



AGRI. ENGINEERING

## ADVANCES IN AUTOMATION FOR PLUG SEEDLING CULTIVATION AND TRANSPLANTING IN GREENHOUSES: A REVIEW

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### ABSTRACT

The world food security needs the adoption of effective and sustainable agricultural practices, which is affected by factors like population growth, labor shortage, and rising production costs. Especially in vegetable farming that is an important source of nutrients is impacted. Plug seedling systems, where transplants are cultivated in regulated greenhouse conditions, have much to recommend them, such as lower establishment costs, more efficient resource use (water, nutrients, pesticides) and better uniformity of crops. However, cultivating and transplanting of these seedlings are laborious activities, which require precision. This review explores the critical role of agriculture automation technologies in solving such challenges. In particular, we review the results of the current automated solutions used along the plug seedling production chain, such as automatic seedling quality evaluation, machine vision-controlled robotics to monitor and grade quality, robotic, and automated transplanting systems. Analysis of the findings demonstrate that these technologies can be helpful in increasing productivity, maintaining high quality and greatly decreasing reliance on manual labor. Lastly, we recognize existing constraints and future trends in order to offer future research and development directions in the field of smart greenhouse automation.

**KEYWORDS:** Agriculture automation; smart greenhouse; automatic transplanting; machine vision; path planning; sustainable agriculture; Pakistan



### INTRODUCTION

The expected sustainable food security in the future demands progressive food production (Wang 2022) because the number of food consumers is extending (Maja and Ayano, 2021). Vegetables are the world wide primary source of essential nutrients (Zamborain-Mason *et al.*, 2025). The developing countries generate 72% of total vegetable yield (Dong *et al.* 2022). Enhancement in the demand of both qualitative and quantities demand of vegetable foodstuffs in the marketplace along with their desirable physical and organic characteristics are complex issues accompanying sustainable vegetable cultivation (Tansuchat *et al.*, 2023). While on other side, due to increase in vegetable production cost in both developed and developing countries, consumers have to spend more money to fulfil their nutrition requirements (Ampim *et al.*, 2022). Accordingly, the key issues deliberated above many academics have contributed their hard work to resolve these complications and it has been observed that both

qualitative as well as quantitative characteristics of the protected vegetable production system are higher in comparison with open field vegetable (Saadi *et al.*, 2025). The practice of growing transplants is gradually accepted by farmers due to its attractive attributes like decrease in establishment cost of vegetables, more effective use of nourishment, pesticide and irrigation water during early phases of vegetable growth, more specific controlled environmental conditions and isolated independent space availability for each individual transplant (Yang *et al.*, 2021). The growing charges of transplants in tray culture and controlled environmental conditions are a high, while the survival of seedlings against sacred situations is more and less transplanting loss due to orderly arrangements and mechanical handling is very easy (Sharma and Khar, 2024). In the seedling production system, manpower had an excellent position among the input parameters due to its thorough impact on capacity planning, job period arrangement, and scheduling. while it was experienced during previous research on large-

scale farming operations, it leads to increment in farming operational cost, shortage of available agriculture labor during peak farming season, and an absolute result of low agriculture output (Miah et al., 2023). The introduction of mechanization technology has been observed practically in every domain of human movement along with agriculture subdivision of both developed and developing regions of the world due to its attractive characteristics such as assistance on the solution of decreasing labor force, improvement in food quality and security, and operational accuracy and stability (Yang et al., 2018). In present era, the most significant part of automation technology is robotics and practical application of robotics in agriculture sector is not the concept of recent time, its applications have been observed in agriculture from the last 20 years (Ning et al., 2025). It is a well known practice in developed countries, transplants of different vegetables are grown in semi and fully control environment in a nursery and practical classification of seedling transplanting involved, transported seedlings from higher density to subordinate density plug trays, replaced unhealthy seedlings with healthy seedlings, filled non-germinated boxes of plug trays, and finally transplanted these seedlings into greenhouse or open fields for further

growth using a manually, semi-automated, and fully automated planting system (Ahmad et al., 2025). The diversifying trend of automation technology adopted in the agriculture sector is due to the day by day rapid addition of food consumers and in future agriculture have to nourished more individual (Yang et al., 2020). Moreover, the agricultural labor force is decreasing due to unpleasant working conditions in fields and attractive wages with pleasant working circumstances of nonagricultural industry (Bochtis et al., 2020). The application of robotics technology in agriculture having a history of 30 years and globally spreading in present age due to its strong computational power and cost reduction features (Khan et al., 2021).

#### **Atomized evaluation of seedling quality:**

A healthy and uniform size seedling is recommended for effective grafting and satisfying transplantation of vegetable nursery (Li et al., 2021), while it is natural the existence of unhealthy and uneven seedlings in tray pots due to wicked seed growth rate and environmental alteration, the average missing seedling rate varies from 5 % to 10% in China (Ahmad et al., 2021). Replacing unhealthy seedlings is essential to prevent the inefficient use of agricultural resources and inputs (Zhao et al., 2022) which increased germination rates

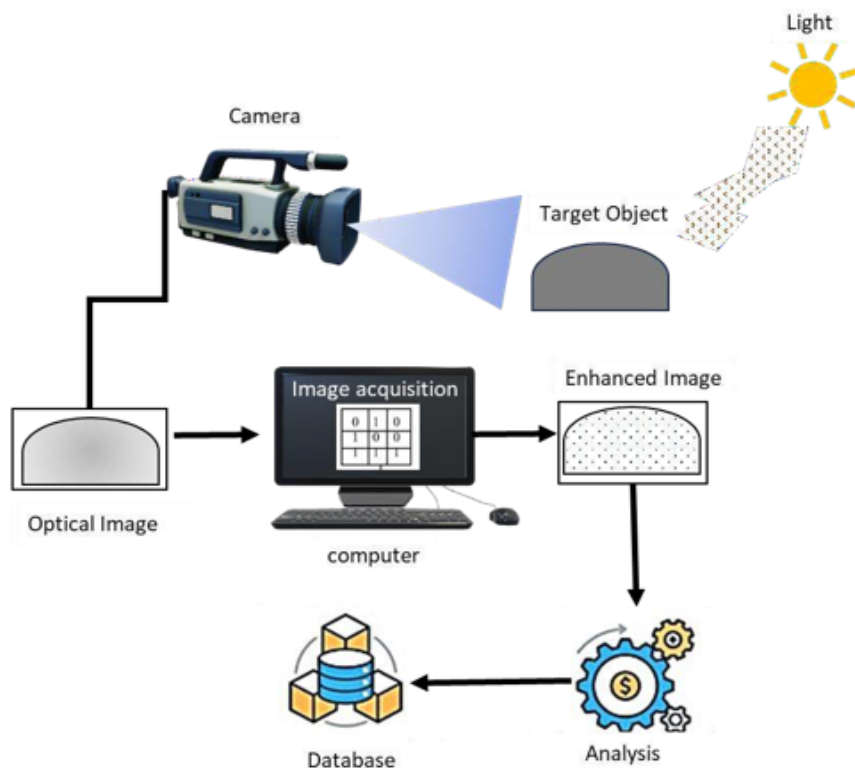


Fig. 1. Schematic view of the principal application of computer vision system in the plug seedling

range from 80% to 95% (Drăghici *et al.*, 2024). Different methods were adopted to recognize the healthy and unhealthy seedlings at the early stage of growing. Low-cost imaging, such as the chlorophyll fluorescence, can be used to measure seedling vigor among cultivars very fast. Such systems offer real-time performance information, and research has demonstrated that such systems have enhanced predictability between seeding and harvest (Iradukunda *et al.*, 2024).

**Application of machine vision technology in plugs seedling cultivation:** Machine vision is a reliable method for obtaining precise and detailed information from the physical appearance of objects (Liu *et al.*, 2023), and its fundamental working principle described in (Fig. 1). The objective of obtaining direct information from the physical characteristics of a target through processing and analysis is linked to various

algorithms and methodologies (Bai *et al.*, 2021). In traditional transplant cultivation systems, human vision serves as the primary means of assessing seedling quality. The replacement of substandard seedlings and the repair of empty trays are typically conducted manually. In contrast, automated transplant systems utilize computer-aided technology, which, due to its speed, reliability, and cost-effectiveness, is garnering significant attention from researchers, developers, and cultivators in the current era (Xu *et al.*, 2023). Computer vision system assembled on its two most imperative elements which are three-dimensional resolution and dynamic range. Mostly two types of image sensors (CCD and CMOS) are recommended for computer vision system while the application of vidicon tubes and charge injection device (CID) is also perceived but limited (Wen *et al.*, 2021).

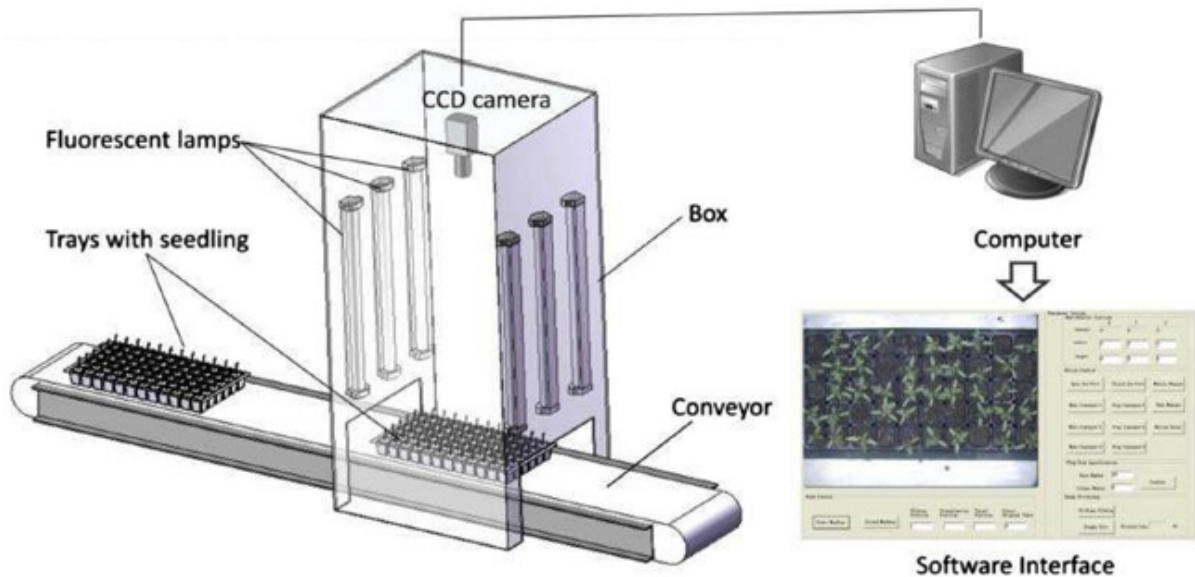


Fig. 2. Image acquisition system in plug seedling mechanism



Fig. 3. Image-processing procedures for leaf-area measurement

Two critical visual parameters, namely shape and size, are integral to assessing the visual quality of seedlings, which is essential for the effective application of machine vision technology in evaluating seedling quality (Zhang *et al.*, 2024). These parameters facilitate the straightforward identification of empty cells in seedling trays and the detection of unhealthy seedlings (Tan *et al.*, 2022). Current greenhouse environments offer both partially and fully controlled conditions conducive to the growth of vegetable seedlings. The production of knockoff plants in greenhouses has been extensively adopted within the agricultural sector. The process of production is facilitated by automation technology in plant factories. However, the smaller size and instability of small nursery plants have historically delayed the automation of the transplanting process, posing a challenge to the development of fully automated plant factories in previous research. The quality assessment of vegetable seedlings cultivated in greenhouses has been explored using image acquisition instruments (Hamidon and Ahamed, 2023). The quality assessment of seedlings can be effectively determined by examining their most relevant external characteristic, namely, leaf size. The measurement of leaf area serves as a determinant of seedling quality (Samiei *et al.*, 2020). The application of computer vision system for measurement of leaf area of seedlings has been observed in many conducted researches. The adoption of the plug seedling identification system is an example of remarkable technology in the agricultural field because the system relies on machine vision to identify vegetable plug seedlings accurately by their spatial features, such as stem leaves and plug bodies. The identification results are transferred to a programmable logic controller (PLC). By this system to handle processes like elimination of non-qualifying

seedlings and the provision of seedlings in an ongoing process (Zhang *et al.*, 2024). Moreover, the study of vegetable seedling size measurement by using stereo cameras and key points detection provides useful information on the non-contact methods of measuring size. The method involves the use of depth maps and pixel position computations to determine the diameter and length of vegetables which can also be extended to the study of leaf area (Zhang *et al.*, 2022). Machine vision technology in automatic transplanters was observed during past research examination for identification and the exact location of empty boxes of the seedling tray which is presented in the (Fig.2) (Tong *et al.*, 2013).

The development of a transplanting robot on the base of vision technology by using CCD camera and the success transplanting rate was 98%, with the assistance of machine vision technology done. Tong developed an automatic transplanting system having 96.2 % success rate by using CCD camera. Later on, he identified the quality of different vegetable seedlings on the base of leaf area with the help of machine vision technologies, identification success rate for tomato, cucumber and pepper were 98.6%, 96.4%, and 95.2% respectively. Non-destructive process of leaf area measurement is presented in (Fig.3) (Li *et al.*, 2022).

**Robotic based plug transplanting:** Vegetable plugs are germinated in a high-density tray due to some cultural and economic reasons, after optimal time period of seedlings germination it is a compulsory procedure to transfer these developed seedlings into the lower-density tray (Liu *et al.*, 2024). The critical process of transplanting plugs from high-density population tray to low-density population tray is extremely labor intensive and the issues of high labor cost and less accessibility of labor during extreme demand period

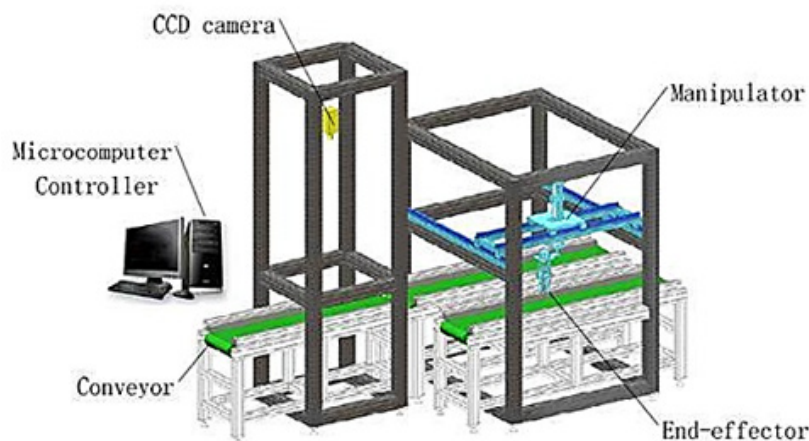


Fig. 4. Automated transplanter for plug seedlings in greenhouses

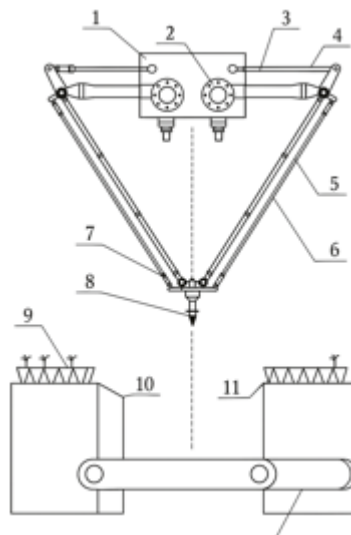


Fig. 5. Sketch of plug seedling transplanting robot. 1. Frame 2. Servomotor 3. Inner active arm 4. Outer active arm 5. Inner followed arm 6. Outer followed arm 7. Moving platform 8. Manipulator 9. Plug seedling 10. Supplying tray 11. Planting tray

of agriculture labor concerned with the commercial production of seedlings (Zhao *et al.*, 2022). Robotics technology for plug transplanting requires an extensive investigation because it is a vital influence to generate synchronization among standard quality transplants demand, labor cost, and management throughout the specific time of transplants cultivation.

The main parts of a robot automated system of transplanting plugs are the vision system, microcomputer controller, conveyor, manipulator and end-effector. The functional classification of these components is as follows: the vision system is charged with the responsibility of receiving visual information about the target location and forwarding the received information to the microcomputer controller. The microcomputer controller interprets and analyzes this data, and then sends commands to the manipulator and end-effector to perform the task of interest (Khadatkar *et al.*, 2025). In order to avoid the shared coming off among plug seedlings during the adjustment in orientation of seedlings for improved photosynthesis in appropriate lighting environment and at the time of plug seedlings transplanting, a monocular vision base technology was presented by (Yang *et al.*, 2014), with successful direction positioning rate of 94%. A prototype of automated plug transplanter with labeled is shown in Fig. 4 developed by (Yang *et al.*, 2017).

**End-effector development:** Different numbers of end-effector introduced in low-density seedling transplanting operation. An automatic transplanter facilitated with multiple end-effector was designed with the claim of

more efficient over transplanter equipped with single end-effector. China placed the highest position in vegetables production among all the countries of the world while the availability of agricultural labor is a prime issue, therefore, research on automation technology for vegetable seedlings transplantation is getting the intention of academics. The development of transplanter with transplanting rate of (20-25) seedlings/min (Liu *et al.*, 2023).

The perfection and innovation in computerized technology, an augmentation in the effectiveness of current vegetable transplanters and high working speed are the demanding constraints for cost-effective transplants cultivation. By bearing in mind the above-mentioned parameters (Hu *et al.*, 2014) technologically advanced a relatively high-speed plug transplanter (unit seedling/1.08s) used in the greenhouse on the base of the 2-DOF parallel transformation mechanism aided with the pneumatic manipulator shown in Fig. 5. The plug trays of different proportions and different categories of medium used for commercial cultivation of vegetable seedlings in a plant factory and as well as by home-grown farmers. The very initial phase in seedling growth is to place the seeds of specific vegetable in the relatively smaller size of seedling trays and then cultivators move towards the placement of these undeveloped seedlings into comparatively large seedling trays for the further growth (Han *et al.*, 2018). In conservative cultivation practices pragmatic in the greenhouse for vegetable seedling human hand is accountable for transplantation of

undersized seedlings from primarily grown medium to nucleus medium, while in comparison with modern age end-effector is indispensable element and reciprocal of hand in robotics transplanting system. End-effectors familiarized in automatic transplanting system have the competence of doing succession and reparative jobs which are clutch the seedlings, hold them strongly during operational conditions, successfully insert them at a targeted place and release the plugs with the accuracy of least mechanical and biological damages experienced by transplant seedlings (Han *et al.*, 2023). Different categories of end-effectors used in transplantation of seedlings in the greenhouse, on the base of picking mechanism end-effectors generally separated into two corresponding categories which are slide form fabricated with covered fingers and clamp form fabricated with naked fingers (Singh *et al.*, 2023). Comparative investigation of the working performance of these two types of seedling grippers designated that some adjustments and drawbacks are associated with both groupings. The gripping and holding performance of clamp type seedling gripper is more well-organized over slide type seedling gripper, while seedling saving performance slide end-effector is better than clamp end-effector (Li *et al.*, 2021). The assessment and comparison of performances were inspected in an experimental base study using three different types of end-effector which are vertical pin type, individual pin type and slope thrust pin type shown in Fig. 6 by mounting on the same seedling transplanter. By

considering this order of types the success rates were 100%, 87% and 100% respectively, while the slope thrust pin has superior characteristics of minimum effects on the roots and its medium (Kang *et al.*, 2012). Transplanting efficiency of plug seedlings practice depends upon two types of factors which are mechanical factors (penetration angle of gripper seedlings, plug extraction acceleration, and sensor sensitivity) and horticultural factors (vacant positions in plug trays, plant science, adhesion between roots and cell walls, root zone moisture, and the number of seedlings in one cell (Kwon *et al.*, 2021). According, the physical properties plug growing medium and extra forces responded on it, unsurpassed penetration angle of end-effector needles was deliberate with the assistance of development of a mathematical model and sleeve needle type end-effector was applied in this research in result plugs transplanting rate of 1800-2400 plugs/h achieved by (Cheng *et al.*, 2024). Advancement in the end- effector for additional development was carried out by Zhuo as shown in the (Fig.7), an innovative design of end- effector with output of 100% transplanting was introduced in plugs transplanting field of research by considering agronomic factors which are moisture contents present in the substrate, bulk density of substrate and proportional volume of the substrate ingredients for the exploration of the extrusion and adhesive forces during the transplanting process and destruction rate of transplanting of plugs was calculated 17% (Han *et al.*, 2025).

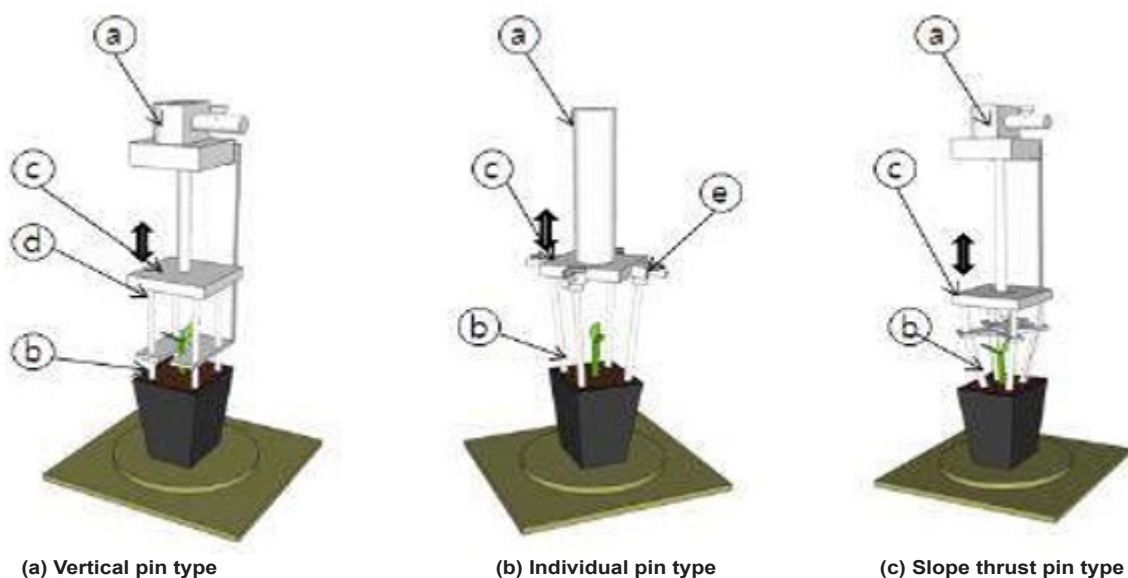


Fig .6. Different categories take-out devices of transplanting robot. Ⓓ Finger operating cylinder  
Ⓐ Pin Ⓒ Pin frame Ⓔ Hinge Ⓕ Pin operating cylinder

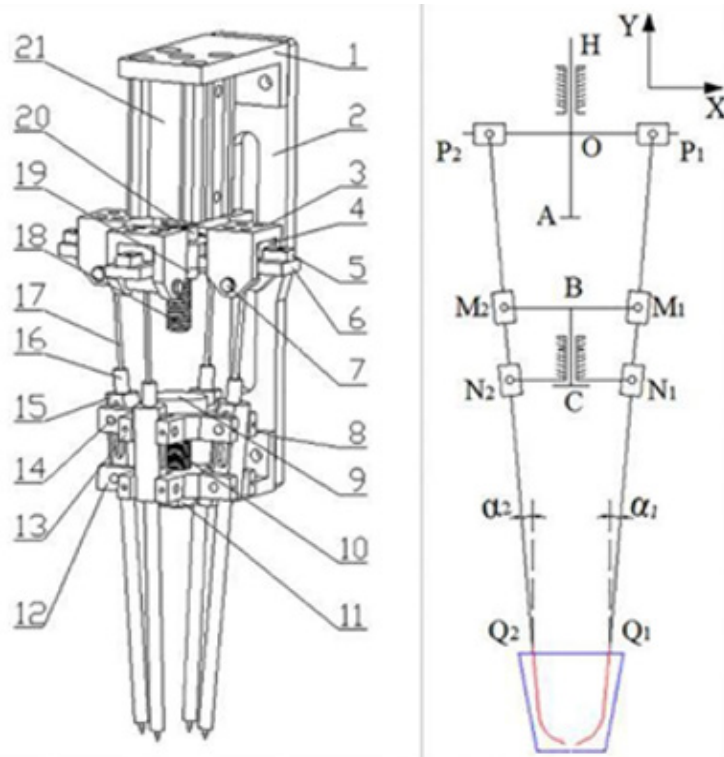


Fig. 7. The structure of the end-effector. 1. Upper Bracket, 2. Mounting Bracket, 3. Slide Sleeve, 4. Slider, 5. Sliding Guide, 6. Upper Cross Plane, 7. Spindle, 8. Lower Bracket, 9. Bolt, 10. Spring, 11. Hexagon Nut 1, 12. Bottom Cross Plane, 13. Middle Cross Plane, 14. Short Pin, 15. Rotation Part, 16. Slide sleeve, 17. Needle, 18. Thread Rod, 19. Hexagon Nut 2, 20. Hexagon Nut 3, 21. Pneumatic Cylinder

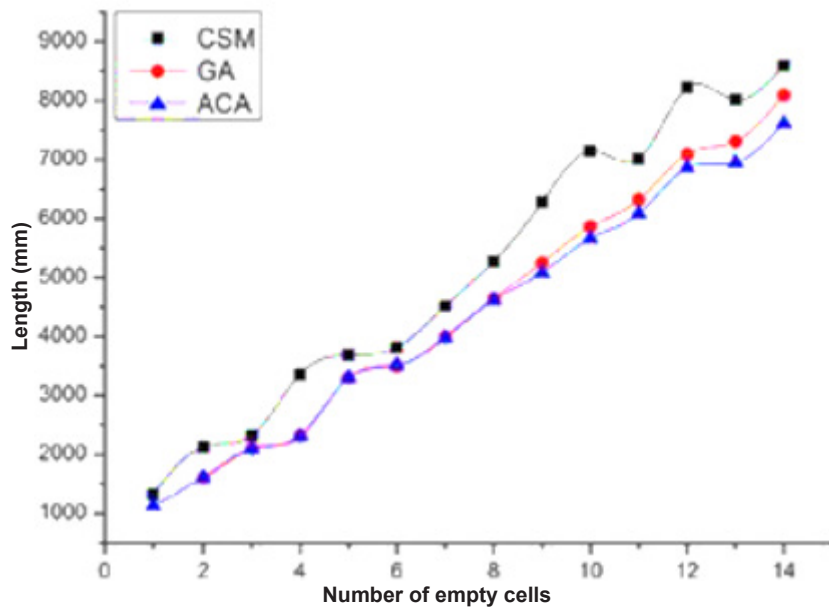


Fig. 8. Performances comparison of CSM, GA and ACA algorithms

**Path optimization for plug transplanting:**

Optimization in end-effector pathway planning for the anticipated working effectiveness of plug transplanting technology is compulsory due to the existence and expanding in scale of a collectively optimized the problem. The ultimate goal of present age intellectuals is a costly effective increment in the overall working efficiency of automatic plug transplanting system which can be facilitated by minimizing the time of re-plugging (Li *et al.*, 2022). Development of an ant colony algorithm and a genetic algorithm was premeditated with the objective of optimizing path planning of replugging robot used in seedling cultivation. Furthermore, comparative performance analysis was also considered in this investigation. The outputs of this prestigious research predicted that above-mentioned algorithms have clear superiority over common sequence method CMS applied in replugging tour planning of seedlings while the task completing efficiency of ACA is relatively higher than GA when considering the time period shown in Fig. 8 (Jiang *et al.*, 2015). Later on, further progress in the development of path planning optimization was observed by considering the orientation and movement of the seedling tray, and application of the greedy algorithm a new strategy was developed. To avoid unwanted increment in cultivation cost and improvement in low-density seedlings transplanter working efficiency a hybrid algorithm called GGA was developed with the combination of two well-known algorithms which are CA and GRA. On the base of results obtained from this research, it was predicted that GGA is a competitive method and have the capability of finishing its task in 2.82s which is less than GA required 9.61s for the same task (Tong *et al.*, 2017).

**Challenges and opportunities for adoption in developing economies:** In order to promote the use of advanced plug seedling automation in developing countries like Pakistan, a holistic approach that focuses on accessibility and localization is essential. Such strategy shall involve development and marketing of cost-effective scalable technologies, such as simplified semi-automated transplanters and open-source machine vision software, which can work effectively in regions where there is little infrastructure and limited finances. International cooperation between research organizations, technology transfer initiatives, and local agricultural agencies is necessary in order to tailor these solutions to particular regional crops, like tomatoes and peppers in the case of Pakistan, and to train local farmers and technicians. Also, pilot programs with governmental or non-governmental subsidies can be established to show the practical advantages and facilitate acceptance, which ultimately should increase

the productivity, reduce the burden on the labor market, and ensure the sustainability of vegetable production in these areas.

**CONCLUSION**

Plug seedling systems are a core element of modern, sustainable vegetable production that is implemented in controlled environments. This solution plays a significant role in improving food security around the world by improving resource use and increasing crop production. This review has shown that automation is not a future thing but a present solution to very important issues in the industry, namely, the increase in labor costs and shortages. The existing automated technologies, such as climatic control, machine vision to evaluate quality, and automated transplanting have shown evidence and measurable outcomes. These technologies have also significantly advanced operational effectiveness, labor requirements by performance of repetitive and accurate job and seedling quality and uniformity by use of consistent and data-driven processes. Despite the high effectiveness of current systems, there are some areas that have a potential to be further innovated. The prospects of the automation of plug seedling systems are subject to impact depending on the following prospects in the future:

- It is expected that future systems will extend beyond the simplistic image processing methods, and include deep learning algorithms that can identify the health of seedlings, identify sub-visible stress indicators, and process real-time choices on grading and sorting with greater accuracy.
- More sophisticated and sensitive grippers should be developed which can deal with delicate and variable seedlings without damaging them. The development would allow the automation of currently manually performed tasks, thus supporting more species.
- Fully integrated and intelligent greenhouse systems involve the combination of the data of autonomous environmental sensors, vision systems, and the robotic technologies into a single platform. This combination makes it easy to have closed control loop, whereby the environmental conditions are automatically regulated as per the real-time physiological conditions of the plants.

Finally, automation has already shown its revolutionary effects on plug seedling growth. The continued incorporation of robotics, artificial intelligence, and data science is expected to make vegetable production more accurate, resilient, and sustainable, which will ultimately lead to the creation of entirely autonomous greenhouses.




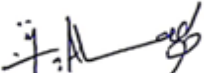
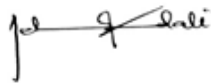
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3.	Bushra Saddique	Data collection and assisted the research work	
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