and reduce variability caused by manual operation. Different cutting mechanisms such as tube grafting, splice grafting, and V-cut grafting are incorporated depending on crop type and stem characteristics (Bie *et al.*, 2017) [11]. Although semi-automatic systems improve productivity and reduce labour requirements, they still depend on skilled operators for proper handling and alignment of seedlings.

Automatic systems

Automatic grafting systems are designed to perform the complete grafting operation with minimal human intervention. These systems integrate automatic seedling feeding, stem detection, cutting, alignment, clipping, and graft transfer operations into a single automated unit (Kubota *et al.*, 2008) [9]. Automatic systems are mainly used in large-scale commercial nurseries where high production capacity and operational efficiency are required and commonly used in commercial vegetable nurseries for crops such as tomato, cucumber, watermelon, eggplant, and pepper.

The machines operate using electric drives, pneumatic actuators, conveyor systems, sensors, and programmable control units. Advanced image processing and sensing technologies are often incorporated for accurate stem positioning and alignment. Automatic systems significantly improve grafting speed, consistency, and labour efficiency while reducing operator fatigue and production cost (Lee *et al.*, 2010) [8]. However, the high initial investment cost, complex design, and requirement for uniform seedling characteristics limit their adoption among small and medium-scale nurseries. The grafting technique

used in such automatic grafting machines is mainly splice grafting technique which is majorly used for the grafting of vegetables.

Robotic grafting systems

Robotic grafting systems represent an advanced stage of grafting mechanization in which robotic manipulators and automated control systems perform grafting operations with high precision and repeatability. These systems use robotic arms, machine vision, servo motors, end effectors, and sensor-based positioning mechanisms to handle delicate seedlings and execute grafting tasks accurately (Bie *et al.*, 2017) [11].

Robotic systems are capable of identifying seedling position, stem diameter, and cutting location through image processing and sensor integration. They are mainly applied in high-value vegetable grafting operations where accuracy and uniformity are essential. Different robotic grafting configurations have been developed for splice grafting, tube grafting, and insertion grafting methods. Although robotic systems offer high precision and reduced labour dependency, their commercial application is still limited due to high cost, technical complexity, and maintenance requirements (Kubota *et al.*, 2008) [9].

Classification based on different parameters

Existing grafting systems can also be classified according to different operational and design parameters. Based on power source, grafting systems are categorized into manual, electric, pneumatic, and hydraulic systems. Based on automation level, they are classified as manual, semi-automatic, Automatic, robotic systems. According to crop type, grafting systems are designed for vegetable seedlings, fruit crops, ornamental plants, and forestry species. Based on cutting mechanism, systems are categorized into splice-cut, whip-tongue cut, V-cut, wedge-cut, tube grafting, and hole insertion grafting mechanisms depending on the grafting technique and stem characteristics (Lee *et al.*, 2010) [8]. These classifications help in selecting suitable grafting technologies according to nursery scale, crop requirement, and economic feasibility.

Design of grafting machines

The design of grafting machines is primarily aimed at improving the precision, efficiency, and uniformity of grafting operations while minimizing damage to plant tissues. An effective grafting machine should ensure accurate cutting and proper alignment between the rootstock and scion, as successful graft union formation depends largely on maximum cambial contact (Hartmann *et al.*, 2011) [1]. The overall design of a grafting machine changes according to the crop species, grafting technique, stem characteristics, level of automation, and production capacity. However, irrespective of the type of machine, the fundamental objective is to perform grafting operations quickly, accurately, and with minimum human intervention.

A grafting machine generally consists of a structural frame that supports the working units and maintains stability during operation. The rootstock and scion are positioned using a feeding mechanism, which may be manual, semi-automatic, or automatic depending on the level of mechanization. Both plant materials are securely held by a clamping mechanism designed to prevent movement during cutting while avoiding damage to stem tissues. The cutting mechanism is the most critical part of the machine and commonly employs straight, wedge, V shaped, U shaped, reciprocating, or rotary blades selected according to the grafting method and crop characteristics (Lee *et al.*, 2010) [8]. After cutting, an alignment mechanism accurately positions the rootstock and scion to maximize cambial contact before they are joined using clips, grafting tubes, Grafting tape or other fastening materials. Depending on the machine design, the complete operation is powered manually or by electric motors, pneumatic cylinders, hydraulic actuators, or servo motors and coordinated through mechanical linkages, programmable controllers, sensors, or machine vision systems (Kubota *et al.*, 2008) [9].

The working principle of most grafting machines follows a sequential process beginning with feeding the rootstock and scion into the ma

chine, followed by holding the stems firmly in position. The machine then performs simultaneous or sequential cutting of both scion and rootstock, aligns the cut surfaces precisely, joins them using an appropriate fastening device, and finally releases the completed grafted seedling. In fully automatic systems, these operations are synchronized using sensors, actuators, and programmable logic controllers to increase productivity and maintain consistent graft quality (Bie *et al.*, 2017) [11]. The integration of machine vision and robotic technologies further enhances cutting precision and alignment accuracy while reducing operator intervention.

An efficient grafting machine should have several important design aspects to ensure reliable field performance and commercial acceptance which are 1) High cutting precision, 2) Minimum mechanical damage to the rootstock and scion, 3) Accurate cambial alignment, 4) High grafting capacity, 5) Low power consumption, 6) Ease of operation, 7) Simple maintenance, 8) Operator safety, 9) Low manufacturing and operating cost, 10) Portability, and 11) Adaptability to different crops and stem diameters. Meeting these requirements is essential for improving graft success rate, reducing labour dependency, and increasing nursery productivity (Hartmann *et al.*, 2011; and Lee *et al.*, 2010) [1, 8].

Recent advances in grafting machine design have focused on the development of intelligent, compact, and modular systems capable of performing precise grafting operations with minimal human intervention. Modern machines increasingly incorporate machine vision, artificial intelligence, servo-controlled positioning systems, force sensors, IoT-based monitoring, and robotic manipulators to improve cutting accuracy, stem recognition, and alignment efficiency. Future grafting machine designs are expected to emphasize low-cost, portability, and multi-crop systems that are suitable for commercial nurseries as well as woody fruit crops, thereby expanding the scope of mechanised grafting technology in horticulture (Devi *et al.*, 2020) [6].

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Performance evaluation parameters

Performance evaluation of grafting systems is essential for determining the operational efficiency, graft quality, productivity, economic feasibility, and suitability of mechanized systems for commercial nursery applications. The evaluation criteria varies with on the power source, automation level, crop type, and working mechanism of the grafting system. Commonly used evaluation parameters include grafting success rate, alignment accuracy, grafting capacity, time per graft, damage percentage, labour saving, cost analysis, and ergonomic performance (Lee *et al.*, 2010) [8].

Evaluation based on power source

Manual systems

Manual grafting systems are completely operated using human effort and are commonly evaluated based on operator skill, grafting time, success rate, and labour requirement. In manual systems, grafting success largely depends on cutting precision and alignment accuracy achieved by the operator (Hartmann *et al.*, 2011) [1]. Since all operations are manually performed, operator fatigue and repetitive motion significantly affect working efficiency and consistency.

The major performance parameters used for evaluating manual grafting systems include: 1) Grafting success rate (%), 2) Time required per graft (s or min), 3) Labour requirement (man-hours), 4) Damage percentage of seedlings, 5) Operator fatigue and ergonomic comfort.

The grafting success rate is generally calculated as:

$$\text{Grafting Success Rate (\%)} = \frac{\text{Number of successful grafts}}{\text{Total grafts performed}} \times 100$$

Manual systems generally show lower productivity and higher labour dependency compared to mechanized systems.

Electric and pneumatic systems

Electric and pneumatic grafting systems are mainly used in semi-automatic and automatic grafting machines. These systems use electric motors, pneumatic cylinders, compressors, and actuators for performing cutting, clipping, and alignment operations. Performance evaluation

tion mainly focuses on operational speed, cutting precision, alignment consistency, and machine efficiency (Kubota *et al.*, 2008) [9].

Important evaluation parameters include: 1) Machine capacity (grafts h⁻¹), 2) Alignment accuracy (%), 3) Power consumption, 4) Cutting precision, 5) Seedling damage percentage, 6) Labour saving percentage.

Machine capacity is commonly calculated as:

$$\text{Machine Capacity} = \frac{\text{Total grafts completed}}{\text{Operating time}}$$

Pneumatic systems generally provide smoother operation and better cutting consistency; however, compressor dependency and air leakage may affect operational efficiency.

Evaluation based on automation level

Manual grafting systems

Manual systems are evaluated mainly based on labour efficiency, operator fatigue, graft success percentage, and time consumption. Since human involvement is maximum, variability in graft quality and alignment accuracy is usually higher (Rivard *et al.*, 2006) [10]. Ergonomic analysis is particularly important for manual systems due to repetitive hand movements and prolonged working hours.

Semi-automatic grafting systems

Semi-automatic grafting machines combine manual seedling handling with mechanical cutting and joining operations. Evaluation parameters mainly include: 1) Cutting accuracy, 2) Alignment precision, 3) Grafting speed, 4) Labour reduction, 5) Damage percentage, 6) Ease of operation. Semi-automatic systems generally reduce operator fatigue and improve productivity compared to manual methods. However, performance may still vary due to manual feeding and positioning errors (Lee *et al.*, 2010) [8].

Automatic grafting systems

Automatic systems are evaluated based on operational efficiency, automation accuracy, production capacity, and system reliability. These systems integrate sensors, conveyors, actuators, and control units for continuous operation with minimum human intervention. Major evaluation parameters include: 1) Automatic feeding efficiency, 2) Stem detection accuracy, 3) Grafting cycle time, 4) Capacity (grafts h⁻¹), 5) Success rate (%), 6) System reliability, 7) Energy consumption. Automatic systems generally achieve high productivity and consistent graft quality; however, system complexity and maintenance requirements are major limitations (Kubota *et al.*, 2008) [9].

Robotic grafting systems

Robotic grafting systems are evaluated based on precision, repeatability, machine vision accuracy, and robotic manipulation performance. These systems use robotic arms and image processing technologies for intelligent seedling handling and alignment operations (Bie *et al.*, 2017) [11]. Key performance parameters include: 1) Robotic positioning accuracy, 2) Image processing accuracy, 3) Repeatability, 4) Cutting precision, 5) Alignment success, 6) Processing speed

Robotic systems provide high operational precision and reduced human error but require advanced programming, calibration, and high investment cost.

Economic and ergonomic evaluation

Economic evaluation is essential for determining the commercial feasibility of grafting systems. Parameters commonly analysed include: 1) Initial machine cost, 2) Operating cost, 3) Maintenance cost, 4) Labour saving, 5) Payback period, 6) Cost per grafted seedling. Labour saving percentage is calculated as:

$$\text{Labour Saving (\%)} = \frac{\text{Manual labour} - \text{Machine labour}}{\text{Manual labour}} \times 100$$

Ergonomic evaluation mainly focuses on operator comfort, posture analysis, repetitive motion reduction, vibration exposure, and physical workload. Mechanized grafting systems generally improve ergonomic conditions by reducing repetitive manual operations and operator fatigue.

Challenges and limitations

Manual grafting systems are simple, economical, and widely used in nurseries; however, they are highly labour-intensive and depend greatly on operator skill and experience. Repetitive operations such as cutting, alignment, clipping, and wrapping increase operator fatigue and reduce working efficiency. Variations in cutting angle and cambial alignment often lead to inconsistent graft quality and lower graft success rates (Hartmann *et al.*, 2011) [1]. In addition, shortage of skilled labour and increasing labour costs have become major constraints in large-scale nursery production (Kubota *et al.*, 2008) [9].

Electric and pneumatic grafting systems improve cutting precision, operational speed, and grafting consistency compared to manual methods. However, these systems require continuous power supply, compressed air systems, and regular maintenance for efficient operation. Problems such as air leakage, pressure fluctuation, improper synchronisation of actuators, and electrical failures can reduce machine reliability and performance (Lee *et al.*, 2010) [8]. Delicate handling of soft seedlings also remains a challenge because excessive force during cutting or clipping may damage plant tissues and reduce graft success.

Semi-automatic grafting systems reduce labour effort and improve productivity by mechanically assisting cutting and joining operations while still requiring manual seedling feeding and positioning. The major limitation of semi-automatic systems is their dependence on uniform seedling size and shape for accurate alignment. Variations in stem diameter, curvature, and seedling height often reduce cutting precision and graft compatibility (Bie *et al.*, 2017) [11]. These systems also require skilled operators for proper handling and operation, which limits complete labour reduction.

Automatic grafting systems provide higher operational efficiency, faster grafting speed, and improved consistency through automated feeding, cutting, alignment, and clipping mechanisms. However, these systems involve complex mechanical, pneumatic, and electronic components, resulting in high initial investment and maintenance costs (Kubota *et al.*, 2008) [9]. Accurate handling of delicate seedlings and maintaining proper alignment under varying stem conditions remain major technical challenges. Most automatic systems also require highly uniform nursery seedlings for efficient performance.

Another major limitation of existing mechanized grafting systems is their limited adaptability for different crops and grafting methods. Most developed machines are designed mainly for vegetable seedlings and are less suitable for woody fruit crops due to differences in stem hardness, geometry, and cambial structure (Lee *et al.*, 2010) [8]. Nursery-specific variations in environmental conditions, seedling growth, and handling practices further affect machine performance and operational reliability. Therefore, improving adaptability, reducing machine complexity, and developing cost-effective systems remain important research areas in grafting mechanization.

Recent advances in grafting systems

Recent advancements in grafting mechanization have focused on improving precision, automation, productivity, and decision-making capabilities through the integration of robotics, machine vision, artificial intelligence (AI), sensors, Internet of Things (IoT), and autonomous systems. These technologies are helping commercial nurseries overcome labour shortages, improve grafting quality, and achieve large-scale production of uniform grafted plants (Lee *et al.*, 2010) [8].

Robotic grafting systems represent one of the most significant developments in nursery automation. Modern grafting robots use robotic manipulators, servo motors, and automated end-effectors to perform cutting, alignment, clipping, and handling operations with high precision and repeatability. Robotic systems can significantly reduce human intervention and improve grafting speed while maintaining uniform graft quality. Research has shown that robotic grafting systems are particularly effective for vegetable crops such as tomato, cucumber, watermelon, and eggplant where uniform seedlings are available (Bie *et al.*, 2017) [11].

Machine vision and computer vision technologies have become essential components of advanced grafting systems. High-resolution cameras and image-processing algorithms are used to detect stem position, stem diameter, cutting location, and alignment accuracy in real time. Computer vision systems help improve cutting precision and reduce human error by automatically identifying suitable grafting points and ensuring proper matching between rootstock and scion. These technologies enhance graft success rates while enabling automated operation of grafting machines (Kubota *et al.*, 2008) [9].

Artificial Intelligence (AI) is increasingly being integrated into grafting systems to support intelligent decision-making and adaptive control. AI algorithms can analyse images and sensor data to identify healthy seedlings, determine optimal cutting positions, predict graft compatibility, and optimize alignment processes. Machine learning and deep learning techniques allow systems to improve performance over time by learning from previous grafting operations. AI-assisted grafting systems have the potential to increase productivity, reduce seedling wastage, and improve graft survival rates under varying nursery conditions (Devi *et al.*, 2020) [6].

The adoption of IoT, smart sensors, and smart nursery technologies has further enhanced automation in grafted seedling production. Sensors are used to monitor environmental parameters such as temperature, humidity, light intensity, and moisture conditions within healing chambers and nurseries. IoT-based monitoring systems enable real-time data collection, remote supervision, and automated control of nursery environments. Combined with autonomous grafting systems, these technologies support precision nursery management, improve resource utilization, and contribute to the development of fully automated smart nurseries capable of producing high-quality grafted plants with minimal human intervention (Wolfert *et al.*, 2017; Liakos *et al.*, 2018; Shamshiri *et al.*, 2018) [13, 12, 14].

Research gaps and future scope

Although significant progress has been made in the mechanization and automation of grafting operations, several research gaps still exist that limit the widespread adoption of grafting systems in commercial nurseries. Most existing studies and machine developments have focused primarily on vegetable crops such as tomato, cucumber, watermelon, and eggplant, while comparatively little attention has been

given to woody fruit crops including mango, cashew, citrus, guava, sapota, and jackfruit. The differences in stem hardness, diameter variation, cambial thickness, and plant morphology make woody crop grafting more challenging and require specialized machine designs (Lee *et al.*, 2010) [8].

A major limitation of current grafting technologies is their dependence on highly uniform seedlings for successful operation. Many semi-automatic and Automatic systems perform efficiently only under controlled nursery conditions where stem diameter and seedling geometry show minimal variation. Further research is needed to develop adaptive grafting mechanisms capable of handling natural variations in plant size, shape, and growth characteristics without compromising graft success rates (Kubota *et al.*, 2008) [9].

The high initial cost of automatic and robotic grafting systems remains one of the biggest barriers to adoption, particularly in developing countries such as India. Most advanced grafting machines are designed for large commercial nurseries and may not be economically feasible for small and medium scale nursery operators. Therefore, there is a strong need for the development of low-cost, energy-efficient, and locally manufacturable grafting machines that can improve productivity while remaining affordable for Indian nursery conditions (Bie *et al.*, 2017) [11].

Recent developments in artificial intelligence, machine vision, and sensor technologies provide significant opportunities for future research in grafting mechanization. AI-assisted alignment systems can improve cutting accuracy, stem matching, and graft compatibility by automatically analysing seedling characteristics in real time. Integration of machine vision, IoT-based monitoring, and autonomous control systems can further enhance precision, reduce human intervention, and improve graft success rates. Therefore, future research should focus on developing intelligent, cost-effective, and nursery-friendly grafting systems suitable for diverse crops and production conditions, particularly for woody fruit crops and Indian nursery environments (Devi *et al.*, 2020) [6].

Another important research gap is the limited availability of portable and multi-crop grafting systems. Most existing machines are designed for specific crops and grafting techniques, reducing their operational flexibility. Future research should focus on developing lightweight, portable, and modular grafting machines capable of handling multiple crop species and different grafting methods. Such systems would be particularly useful for decentralized nursery operations and field-level propagation activities.

Conclusion

This review highlights the classification of existing grafting technologies based on automation level, power source, crop type, and cutting mechanism, and summarizes the major developments in grafting machines reported by various researchers. The design of grafting machines has evolved from simple manually operated devices to intelligent systems integrating machine vision, robotics, sensors, and artificial intelligence. Regardless of the level of automation, successful machine performance depends on accurate cutting, proper cambial alignment, minimum damage to plant tissues, and reliable joining mechanisms. Performance evaluation of grafting systems indicates that mechanization can substantially increase grafting capacity, reduce labour requirements, and improve operational consistency, although machine cost, complexity, maintenance, and adaptability continue to limit widespread adoption.

These reviews also identify several challenges associated with current grafting systems, particularly their dependence on uniform seedlings, limited adaptability to different crops, and the scarcity of machines specifically designed for woody fruit crops. While considerable progress has been achieved in vegetable grafting, research on mechanized grafting systems for woody horticultural crops such as mango,

cashew, citrus, and guava remains limited. While advanced technologies such as robotics, AI, computer vision, and IoT systems offer promising opportunities for improving precision, automation, and real time decision making in future grafting operations. Overall, future research should focus on developing low-cost, portable, energy efficient, and multi crop grafting systems that are suitable for different nursery conditions, and continued collaboration among agricultural engineers, horticulturists, automation specialists, and manufacturers will play a crucial role in developing practical and economically viable grafting systems that enhance nursery productivity while ensuring high graft quality and sustainability.

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How to cite this article: Karmarkar SP, Dhande KG, Deogirikar AA, Mohod AG, Parulekar YR, Yadav RP. Strategies to mitigate challenges in mechanization of grafting system for production of horticultural nursery – A review. *International Journal of Research in Agronomy*. 2026;9(9):1492-1498. doi: <https://www.doi.org/10.33545/2618060X.2026.v9.i9t.6723>