Automation in transplanting: a smart way of vegetable cultivation

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Vegetable transplanting is a labourious and time-consuming field operation when performed manually. The semi-automatic vegetable transplanters are cumbersome to operate due to limitations on manual feeding rates of seedlings which vary with respect to work duration and skill of the operator. Automation in the field of vegetable transplanters has provided opportunities for savings in labour and time required for transplanting operation in open field and controlled environmental structures, i.e. shade nets or poly-house. The advent and recent advances in transplanting technologies suggest ample scope of working on automated seedling pickup and drop mechanisms using robotics. Use of seedling pickup mechanism in automatic transplanters can repeatedly extract single seedling automatically from the seedling pro-tray with the help of a pair of pins or forks and drop at pre-defined location. In general, these systems comprise either a machine vision system or end-effector mechanism for extracting the seedling; gripper and a manipulator; indexing drum-type seedling removal device with ejector; or a pick-up system, feeding system and a planting system. Such automated systems have helped ease the transplanting operation and efficient planting of seedlings by maintaining the accuracy, precision and effectiveness in planting seedlings with minimum human intervention. This study highlights the research gaps and developments in smart transplanting technologies used in the field of vegetable cultivation.

Keywords: Agriculture, automation, smart farming, vegetable transplanting.

VEGETABLES are considered as one of the important food items of Indian diet without which any meal is incomplete. Due to this need, the cultivation and production of vegetables are increasing day-by-day. China stands first in the production of fruits and vegetables with 30% share, followed by India contributing 14% of the global vegetable production, both in terms of area and production. According to the Horticulture Statistics Division[1], the total area under horticultural crops is 10.106 million hectare (m ha) with production of 169.064 million tonne (mt). More than 70 types of vegetables are grown in India, and those like tomato, brinjal, chilli, cauliflower, cabbage, okra, onion, radish, carrot, garden peas and a few cucurbits are commonly grown. Vegetable production in the country has increased from a mere 16.5 mt in 1950–51 to 169.06 mt in 2015–16 mainly due to the introduction of hybrid varieties of vegetables and technological interventions in cultivation practices. However, the productivity of vegetables in India is as low as 16.73 t ha^{-1} (ref. 1) compared to the world average productivity, i.e. 18.8 t ha^{-1} (ref. 2).

Generally, seedlings of vegetables like tomato, brinjal, chilli, cabbage, cauliflower, etc. are raised in nurseries. Seeding and transplanting operations which are mainly performed manually account for 40% of total working hours of cultivation[3]. The traditional practice is to hold a bunch of seedlings/seedling tray in one hand, and separate seedlings by the other hand and press down the roots in the soil with bare hands. The work is drudgerious and laborious as the operation is done in a bending and squatting posture. The labour requirement in manual transplanting of vegetable seedlings varies from 180 to 420 man-hour ha^{-1}. As the vegetable crops are sensitive to higher temperature and require timely operations, transplanting should be completed as early as possible after removing the plants from the nursery. However, labour shortage during peak season causes delay in transplanting, leading to mortality of seedlings and eventually yield loss.

Status of vegetable transplanting

Manual transplanting

In India, vegetable seedlings are transplanted manually with the help of hand tools like spade, shovel or khurpi. However, some hand-held tools have also been developed by local manufacturers to ease the transplanting operation and reduce the drudgery involved in manual transplanting method. Few low-cost hand-held vegetable transplanters were developed having field capacity of about 0.02 ha h^{-1} and field efficiency of 82.3% (ref. 4), and transplanting rate of 15–17 seedlings min^{-1} (ref. 5).

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Mechanical transplanting

A mechanical transplanter should perform the following three functions: (i) open the soil in the form of narrow furrow; (ii) place seedlings vertically upright in it, and (iii) close and compact the soil around these seedlings without damaging them. The vegetable transplanters can be classified as automatic (AVT) and semi-automatic type transplanter (SVT). The existing systems developed are generally semi-automatic type which consists of either pocket-type, cup- or bucket-type or conveyor-type metering mechanism that uses bare root, plug or paper-pot-type seedlings for transplanting. According to the metering mechanism, the vegetable transplanter can also be classified into different types (Figure 1). Also, it has been observed that the existing system is costly, labour-intensive and has less field efficiency. The Bureau of Indian Standard (BIS) has not yet formulated test codes for performance testing of vegetable transplanters. However, based on the available literature, the limiting values for performance of vegetable transplanters can be classified as very good, good, satisfactory and inadequate (Table 1).

Semi-automatic vegetable transplanters: The walk-behind-type transplanters are available as an attachment to self-propelled prime movers or power tillers. As the operator has to concentrate more on feeding the seedlings manually into the cups, these types of transplanters are prone to miss feeding of seedlings at higher transplanting rates. The riding-type transplanters are generally tractor-operated and are available in 2–3 rows. Some developments in the field of SVT for vegetable seedlings have also been reported that uses bare root, plug or paper-pot seedlings.

Automatic vegetable transplanters: An AVT may be walk-behind or riding-type machines, which substantially reduce the labour requirement for feeding the seedlings[6]. The walk-behind-type transplanters are generally self-propelled whereas riding-type are either self-propelled or tractor-operated, where the number of rows is more than four. In India, AVT are not available due to either lack of appropriate technology at affordable cost to the farmer or the existing technologies do not completely serve the farmer's on field requirement.

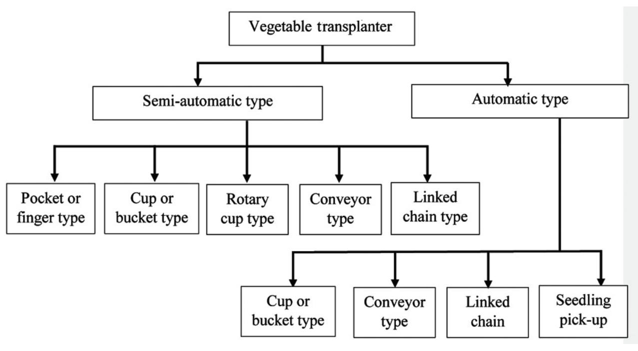

Figure 1. Classification of vegetable transplanter-based on metering mechanism.

Automation in vegetable transplanting

To ease the transplanting operation, different types of metering mechanisms have been developed for mechanical transplanters. These include pocket-type or finger-type, cup- or bucket-type, rotary cup-type, conveyor-type, linked-chain-type and seedling pick-up type mechanisms.

Pocket- or finger-type mechanism

A pocket-type metering mechanism is generally used for transplanting bare root seedlings in SVT, viz. eggplant, tomato, cabbage, cauliflower, celery, sweet potato, broccoli and lettuce. The unit consists of 6–12 spring-loaded pockets arranged at equal intervals on a drum.

Chaudhari *et al.*[7] developed a two-row semi-automatic tractor-drawn finger-type vegetable transplanter for transplanting bare root vegetable crops like tomato, brinjal, cauliflower, chilly, etc. Singh[8] reported two-row tractor mounted vegetable transplanter developed and evaluated at Punjab Agriculture University, Ludhiana for bare root seedlings (Figure 2). A pocket (picker wheel)-type metering mechanism was used, which was driven from the ground wheel of the transplanter. The plant spacing in a row could be varied from 30 to 60 cm by changing the sprockets or the number of plant pockets on the metering device. The per cent miss planting was found to be about 2.0–3.5 at a forward speed of 0.8–1.0 km h^{-1} depending on plant spacing in the row and skill of the operator. An optional bed-forming attachment

Figure 2. Pocket-type tractor drawn two-row semi-automatic vegetable transplanters[8].

Table 1. Performance criteria for mechanical vegetable transplanters

Classification	Field efficiency (%)	Transplanting efficiency (%)	Miss planting (%)	Multiple planting (%)
Very good	>75	>90	<5	<5
Good	65–75	80–90	5–10	5–10
Satisfactory	55–65	70–80	10–15	10–15
Inadequate	<55	<70	>15	>15

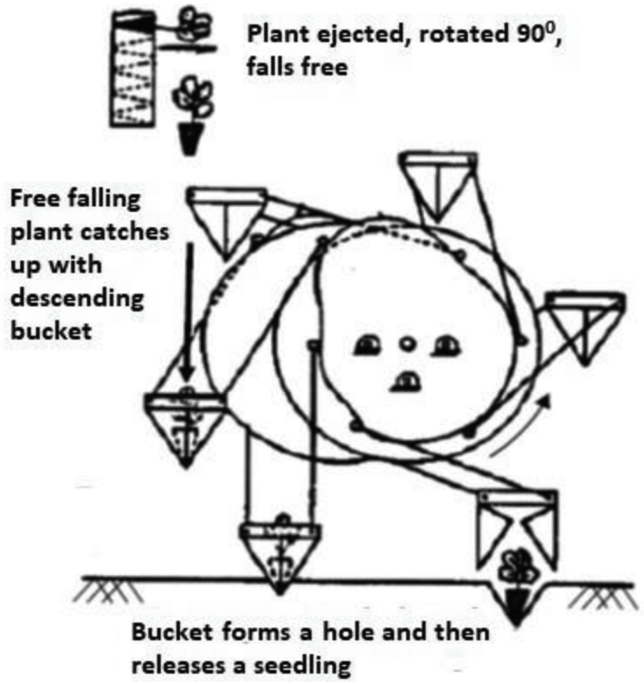

Figure 3. Cup-type mechanism of dibbling transplanter for planting vegetable seedlings[10].

was provided with this machine so that both bed-forming and transplanting could be accomplished in a single pass leading to saving of time, energy and labour.

Kazmeinkhah[9] designed a steckling-type SVT for sugar beet. It was found that, the transplanter could place the steckling with a row spacing of 65 cm and a plant spacing of 50.3 cm at a chosen depth of 13 cm. Deviation of the steckling placements relative to their theoretical positions was 4.5% and 3.6% respectively, along the row and in a direction perpendicular to the row. The required draft was 4.05 kN at a forward speed of 0.6 km h^{-1} and a maximum planting depth of 18 cm.

Cup- or bucket-type mechanism

The cup- or bucket-type metering mechanism is generally used for transplanting plug or potted seedlings in SVT and AVT, viz. eggplant, tomato, chilli, etc. The unit consists of a conical cups, delivery tube and soil compaction wheel. The conical cups were attached on the drum, which is driven with a soil-compacting wheel. Munilla and Shaw[10] developed a high-speed dibbling transplanter that extracts seedlings directly from a commercial growing trays (Figure 3). The functions of dibbling the holes, withdrawing and depositing the plants were all accomplished at zero relative velocity.

Brewer[11] developed an experimental single-row AVT which dropped bare-plug seedlings from shipping modules into rotating dibbles through static cassettes. The transplanting rate was reported to be 60–300 seedlings min^{-1} with 300 mm of plant to plant spacing. It requires short and sturdy seedlings for transplanting. Imad[12] developed and evaluated a single row transplanter carried by a 45 kW tractor and utilized a feeding belt system to facilitate the establishment of bare-rooted or block transplants.

Rotary cup-type mechanism

The rotary cup-type metering mechanism is generally used for transplanting plug or potted seedlings in SVT, viz. tomato, cabbage, cauliflower, celery, lettuce, chilli, etc. The unit consists of a horizontal rotating shaft, cups attached in a circular fashion, delivery tube and soil compaction wheel. The seedlings are fed manually into the delivery tube.

Choon[13] reported that the Japanese-made walk-behind-type single-row SVT powered by a 2.25 kW petrol engine was suitable for the ridge planting of plug seedlings of chilli on plastic mulches. The transplanter was provided with a rotating cup-type metering device having 6–8 cups attached in a circular fashion on a shaft rotating in a horizontal plane. As the shaft rotated, the cups were fed with seedlings; then the seedlings were carried to the bottom of the cup which opened and dropped them in the furrow. The row and plant spacing in a row could be adjusted in the range 0.8–1.0 m and 0.35–0.6 m respectively.

A tractor-mounted SVT developed by Cráciun and Balan[14] was evaluated for transplanting of pot seedlings of tomato, chilli, cabbage, broccoli, onion and watermelon. The transplanting rate was 60–80 seedlings min^{-1} per row with minimum row spacing of 30 cm. A minimum plant spacing of 9.5 cm in a row for onion to maximum plant spacing of 63.3 cm for watermelon was reported. Hayashi *et al.*[15] developed a SVT for chrysanthemum cuttings with a supply mechanism using rotating cups (Figure 4).

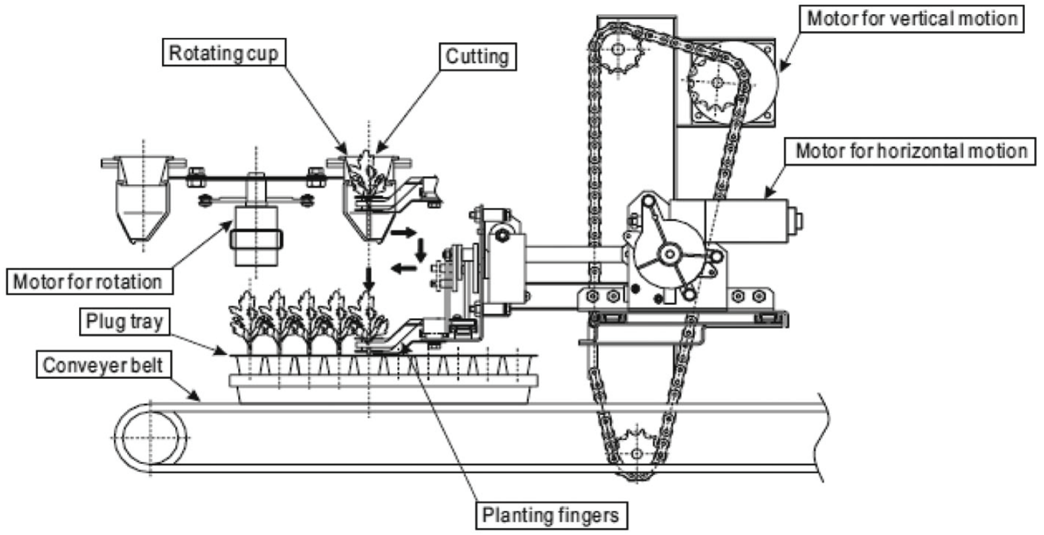

Figure 4. Rotating cup-type mechanism used by standard model for planting vegetable seedlings[15].

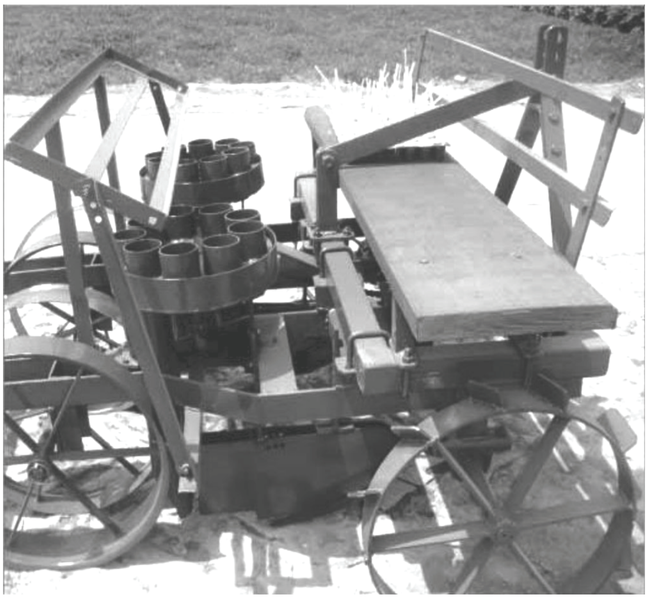

Figure 5. Tractor-drawn two-row revolving magazine type SVT[16].

Two models were developed: a standard model for chrysanthemum cuttings with no lower leaves, and a model that automatically removes the lower leaves. In laboratory and field experiments, the first model had a failure rate of 0.5–3.1% and increased the maximum work efficiency to 2.4 times that of manual planting. The second model had a failure rate of 0.8–4.5%, but also increased maximum work efficiency to 2.4 times that of manual planting.

Narang *et al.*[16] developed a two-row vegetable transplanter with revolving magazine-type metering mechanism (Figure 5) and evaluated it on field for brinjal crop. The brinjal seedlings were grown in 98-cell (single cell volume of 22 cm^3) plug trays in soil-less media. The per cent miss planting varied from 2.22 to 4.44. For the plants transplanted upright with planting angle $<30°$ the depth of planting ranged between 50 and 60 mm and plant mortality, 20 days after transplanting was reported to be 3.33–4.0%.

Conveyor-type mechanism

The conveyor-type metering mechanism is generally used for transplanting potted seedlings in SVT and AVT, viz. tomato, cabbage, celery, broccoli, etc. The unit consists of a horizontal belt-conveyor and soil compaction wheel. The belt is either plain or has a series of cross-wire partitions on which seedlings are placed. The belt conveyor is driven from the ground wheel of the machine using a chain drive.

The plug seedlings are placed in batches by hand on a horizontal (feeding) conveyor with cross-wire partitions and delivered to split cone cups[17,18]. Feng *et al.*[19] described the development of 8.8 kW four-wheel drive tractor-powered fully automatic 2ZG22 transplanter available in China. The seedling tray carries 100 seedlings with ten seedlings in each row. During the operation, a single row of 10 plug seedlings from the tray is aligned with the belt conveyor and the operator pushes the seedlings to the belt conveyor. The seedlings are carried forward by the belt conveyor to the metering device which blocks and then releases the plug seedlings in accordance with the timing set using a cam-operated controller to obtain the required plant spacing in the row.

Kumar and Raheman[20] developed a 9.75 kW walk-behind-type hand tractor powered two-row fully AVT for individual paper-pot seedlings (Figure 6). The vegetable transplanter carries 108 seedlings on two feeding conveyors in upright orientation, which supply them to the metering conveyors to be planted in an upright orientation in furrows.

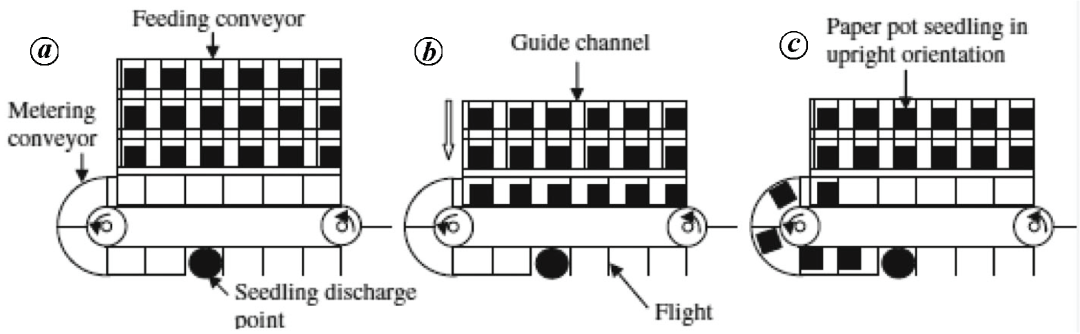

Figure 6. Conveyor-type metering mechanism for two-row walk behind hand tractor automatic vegetable transplanters. ***a***, Arrangement of seedling on feeding conveyor. ***b***, Feeding of seedling to conveyor. ***c***, Continuous conveying of seedling towards discharge point[20].

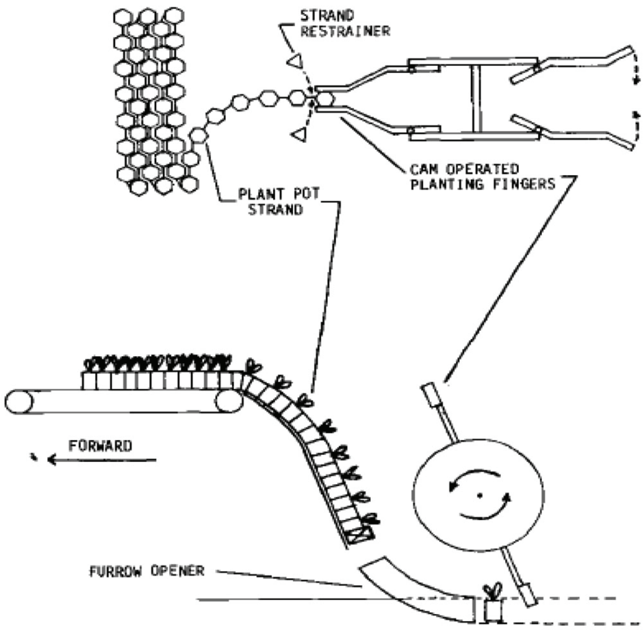

Figure 7. Linked chain-type mechanism for self-feeding transplanter used for plants grown in honeycomb cells or paper pot seedlings[24].

Linked chain-type mechanism

The conveyor-type metering mechanism is generally used for transplanting potted seedlings in SVT and AVT, viz. tomato, cabbage, celery, broccoli, etc. These pot seedling are linked together by a continuous chain or grown in hexagonal paper tray, and the system is dragged manually or by a power source[21–23].

Suggs *et al.*[24] reported the working principle of two proprietary machines for transplanting strand of paper-pot seedlings (Figure 7). The machine (Ferris wheel transplanter) grips the seedlings between a pair of hands which then rotates in Ferris wheel fashion into the furrow and release the seedlings. It can be operated well at planting rate of 100 seedlings min^{-1}. The other machine (roll feed transplanter) feeds the strand of seedlings between a pair of feed rollers and into a rapidly rotating pair of accelerator rollers which break the strand between the seedlings and propel them into the drop tube. The planting rate of this transplanter is 140 seedlings min^{-1}. Tsuga[3] developed three models of two-row riding-type AVT. These prototypes were suitable for cell mould seedlings and pulp mould cell pot seedlings of cabbage, Chinese cabbage and lettuce. The annual use and break even area transplanted in Japan was reported[3] to be 53 and 8.2 ha $year^{-1}$, respectively.

Seedling pick-up type mechanism

The most advanced type of vegetable transplanter uses robotics, where the pick-up mechanism is mostly controlled with electronics in AVT. This type of mechanism is gaining attention for efficient planting of seedlings and maintaining accuracy, precision and effectiveness in planting them with minimum human intervention. Here, seedling pick-up is an important concept, where a single seedling is extracted automatically from the tray with the help of a pair of pins or forks, then discharged into the furrow and again retracted to its starting position. This type of mechanism uses computer graphics or machine vision system and end-effector mechanism for extracting the seedling[25,26]; gripper and a manipulator[27–29]; indexing drum-type seedling removal device with ejector[30,31], or a pick-up system, planting system and feeding system (Figures 8 and 9)[32–36].

Human performance in transplanting operation

The performance of the transplanting operator is affected by the man–machine interaction and is an important consideration for evaluating the machine. The performance has been quantified in terms of number of seedlings fed, number of seedlings missed, body part discomfort score, mental fatigue, etc. These human factors affect the design of the machine and therefore, have been studied by researchers.

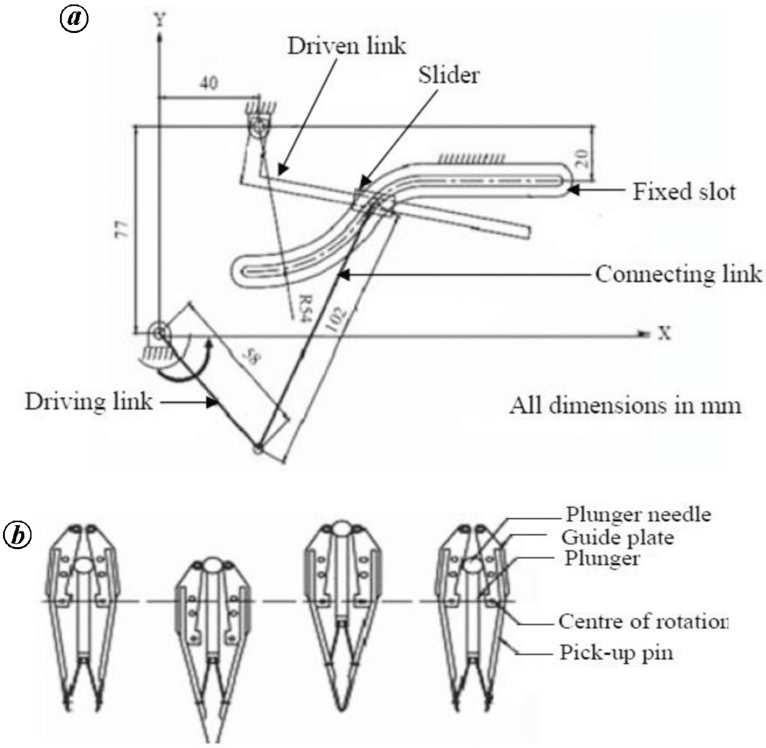

Figure 8. ***a***, Five-bar mechanism for seedling pick-up mechanism[34]. ***b***, Pin driver for seedling pick-up[34].

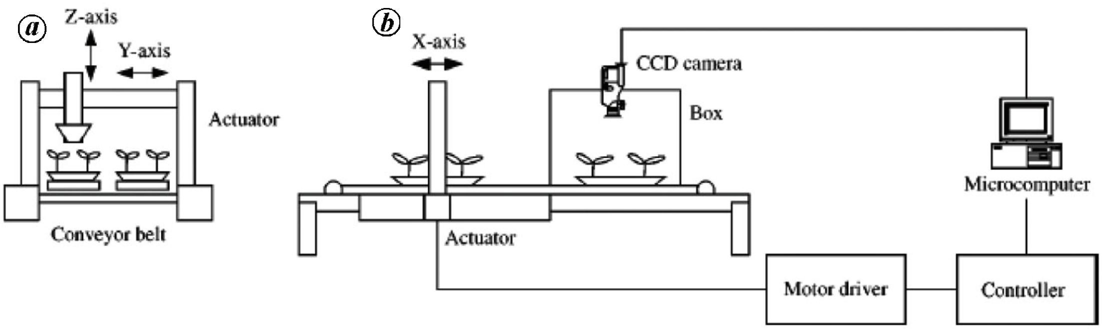

Figure 9. Schematic diagram of the robotic transplanter: (***a***) front view of the manipulator and (***b***) side view of the manipulator, tray moving system and vision system[33].

The semi-automatic potato planter reported to have both physical as well as mental load on operators which increases with increase in planting frequency. However, increase in operation time resulted in increase of only mental fatigue[37]. Singh[38] conducted ergonomic study on the operators's seat height with respect to seed hopper, seed rate and duration of work on physiological parameters like heart rate, pulmonary ventilation rate and metering performance in terms of missing and doubles. It was found that the feed rate and duration of work had a linear relationship with physiological parameters and the number of missing and doubles. The height of the seat with respect to the metering drum for an inclined angle of 130°–135° between the fore arm and upper arm caused less fatigue to the operator. Dixit[39] conducted study on feeding operation to know the effect of vertical and horizontal location of operator's seat with respect to hopper position, different forward speeds and physiological parameters, viz. heart rate, pulmonary ventilation rate and stress on eyes of the operator. It was concluded that the seat should be located such that the angle between the thigh and lower leg should be close to 75° so that it does not cause obstruction during potato feeding.

Jadhav[40] conducted ergonomic studies to determine the effect of subjects, vertical distance of operator's seat from ground, horizontal distance of operator's seat with respect to rotary finger and speed of operation on physiological response, i.e. heart rate, muscle potential and

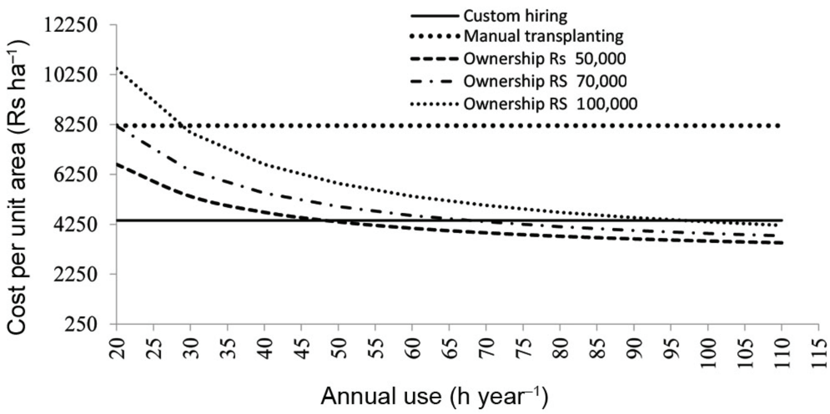

Figure 10. Break-even analysis of two-row tractor-mounted transplanter (having different initial costs).

psychological response, i.e. stress on eyes for rotary finger-type transplanter. It was concluded that the most comfortable arm posture (angle between upper arm and lower arm was 90°) was at minimum arm reach with middle seat position. Minimum stress on eyes was observed at middle seat position due to ease in locating the rotary fingers. However, miss transplanting increased from 0.11% to 9.06% with increasing forward speed (0.5–1.5 km h^{-1}). It was concluded that optimum operating parameters were forward speed of 1 km h^{-1}; vertical distance of operator's seat from ground of 750 mm and horizontal distance of operator's seat with respect to rotary finger equal to half arm reach.

Cost economics

It is important to determine and optimize three major cost factors, viz. material, overhead and labour costs, to maintain economy of an operation process. In manual vegetable transplanting operation, labour cost is the only major operating cost[41] and therefore, mechanized vegetable transplanting reduces the cost of transplanting vegetables by reducing the number of man-hours needed to accomplish same amount of work. However, fixed cost such as initial cost of the transplanter, depreciation, its operating cost and variable cost decide the break-even point of minimum annual use to justify ownership of the transplanter. The labour rates prevailing across various states for both genders vary widely from a Rs 167 to 259 (US$ 2.5 to 3.9)[42] for unskilled labour and Rs 200 to 350 (US$ 3.0 to 5.4) for tractor drivers[43]. Considering the average labour cost of Rs 235 (US$ 3.6) per day and 220 man-hour ha^{-1} for transplanting of seedlings, the total cost of manual transplanting is about Rs 8250 ha^{-1}. The tractor-operated transplanters developed in India have an average initial cost of Rs 50,000 (US$ 770). Considering depreciation, interest rates, other fixed costs according to Indian Standards (IS): 9164 (ref. 44), and average wage of a tractor driver as Rs 300 (US$ 4.6) per day, the break-even point for ownership of machine versus custom hiring services is calculated to be 47 h of annual use. Considering average range of initial cost variations depending on profit margins by manufacturers, structural design variations and accessories, the initial cost may range from Rs 50,000 to 70,000 (US$ 770 to 1080), thereby shifting the break-even point to 67 h of annual use of the machine (Figure 10). Even if an AVT capable of automated metering at the same rates of manual feed transplanter is considered with an estimated cost of Rs 1 lakh, its use is justified with minimum annual use hours of 28 h against the present manual transplanting rates. Thus, efforts to develop an AVT need emphasis for higher effective field capacity and optimum use of tractor power.

Constraints

In India, one of the major constraints in increasing vegetable productivity is the low level of mechanization[45]. Mechanized cultivation, along with other improved crop-production practices, can increase crop yield and quality. One cultivation practice that would benefit from mechanization in vegetable production is transplanting of seedlings of tomato, eggplant, cabbage, cauliflower and chilli, among others[46]. Manual transplanting on a large commercial scale is labour-intensive, expensive and often does not result in uniform distribution of plants compared with mechanical transplanters[47]. Feeding of seedlings to the delivery unit is difficult for bare root seedlings due to singulation, selection, alignment and manual transfer of seedlings[24].

Vegetable transplanting should always be done in the evening so that plants establish in the cool weather at night and recover from the shock of transplanting before the next morning. In addition, transplanting should be completed as early as possible after removing the plants from the nursery[48]. Vegetable crops are sensitive to fluctuation in weather conditions and thus require timely operations. However, labour shortage during peak season causes delay in transplanting, leading to drastic reduction in yield[7]. The manual transplanting work is labour-intensive and tiring because the operation requires bending/sitting and squatting postures. The transplanting in bending posture requires extra energy expenditure of about 8 kJ min^{-1} and increases the heart rate by 51% (ref. 49). Vos[50] observed that the bending posture followed in paddy transplanting has a harmful effect on the spinal cord of the workers. It also required extra energy expenditure about 2 kcal min^{-1} and increased the heart rate by 35%. Similar bending postures are also observed in manual vegetable transplanting operation. The manual transplanting also causes muscular fatigue to the operator due to long duration of squatting posture. Thus, transplanting is a tedious, time-consuming and expensive operation which needs mechanization.

Conclusion

It is evident from the literature that the pocket-type metering mechanism for bare root seedlings and rotary cup-type metering mechanism for plug and pot seedlings have been successful in SVT. As the seedlings are manually fed to the metering devices, the performance of the metering device (i.e. per cent missed planting) is mainly dependent on the forward speed of the machine. AVTs require uniformity in the growth of seedlings and root soil of the seedlings with respect to their size, shape and firmness. Feasibility of several seedling-removal or pick-up devices has been tested in the SVT for plug seedlings with a view to overcome the variability in size, shape and orientation, and resistance to singulation (entanglement) of seedlings. The reported success rate of the devices under field conditions varied from 96% to 98%. The mechanical seedling removal from the tray facilitated higher rate of metering of seedlings and planting in AVT. Therefore, AVT could be operated at higher forward speed than SVT.

A review of the literature also suggested that the existing vegetable transplanters developed have low field efficiencies. It was observed that the labour requirement for transplanting with single-row machine was higher than traditional practice, which is due to low machine capacity. The operating speed of the machine is limited to 1 km h^{-1} to avoid miss planting and thus results in low field capacity. This suggests ample scope of working on automated metering mechanisms for vegetable seed pick-up and drop by the use of robotics in agriculture. Research on developing automated seedling feeding mechanisms can increase the number of transplanting speeds, thereby utilizing the tractor power effectively and reducing cost of cultivation. Further research should be carried out to eradicate the bottlenecks present in systems available till date for enhancing the adoption level of mechanization.

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