Comparative analysis of a novel onion transplanter for bare-root seedlings against traditional cultivation techniques

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Abstract: The demand for onion is increasing day by day across the world because of its medicinal properties and population pressure. The main concern is the availability of sufficient onion throughout the year. Productivity is negatively affected by poor mechanization in seed sowing and handling of onion seedlings due to untimely sowing and poor bulb growth. In order to improve mechanization in handling bare-root onion seedlings, a single-row prototype mechanical onion transplanter (TMch) was developed. The performance of the developed unit was compared with existing onion cultivation techniques. The TMch method offered superior and uniform plant spacing compared to existing methods such as mechanical planting (SSP) and manual seed sowing (SSM), facilitating the conservation of expensive onion seed and vegetative propagation growth of onion bulbs through enhanced nutrient availability and soil space utilization. This study also exhibited that the developed transplanter offered a better onion seedling survival rate (92%) with an above-average onion weight as compared to SSP and SSM methods, but recorded lower than that of the manual transplanting (TM). The TMch method also provided more reliable results with respect to onion size distribution. Findings concluded that the prototype onion transplanter has sufficient potential to increase onion productivity by improving the level of mechanization in dealing with bare-root onion seedlings. The main issue found in this study was the separation of bare-root onion seedlings, which required substantial time and the need for a more automated approach to onion seedling separation.

Keywords: mechanical onion transplanter, bare-root onion seedlings, cultivation techniques, cured onion
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1 Introduction

Onion contains a series of fleshy layers and is covered with a thin protective tunic layer, and is found mainly in round to oval shapes. The demand for onion is increasing across the world due to its high pungency, nutritional value[1,2], and the growing population. However, onion cultivation is generally done manually, resulting in improper seedling spacing and intensive competition for available nutrients. Late sowing and poor onion bulb growth collectively affect the productivity and production. In manual onion cultivation, researchers[3,4] reported the problem of intensive labor requirements for transplanting (185-260 man-h/hm^2[5]; 400 man-h/hm)^2[6] and higher amount of seed needed.

In order to improve onion productivity, total onion production, and reduce over-dependence on intensive labor requirements, mechanization in onion cultivation is essential. However, mechanization can be done for two cases: first, machines having well-designed metering mechanisms for direct sowing of onion seeds; and second, machines for transplanting onion seedlings.

A number of studies have been conducted on machines for sowing onion seeds to ensure timely sowing, appropriate seed-to-seed spacing, and to reduce the labor requirement[7-9]. Researchers have designed various tractor-drawn equipment with metering mechanisms for the direct sowing of onion seeds (vertical rotor cell type[3]; inclined plate type[8]) and reported potential results indicating reduction of total labor requirements and high field capacity as

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compared with that of the manual seeding methods. However, under these developments, the low germination percentage and poor growth of onion bulbs were observed, eventually leading to low onion production and productivity. In addition, these developments fail to address the issue of higher onion seed requirement. As a result, it is economically non-viable for farmers due to the high cost of onion seed.

Many studies have focused on seed pelleting to produce seed of appropriate uniform size and shape. Seed pelleting is useful in onion-like small seeds, and pelleted onion seeds can be used in adjustable pneumatic planters to achieve precise seed spacing and depth in field[10,11]. Better precision using these planters can be achieved by optimizing vacuum pressure, speed, and orifice size through multiple laboratory experiments[12] or using the seed properties in the mathematical equation developed by Mahapatra et al.[13]. However, seed pelleting is an additional process needed to be done for pneumatic precision planting, which increases seed price. Besides this, the field needs to be inspected after germination and manual placement of seeds, or seeding is required where germination fails. However, the problems associated with machineries engaged in direct seeding of onion seeds may be addressed by transplanting onion seedlings with transplanting machines. Researchers have attempted three types of seedlings, namely bare-root type, plug type, and pot type seedlings, in mechanical transplanting[14-21]. An eight-row semi-automatic onion transplanter was developed by More[22] for bare-root onion seedlings with remarkable field capacity. Turbatmath[18] tested a semi-automatic onion transplanter with two different types of mechanisms named as plug and finger type mechanism. Findings revealed a field efficiency of more than 70%, with a missing percentage of up to 10%. In addition, a six-row semi-automatic plug metering type transplanter developed by scientists[23,24] recorded a field efficiency of more than 75% with appropriate seedling spacing of around 125 mm. In commercially available transplanters and in previous studies[18,22,23,25], most of the onion transplanters are semi-automatic type, which deal with plug type or pot type onion seedlings, reduce labor requirements, and offer high field efficiency, but in these systems, human sitting arrangement was essential for seedling singulation and their effective delivery. Manual seedling arrangement limits the operational speed of the systems in the field, leading to poor field efficiency, and negatively impacts the environment by carbon emissions. Additionally, these systems cannot maintain uniform seedling-to-seedling spacing, leading to lower onion productivity and production. The uniformity of seedling spacing is highly dependent on skill of the workers, who continuously regulate onion seedling singulation while sitting on the machine. This type of working arrangement and repetitive continuous movements, especially at higher operational speeds, may be hazardous to human health. To overcome the above-mentioned issues, certain automatic transplanters were developed[20,21,26,27] to replace human intervention in seedling singulation. The automatic transplanting system developed by Li et al.[21] included a follow-up seedling picking and depositing mechanism for paper plug seedlings. It synchronized seedling-picking claws with the moving seedling cups and ensured relative spatial stillness during seedling deposition, significantly enhancing seedling deposition accuracy. Magar et al.[20] analyzed a vegetable automatic transplanter for plug type seedling based on a newly designed automatic plug-tray seedling extraction device. Its seedling extractor performed optimally at an extraction rate of 38 seedlings per minute, bulb moisture content of 75%, and needle penetration depth of 30 mm. However, these automatic onion transplanters have a complex working mechanism, initial high cost, and need expertise to handle. Additionally, these transplanters generally deal with pot type and portray or plug type seedlings, and human intervention is required for the seedling tray replacement. In developing countries like India, bare-root onion seedling is preferred by small and marginal farmers, where these developed onion transplanters are unfit to work. Thus, this highlights a clear research gap for the development of a low-cost onion transplanter, which can deal with bare-root onion seedling and eliminate human intervention, specifically for seedling singulation.

Therefore, a novel magazine-based transplanting mechanism for onion cultivation was designed and developed by considering the morphological characteristics of the bare-root onion seedling and to remove human intervention in seedling singulation. Specifically, it was designed to meet the demands of small and marginal farmers and to deal with bare-root onion seedlings, which was a major issue with most of the available onion transplanters. The major aim of the study was to evaluate the developed onion transplanter for assessing performance attributes compared to three other onion cultivation techniques, and to test its accuracy and efficiency in the field. The novelty of the developed system lies in its ability to address key research gaps by removing human interference in seedling singulation in semi-automatic systems and overcoming the challenges associated with handling bare-root seedlings in most of the automatic onion transplanters.

2 Material and methods

This study was conducted in the clayey (vertisol soil) field (23.312 98°N, 77.404 63°E) in 600 m^2 area at ICAR-Central Institute of Agricultural Engineering Bhopal, in rabi season of 2019. Experimental plots for each treatment were randomly selected within the field to remove the impact of the biasing factor. The onion sample of cultivar *Fursungi* (KSP 117) was used for the entire experimental plot under four different planting methods, i.e., manual transplanting (TM), mechanical transplanting (TMch), mechanical planting (SSP), and manual seed sowing (SSM).

2.1 Detailed description of selected onion cultivation techniques

Transplanting and direct seed sowing methods are the most prevalent cultivation practices used for growing onion crops. They include mechanical planting (SSP), manual seed sowing (SSM), manual transplanting (MT), and mechanical transplanting (TMch).

2.1.1 Manual seed sowing (SSM)

In this method, furrows were manually constructed in the field, into which the seeds were attentively placed at specified intervals and promptly covered by hand, as shown in Figure 1a. An appropriate seed-to-seed spacing was highly dependent on the laborer's sowing skill. However, onion seeds are very small in size, which leads to difficulty in delivery at the right place and maintenance of uniformity in seed placement. Hence, thinning operation becomes essential to achieve optimal spacing for bulb maturation[28]. In this research, all pertinent parameters at the initial seed-sowing stage and final onion bulb-harvesting stage were meticulously recorded and subjected to analysis.

2.1.2 Mechanical planting (SSP)

An existing commercially available tractor-operated inclined plate planter was used for direct sowing of onion seed in the field as shown in Figure 1b. The planter consists of an inclined plate metering unit (six rows), baffle plate to maintain constant flow of the seeds, ground wheel to impart rotational motion to the metering plate, and roller for covering the seeds. In addition, six separate boxes were provided for each furrow opener. To minimize the need for frequent refilling of seed boxes, one kilogram of seeds were filled in each box. The sowing operation was then carried out in the randomly selected plots. The parameters like field capacity, seed-to-seed spacing, survival rate, and labor requirement were collected initially. Onion bulb-related parameters were recorded at the final mature stages for analysis.

a. Manual seed sowing (SSM) b. Mechanical planting (SSP) c. Manual transplanting (TM)

Figure 1 Different cultivation methods of onion adopted in the field

2.1.3 Manual transplanting (TM)

The traditional method of onion cultivation in remote areas relies heavily on manual transplanting. In this method, onion seeds were sown on the selected area for nursery purpose and the delicate onion seedlings were diligently nurtured. The mature onion seedlings (age: 6-8 weeks) were used for manual transplanting, as shown in Figure 1c.

2.2 Conceptual design and development of prototype mechanical transplanter

2.2.1 Design requirement of bare-root onion seedling transplanter

To assure the correct operation of the developed onion transplanter, the design of its critical components, i.e. magazine, metering and dropping system, is essential. These components are directly associated with handling, conveying, and delivering of bare-root onion seedlings. Therefore, morphological characteristics of bare-root onion seedlings were assessed prior to design of the mechanical transplanter. Evaluated morphological features were used for design of critical components, reduction of failure risk of the mechanism, and simulation of machine-seedling interaction in a precise manner.

2.2.2 Morphological characteristics of onion seedlings for transplanter design

Morphological properties of onion seedlings like height, diameter, and canopy of seedlings are crucial, hence it should be considered for the design and safety of transplanting machine, as suggested by researchers[23,29-34]. Similarly, guava morphological characteristics like leaf area index were considered for the optimization of a designed novel spraying system[35,36]. These studies suggested that morphological characteristics cannot be ignored in the design of most agricultural machines. Therefore, the morphological characteristics (height, stem diameter, bulb diameter) of bare-root onion seedlings (variety: KSP 117, seedling age: 30-70 d) were studied as shown in Figure 2. The recorded morphological parameters of onion seedling are presented in Table 1. These parameters were used to design the magazine or cassette and the dropping system of transplanter.

a. Morphological features of seedling b. De-topped seedlings c. Property measurement

Figure 2 Bare-root onion seedling and its measurement

Table 1 Morphological properties and their range

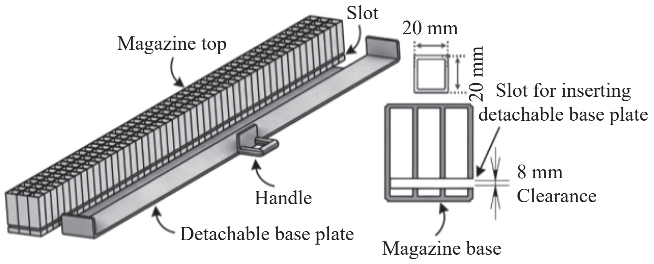
Morphological properties	Measured value	
	Minimum	Maximum
Bulb diameter/mm	2.82	3.82
Stem diameter/mm	0.86	2.12
Seedling height/mm	115.4[o]	263[o]
Seedling height/mm	100[d]	120[d]

Note: 'd' indicates a de-topped seedling; 'o' indicates an original seedling from the field.

2.2.3 Design of magazine

The magazine is the major key component of the developed system after the staggered metering plate, which holds a finite number of seedlings in one magazine set. So, a number of magazine sets can be stacked in the machine and directly fed into the running system while the machine is operated in the field. The magazine is placed on a conveyor belt which directs it towards the metering plate where seedlings are dropped one by one through the seedling delivery funnel. The magazine provides a continuous flow of seedlings to the metering plate. The system facilitates uninterrupted seedling transplanting until the magazine is empty, eliminating the need for human intervention. Considering a plant spacing of 100 mm[37], one magazine can cover approximately 15 m of field transplanting in a single run. When one magazine is empty, another filled magazine must be manually fed behind it. This process of transplanting continues until all magazines in the transplanter's rack are empty.

Considering cost effectiveness, corrosion resistance, light weight, and delicacy of onion seedlings, the magazine was fabricated using polyvinyl chloride (PVC). The registered large onion bulb and stem diameters (Table 1) were taken into consideration for determining the magazine slot size (L×W×H: 20 mm×20 mm×90 mm), so that free flow and delicacy of the onion seedlings can be maintained while working. The height of each slot in the magazine was kept at 90 mm to accommodate matured onion seedlings of varying ages, hold these vertically, and deliver them safely into the delivery funnel. However, the magazine was developed with three adjacent rows to accommodate a systematic set of 150 onion seedlings together (50 seedlings/magazine). Seedlings from the adjacent magazine rows were metered one after another using a staggered metering plate and then delivered through the delivery funnel behind the furrow opener. The overall dimensions of the magazine were kept at 1000 mm×60 mm×90 mm (L×W×H); the detailed design is shown through the CAD model in Figure 3. In addition, to reduce the replacement of empty magazines, the length of each magazine can be increased, while the field capacity of the developed system can be multiplied with multi-row machines in the future.



a. Isometric view of magazine b. Front view of magazine

Figure 3 CAD drawing of developed magazine for onion transplanter

To make the magazine portable, a detachable base plate was used (Figure 3a), having dimensions of 1000 mm×70 mm×6 mm (L×W×T). It enabled separate filling of seedlings outside the field and facilitated easy handling. A slot of 8 mm height and 58 mm width was provided at 20 mm above the magazine's base in order to insert the detachable base (Figure 3b). Initially, the detachable base plate is inserted into the slot provided in the magazine using an attached handle, which allows for effortless filling of the magazine with onion seedlings outside the farm. These seedlings can then be fed directly onto the conveyor belt by placing the magazine in order and easily removing the detachable base plate. As a result, the saplings are retained by the belt and moved along with it towards the dropping funnel, and finally the empty magazine is collected from the other side to reuse.

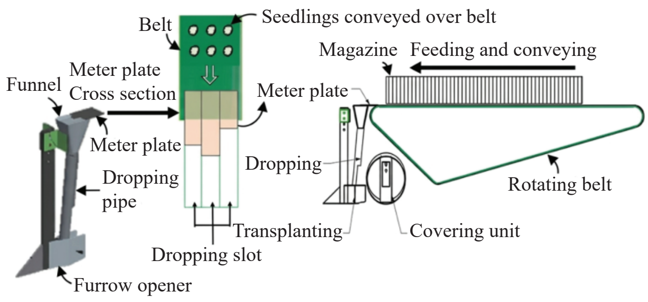
2.2.4 Conveyor belt selection and weight

Selection of belt dimensions mainly depended on the magazine size and load sustained over the belt. PVC conveyor belts are ideally suited for rough usage below ground[38]. It is mainly used due to its high strength, flexibility, and economic conveying capacity under light to medium duty application[39]. Since the width of the magazine was 60 mm, a wider width was selected to effectively hold and convey the magazine without any interception or damage to seedlings. A commercially available flat belt having dimensions of 3000 mm×88 mm×3 mm (L×W×T) was chosen to make an endless conveying system. The volume of the belt was calculated to be 7.92×10^{4} m^3. Belt density was taken as 1300 kg/m^3[40]. So, the weight of the conveyor belt was found as 1.02 kg. The weight over the belt was taken as 1 kg. Here, 0.8 kg weight was considered for the magazine and 0.2 kg weight for seedlings. Therefore, the total weight was observed as 2.02 kg. The necessary belt pull was calculated by multiplying total weight with the coefficient of friction. The coefficient of friction was taken as 0.30 for the rubber belt and cast-iron pulley[41]. A belt pull of 0.61 kg was calculated.

The belt power was measured by the product of required pull obtained and respective belt speed (0.137 km/h). Hence, the power necessary to operate the belt was calculated as 0.23 W.

2.2.5 Design of metering plate and dropping system magazine

The bare-root seedlings moved towards the dropping points as the set of magazines loaded with seedlings was carried ahead over the rotating conveyor. Prior to dropping, seedlings were shifted from the conveyor belt to the metering plate present at the entrance to the dropping funnel. Here, the seedlings were metered and then dropped (Figure 4).



a. b. c.

Figure 4 Staggered type metering and dropping mechanism of developed onion transplanter

To facilitate seamless transfer of seedlings from the conveyor belt to the metering plate, the metering plate should be carefully connected to the dropping funnel and well leveled with the belt upper surface, as illustrated in Figure 4c. The width of metering plate was kept the same as the width of the magazine (60 mm), so as to hold seedlings effectively on the magazine. However, to drop a single seedling at an equal interval of time from alternative adjacent magazines, the dropping point through the metering plate was changed. The dropping point was regulated by the relative length of metering plate over the dropping funnel (Figure 4b). Thus, lateral alternate dropping at equal intervals was obtained by exposing one slot to the funnel entrance at a particular time. The speed ratio from ground wheel to conveyor belt was decided based on the slot size (L×W: 20 mm×20 mm), number of consecutive magazine rows, forward speed, and desired plant-to-plant spacing.

The dropping system of the developed transplanter was designed to accommodate the seedling's delivery from three consecutive rows of the magazine to the delivery funnel. This delivery funnel was designed in a rectangular shape with dimensions of 60 mm width by 80 mm length. The width of delivery funnel (60 mm) was decided based on the magazine width, while the length (80 mm) was selected to provide effective time for gravity dropping of seedling. The delivery funnel was designed with a wider rectangular section at the entrance, which was gradually narrowed to reach the circular section exit. To avoid any obstruction in delivery of the onion seedlings through the delivery funnel, three individual slots of 30 mm height were made in the entrance of the funnel to collect seedlings from each row's magazine. This all-rectangular section merged into a single conical-shaped delivery pipe of 30 mm diameter (Figure 5). The slot's height (30 mm) provided on the rectangular section of the delivery funnel was decided based on the straight solid section of seedlings measured from bulb to stem out of the full length of de-topped seedling (120 mm). Smooth internal walls were intended to maintain root plug down orientation of seedling. A tapered funnel leading to a narrow exit provided for central delivery of seedlings during transplanting. The total height of the system was 350 mm above the ground surface for minimal seedling damage. It was attached behind the shoe-type furrow opener in order to avoid deflection of seedlings, and the delivery tube provided was cut according to the height of the seedlings. The rear half section of the delivery tube was cut up to a height of 150 mm from bottom, as the maximum length of de-topped seedlings was 120 mm.

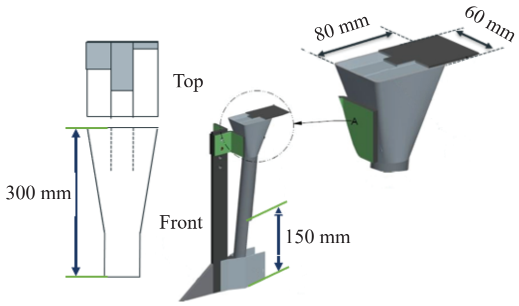


Figure 5 Diagrammatic representations of delivery funnel and metering plate

2.2.6 Power train of conveying mechanism

The recommended plant spacing for onions under both conventional and mechanized cultivation varies between 60-150 mm[42,43]. Thus, theoretical plant spacing was decided as 100 mm, which is the most economical for design of transplanting mechanism[25,37]. The length of each magazine slot was 20 mm, and there were three adjacent magazines operating side by side. Thus, the staggered metering plate was designed to open a slot completely when forward travel of the magazine was equal to one-third of slot length. The magazine was required to move 6.7 mm ahead for every 100 mm of forward travel by ground wheel. This movement represents 6.7% of the theoretical plant spacing. The desired linear motion of flat belt conveying system under the mechanism was calculated as 0.13 km/h by considering the maximum forward speed for transplanting as 2 km/h and plant spacing of 100 mm. So, the velocity and gear ratio was measured for both functional mechanisms as follows:

$$\text{Velocity ratio}=\frac{\text{Velocity of Magazine Conveying}}{\text{Velocity of Ground Wheel}}=\frac{6.7}{100}=0.067 \quad (1)$$

Thus, the velocity ratio was determined to be 0.067. Such a low velocity ratio indicates a high mechanical advantage, which ensures stable system operation and allows the ground wheel to exert greater leverage over the movement of the magazine. It required higher mechanical reduction to obtain slower linear movement of the magazine. Thus, the gear ratio was obtained by taking the reciprocal of the velocity ratio. The gear ratio of this system was found to be 14.92. This was applicable for both the output drive shaft of belt and powered roller conveyor.

The linear velocity of the conveyor belt and powered type conveyor roller needed to be synchronized (by maintaining the same velocity) so that the magazine was able to move smoothly over the belt. Meanwhile, the magazine was assisted by a power type conveyor roller at the back end of the system, which directed it toward the delivery funnel. Compound chain drive was used to achieve and synchronize the velocity between the powered type conveyor roller and flat belt drive system, as shown in Figure 6, which presents the whole path of the chain drive system from ground wheel to conveyor belt.

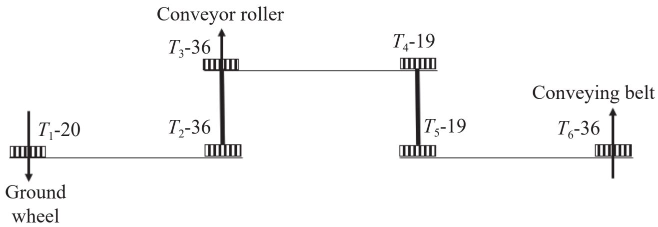


Figure 6 Gear drive combination for functioning mechanism

Rotational movement was transferred from ground wheel to power type conveyor roller. The ground wheel diameter was taken as 0.8 m. Hence the velocity and rotational speed were determined using the following equations:

$$V_{gw}=\pi D_{gw}N_1 \quad (2)$$

$$V_{PR}=\pi D_{PR}N_2 \quad (3)$$

where, V_{gw}: Ground wheel velocity (taken as 2 km/h); V_{PR}: Velocity of powered type conveyor roller (Velocity ratio×V_{gw}); D_{gw}: Diameter of ground wheel (assumed as 0.8 m); D_{PR}: Diameter of ground wheel (0.095 m); N_1: Ground wheel revolution, r/min; N_2: Revolution of powered type conveyor roller, r/min.

Thus, the rotational speed for ground wheel and power type conveyor roller were found as 13.26 and 7.43 r/min, respectively.

A single-stage chain drive system was used to transmit power to the powered type conveyor roller. In this drive, a sprocket of 20 teeth (T_1) was taken, and hence the number of teeth in the driven shaft sprocket (T_2) was calculated to be 36 using the equation ($N_1T_1 = N_2T_2$).

To drive the conveyor belt, power was further transferred from T_2 to T_6 using a compound drive system. However, as the powered conveyor roller and conveyor belt run at the same linear speed, the gear ratio was maintained as 1 between T_2 and T_6. The total gear ratio from ground wheel to conveyor belt was calculated to be 14.92. Considering the selected possible combination of sprockets (T_3-36, T_4-19, T_5-19, and T_6-36), rotational speed in the final driven shaft was measured using Equation (4):

$$N_6 = N_1\left(\frac{T_1T_3T_5}{T_2T_4T_6}\right) \quad (4)$$

Thus, the rotational speed of the final driven shaft which provides power to the conveyor belt was calculated as 7.4 r/min.

2.2.7 Shoe-type furrow opener design for transplanting

Type of furrow opener is paramount, as it directly impacts the performance of transplanting. Effective furrow opener selection may produce proper seedling depth and placement for generous growth. It principally depends on the type of crop, seedling type and age, seedling morphology, soil type, and moisture availability in the soil. Optimum sowing depth or seedling placement varies depending on the moisture content and deeper placement recommended in dry soil conditions[44]. Shoe-type furrow opener was selected due to the morphological need for placement of seedlings during transplanting. Shoe-type furrow opener is mostly preferred for seed drilling or planting purposes. However, the morphology of bare-root seedling was more suited to equip the furrow opener with transplanting mechanism. Performance of the shoe-type furrow opener was compared with modified shoe-type and inverted T-type furrow openers by researchers[45]. Their study reported that in the shoe-type furrow opener, some soil particles were thrown out from the strip due to furrow width, which creates a barrier to soil back-flow prior to placement of the seeds. Thus, precision of seed placement was lower for the wider strip (60 mm). However, in this study it creates favorable conditions for seedling placement, as the seedling's bulb can easily be placed in wider strips and covered by a disc type covering device. Thus, the shoe-type furrow opener was designed and fabricated to equip with the transplanting mechanism. The furrow opener was mounted to one end of the shank which was connected to the transplanter frame.

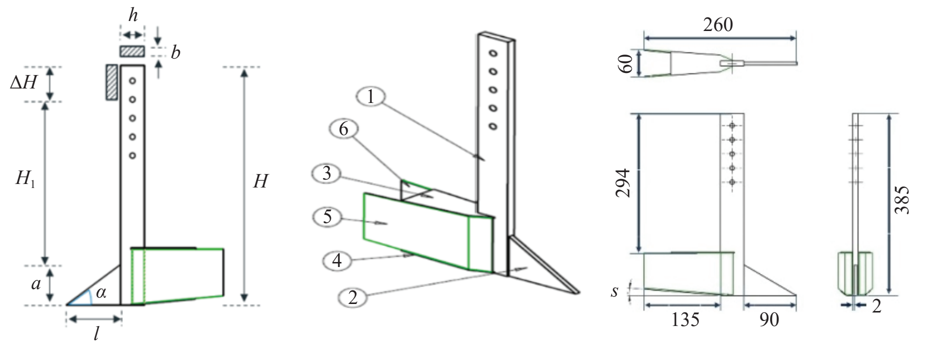


Figure 7 Shoe-type furrow opener (1: Shank; 2: Share; 3: Boot upper cover; 4: Boot bottom; 5: Boot; 6: Inner side of boot part (b×h = shank cross-sectional area, mm; l: Length of shoe, mm; α_1: Rake angle, deg; K_o: Specific soil resistance, kg/cm²; H: Height of shank from the tip of opener to the frame, mm; and ΔH: Upper length of tine which is used for fastening, mm)

The furrow had an assumed width (W) of 50 mm and a depth (d) of 50 mm, resulting in a triangular cross-sectional area of 1250 mm². This specific geometry was analyzed in the context of very heavy soil, where soil resistance was taken as 0.89 kg/m². Although soil resistance varied from 0.64 to 0.89 kg/cm² for medium to very heavy clayey soil, respectively, the highest value was considered for reliable design. Soil resistance is considered a major cause for bending the tine, hence to ensure structural rigidity a factor of safety of 3 was considered. Force exerted on a single furrow opener was found to be 11.13 kg (109.14 N), hence the maximum total force exerted on furrow openers was calculated as 33.39 kg (327.55 N).

The center of gravity of the triangular section was located at two-thirds of the operating depth, which was measured as 33.33 mm. So, the effective length of the shank was calculated by deducting 16.7 mm from the bottom and 25 mm from the top where it is fastened, and found to be 358.33 mm.

Taking the shank as a cantilever beam, the maximum bending moment was obtained for a cantilever length of 358.3 mm and the force was assumed to be acting at centroid of triangular section geometry. It was considered acting at 16.7 mm height from bottom of the furrow opener. The length of the shank used for fixing plate to the main transplanter frame was taken as 50 mm. Thus, the maximum bending moment 'M_{sh}' (draft×shank length) of the given shank length was 1196.36 kg-cm.

From the classical flexure Equation (5), the section modulus of the shank was determined.

$$\delta = \frac{MC}{I} \tag{5}$$

where, δ is bending stress, kg/cm² (1000 kg/cm², as quoted by Verma et al.)[46]; M is bending moment, kg·cm; I is moment of inertia in a rectangular portion, cm⁴; C is distance from the neutral axis to the point at which stress is determined, cm.

The section modulus axis (Z) was determined using the following Equation (6):

$$Z = \frac{I}{C} \tag{6}$$

From Equations (5) and (6), Equation (7) was derived, and by substituting the value of bending moment (M) and bending stress (δ), section modulus (Z) was found to be 1.196 cm³. Section modulus of furrow opener (Z) was calculated in Equation (8)[47], and the assumed ratio of thickness to width of tine was b:h = 1:4[46]. The thickness was determined as 0.765 cm.

$$Z = \frac{M}{\delta} \tag{7}$$

$$Z = \frac{bh^2}{6} \tag{8}$$

where, b is thickness, cm; h is width, cm

Thus, following a structural analysis and a review of standard sizes, the shank thickness and width was finalized at 8 mm (7.66 ≈ 8 mm) and 35 mm (32≈35 mm) respectively.

Hence the cross section of the shank was obtained as 8×35 mm. To assure the machine workability regarding vibration, depth control, fatigue, plastic deformation, etc., maximum deflection on this section needs to be assessed. Moment of inertia was calculated using Equation (9), before calculating the shank deflection.

$$I = \frac{bh^3}{12} \tag{9}$$

I = 28 583.33 mm⁴

This section would yield a maximum deflection, which can be assessed using Equation (10) as follows:

$$Y_{\max} = \frac{Dl^3}{3EI} \tag{10}$$

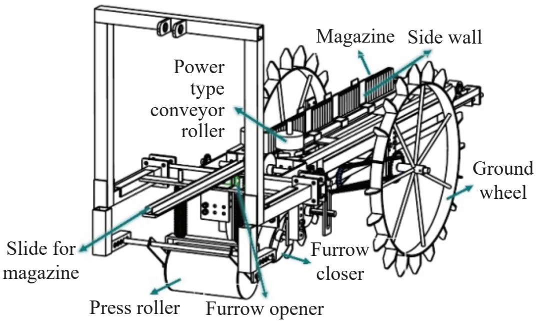
where, $Y_{\max}$: deflection due to loading, mm; l: length of shank, mm; E: modulus of elasticity (2×10⁴ kg/mm² for mild steel); I: moment of inertia, mm⁴; $Y_{\max}$ = 1.24 mm.

Therefore, the maximum deflection of shank was observed to be 1.24 mm, which represents stiff and stable behavior under heavy soil condition.

Consequently, the power required for the transplanting operation with a shoe-type furrow opener was obtained by multiplying the draft and forward speed of travel and found to be 0.18 kW.

2.3 Constructional arrangement of prototype mechanical transplanter (TMch)

Initially, conceptual design of the onion transplanter was prepared in the AutoCAD (Figure 8a), similar to Singh et al.[48], and then a single-row onion transplanter designed to reduce large labor involvement in onion seedling singulation was fabricated. Overall dimensions of the developed transplanter were 2770 mm× 720 mm×780 mm (L×W×H) and operated by a small tractor as shown in Figure 8. The developed transplanter comprises a flat conveyor belt which is continually rotated as the system moves forward on the farm. Through a compound chain drive arrangement used to transmit power, the ground wheels transmitted rotational motion to the power-type conveyor roller, which assisted in straight and forward movement of the magazine. The linear velocity of the conveyor belt was synchronized with the peripheral velocity of the vertically oriented power type conveyor roller (Figure 8a). The conveyor roller, along with the side walls, guided the magazine loaded with seedlings in a straight path towards the dropping funnel, where at the top seedlings were metered and dropped one by one. To ensure transplanting with the desired seedling spacing of 100 mm, a gear ratio of 14.92 was maintained for the conveyor belt. A direct chain drive system powered the vertical conveyor roller, while a compound chain drive powered the flat belt conveying mechanism. A shoe-type furrow opener and a disc-type covering unit were used to place seedlings at desired depth and adequately cover post placing on the farmland.



a. CAD view

b. Field working of developed onion transplanter view

Figure 8 CAD view (a) and Field working of developed onion transplanter view (b)

2.4 Working principle of mechanical transplanter

Power was transmitted from ground wheels to both the powered-type conveyor rollers using direct chain drive, where bevel gear was used to rotate the rollers opposite to each other and produce forward movement. The flat conveyor belt was also powered from the intermediate shaft through chain and sprocket. A total of three magazines, each with 50 slots, were connected side by side. Thus, the magazine, with 150 slots, was filled with onion seedlings and set on the top of the conveyor belt. The vertically oriented powered rollers along with mechanical guide enabled smooth forward movement of the magazine along with onion seedlings. The magazine moved over the seedling dropping funnel where seedlings were dropped sequentially at equal time intervals. The staggered metering plate was equipped over the delivery tube as shown in Figure 5, which sequentially dropped the seedlings from slots of adjacent magazine in a furrow. Finally, the seedlings were placed and immediately covered with soil from both sides to compact and facilitate effective transplantation in prepared soil bed.

The magazine was designed with three adjacent rows to accommodate and transplant a large number of seedlings in a single operation. It was equipped with a detachable base plate at the bottom, which made it portable. This feature assisted farmers by allowing them to conveniently fill the seedlings outside the field. The filled set of seedlings was then directly inserted into the rack of the transplanter. Subsequently, the magazine was manually placed onto the conveyor belt and the base plate was removed, allowing all seedlings to be held by the conveyor belt. Due to the linear motion of the conveyor belt, the magazine conveyed the seedlings smoothly and metered them in a predefined manner. The powered conveyor rollers and guiding walls were incorporated as additional components to ensure straight and stable movement of the magazine. Once the loaded cassette was fully conveyed over the metering plate, the empty cassettes were refilled outside the field for the next batch.

A single onion seedling at a time was allowed to drop into the delivery funnel. This was ensured by the staggered metering plate located above the funnel. All three adjacent rows of the magazine were conveyed toward a single seedling delivery funnel and shifted to the metering plate. The staggered metering plate allowed seedlings to free fall from adjacent slots in an alternate manner as slots were opened at the base one by one. The relative length of the staggered metering plate interacting with adjacent rows of the magazine was decided corresponding to the number of rows in the magazine. It was calculated by dividing slot length (20 mm) with number of rows in the magazine (3) and found to be 6.7 mm in this case. Accordingly, the relative linear motion of the magazine was set by simultaneously considering plant spacing. This pattern of arrangement of staggered metering plate allowed release of only one seedling at a time.

Using the developed mechanism, onion seedlings were transplanted in randomly allocated plots, and data related to sowing and post-harvest parameters of the onion crop were collected and analyzed.

2.5 Assessment of output parameters

The assessment encompassed the following output parameters: plant-to-plant spacing (Figure 9b), seed-to-seed spacing, sowing depth (Figure 9c), average onion bulb weight, onion size distribution, survival rate, and field capacity, all of which were evaluated for each onion field cultivation technique (Figure 9a).

2.5.1 Plant-to-plant spacing or seed-to-seed spacing

The environment's conduciveness is a prerequisite for the growth of onion seedling or seed, which is potentially influenced by the seed-to-seed spacing and seedling-to-seedling spacing. This is because appropriate spacing determines the level of nutrients available and free space for growth of onion. It also affects the quantity of seeds or seedlings required and influences economic viability. Therefore, it was included for analysis and comparison. In this research, the seed-to-seed spacing or seedling-to-seedling spacing was measured between two consecutive seedlings or onion seeds using a meter scale (Figure 9b). For each method, fifty observations were randomly taken, and the estimated mean of seed-to-seed spacing or seedling-to-seedling spacing was calculated by taking the average of all observations.

a. Onion field cultivation b. Seedling to seedling spacing c. Sowing depth

Figure 9 Assessment of seedling parameters

2.5.2 Sowing depth of onion seed or onion seedlings

The depth at which onion seedlings and seeds are planted is crucial for their overall development. It impacts the survival rate of the seedlings, as moisture content and the amount of soil volume available are dependent on it. Small seeds require a shallow 12-25 mm placement, whereas medium-sized seeds, such as mung bean, perform best at 30-35 mm[49]. Therefore, in this research, the depth of planting seeds under SSM and SSP methods were measured using a meter scale (Figure 9c). The seedling transplanting depth of onion for traditional and mechanical methods was reported in the range from 17-32 mm[23]. Thus, the depth of transplanted seedlings under TMch and TM methods were also measured by opening furrows at randomly selected locations in the field. Ten observations were taken for three rows and the mean depth was derived by calculating the average of all the observations under each onion cultivation technique.

2.5.3 Average weight of onion bulb

The weight of onion bulb is a very important parameter, which significantly affects the productivity and total production of onion crop. Different onion cultivation techniques affect the weight of the onions as they create varying levels of suitable environments around each onion. These environments are essential for the growth of the onion bulb. Therefore, in this study, the average weight of the onion bulb was considered for analysis. Hence, onions from each plot with different cultivation methods were harvested at an age of 150 days (d). Randomly, thirty onion samples were taken for each method of cultivation and weight was measured using an electronic balance (Figure 10a). The average weight was calculated as the mean value of thirty onions for each cultivation method and used for the purpose of analysis.

a. Onion bulb weight b. Onion bulb diameter

Figure 10 Onion bulb parameters assessment after harvesting

2.5.4 Onion size distribution

The quality of onion production depends on the onion size distribution, which is done on the basis of grading of onion into different sizes. Generally, large and extra-large onion size is preferred in comparison to small and medium size due to ease in processing, minimum wastage, and handling. The onion bulb is significantly affected by the different onion cultivation techniques due to different degrees of soil and environment conditions developed with respective methods of cultivation. Therefore, onion size distribution was done and used for comparison. In this study, observations were recorded at 150 d after planting (DAP) under each cultivation method, and a hundred onion samples were harvested randomly and categorized (Figure 10b) into various size distributions (10-20 mm: Small; 21-40 mm: Medium; 41-70 mm: Large; >70 mm: Extra-large) on the basis of maximum equatorial diameter, as per recommendation of AGMARK standard[50] for onion bulb grading at the commercial level.

2.5.5 Survival rate of plants (%)

The success of each technique of onion cultivation is reflected in terms of the survival rate of onion seedlings. Generally, higher seedling survival rate is achieved with proper depth and appropriate seedling-to-seedling spacing, and leads to higher production and productivity. However, survival rate is significantly affected by factors such as soil quality, environmental conditions, and seed quality, as suggested by researchers[51-53]. The soil and environmental condition are influenced by the onion cultivation technique. Therefore, in this study, the seedling survival rate was estimated with respect to both onion seedling transplanting methods (TM and TMch) and used for comparison. Survival rate was estimated by calculating the percentage of number of seedlings survived out of total number of seedlings transplanted within three 25 m-long furrows after 20 d of transplanting, as recommended by Ozmerzi et al.[54]

2.5.6 Field capacity

Field capacity reflects the area covered with respect to time taken by each method. Achieving higher field capacity is one of the important goals for each method, because it makes field operation more economical and environmentally friendly. It lowers fossil fuel consumption and saves precious time by timely sowing or transplanting. Therefore, in this study, the effective field capacity with respect to each onion cultivation technique (SSM, SSP, TM, TMch) was calculated by considering time involved in different activities, namely time losses for turning, adjustment, and filling of trays following the method adopted by Kavitha et al.[55]

2.6 Statistical analysis

Data analysis employing full factorial, descriptive statistics, and one-way ANOVA was carried out using SAS 9.3 software to assess the effect of various treatments (cultivation methods) on selected dependent parameters (plant spacing and average cured bulb weight). Additionally, a pairwise comparison test, utilizing Tukey's test, was also performed to ascertain significance at a 5%

level of significance.

3 Results

3.1 Plant-to-plant spacing

The graphs were plotted for three randomly selected rows in the experimental plot to assess the spacing acquired under each cultivation method. It also evaluated the seed or seedling delivery/distribution pattern of onion for all selected onion cultivation methods to analyze their effectiveness and efficiency on the basis of maintaining uniform plant spacing, as depicted in Figure 11. It disclosed the seedlings or seed distribution pattern within three rows. From the figure, it is clear that the developed mechanical transplanter (TMch) and manual transplanting (TM) showed more uniform plant spacing within three selected rows as compared to both manual seed sowing (SSM) and mechanical planting (SSP) methods. Both TMch and TM displayed more discipline to transplant the onion seedlings along the row with uniform seedling spacing and save costly onion seedlings, while the other two methods frequently delivered more seeds and lacked uniformity in seed-to-seed spacing.

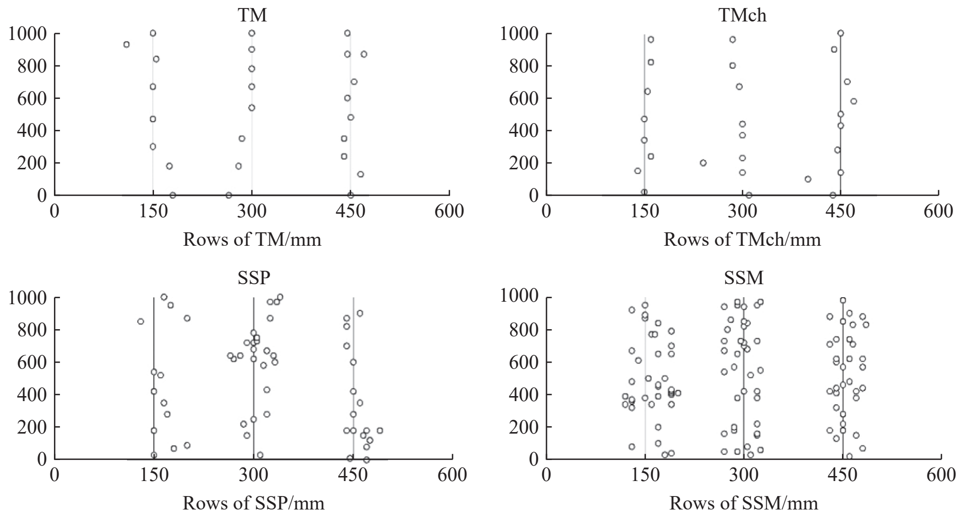


Figure 11 Distribution patterns of onion seeds or seedlings (TM, TMch, SSP, and SSM)

In order to quantify, the distance between seeds or seedlings was calculated using all four methods. It was found that intra-row spacing under manual transplanting (TM) was observed at 125.8±23.1 mm (Mean±SD), i.e. slightly higher than recommended spacing (100 mm). In the case of manual seed sowing (SSM) method, seed-to-seed spacing was 47.6±18.90 mm, which is far less than the recommended spacing. However, both higher and lower seed-to-seed spacing negatively affected onion productivity. Higher seedling spacing than recommended reduces the number of seedlings available per unit area, whereas lower spacing than recommended decreases the availability of soil nutrients for onion seedlings due to the presence of multiple seedlings in the same place. In the case of mechanical transplanter (TMch) and mechanical planter (SSP) methods, seedling spacing was observed as 139.0±36.32 and 102.6±61.70 mm (Mean±SD), respectively (Table 2). Among all techniques, the seedling spacing was found to be highest under mechanical transplanting. This might be the case due to the involved slippage under TMch method in field conditions.

Table 2 Descriptive statistics for seedling-to-seedling or seed-to-seed spacing (mm)

Techniques	N	Mean/mm	SD/mm	SE/%	95% Confidence interval for mean	
					Lower level	Upper level
TM	50	125.8	23.31	3.30	119.18	132.42
TMch	50	139.0	36.32	5.14	128.68	149.32
SSP	50	102.6	61.70	8.73	85.06	120.13
SSM	50	47.6	18.90	2.67	42.23	52.97

N: Number of observations; SD: Standard deviation; SE: Standard error.

In Table 3, the F statistics (calculated value 54.008) were found to be higher than that of F tabulated value (0.0001). Thus, the analysis of variance revealed a significant difference between the different groups of cultivation methods at 5% level of significance.

In order to determine the significant difference in outcomes between specific pairs of treatments based on seedling-to-seedling or seed-to-seed spacing, a post hoc test (Tukey HSD) was performed. In addition, seedling-to-seedling spacing results within each cultivation practice were compared with those of the other three methods under multiple comparison tests, as shown in Table 4. The study found no significant difference in seedling-to-seedling spacing between TMch and TM methods at a 5% level of significance. However, the spacing results of TMch showed a significant difference compared to SSP and SSM methods at the same significance level. Moreover, each SSP and SSM showed a significant difference separately with the rest of the onion cultivation techniques at a 5% significance level.

Table 3 ANOVA for seedling-to-seedling spacing or seed-to-seed spacing (mm)

	Sum of squares	*df*	Mean square	*F*	*Sig.*
Between groups	2441.455	3	813.818	54.008	<0.0001
Within groups	2953.420	196	15.068		
Total	5394.875	199			

df: Degree of freedom.

The spacing results under the TMch method differed significantly from the SSP and SSM at a 5% significance level. However, there was no significant difference compared to the TM, as indicated in Table 3. The TMch method facilitated 13.2 mm lesser spacing as compared to the TM with no significant difference, while it revealed 36.4 and 91.4 mm higher spacing than that obtained under SSP and SSM methods, respectively. Therefore, both SSP and SSM methods led to excessive wastage of costly onion seed, and thinning operation became essential, otherwise overall onion production and productivity would be affected.

Table 4 Multiple comparison under Tukey HSD test for spacing (mm)

(I)	(J)	Mean difference (I-J)
TMch	TM	−13.2
	SSP	36.4*
	SSM	91.4*
TM	TMch	13.2
	SSP	−23.2*
	SSM	−78.2*
SSP	TM	−23.2*
	TMch	−36.4*
	SSM	55.0*
SSM	TM	−78.2*
	TMch	−91.4*
	SSP	−55.0*

* Depicts the significant difference in average weight to that of other corresponding treatments.

3.2 Sowing depth of onion seedling or onion seed

The mean depth of seedling or seed sowing estimated for three selected rows under four different onion cultivation techniques is depicted in Table 5. Results of transplanting agreed with the performance revealed by Pandirwar et al.[23] for manual and mechanized transplanting of onion seedlings. In the present study, the depth facilitated by TMch and TM methods varied in 30.5-27.0 mm and 29.5-26.0 mm, indicating that it slightly surpassed that of SSP and SSM. Statistically, there was non-significant difference observed at 5% level of significance. But the result showed a mean seedling depth under TMch method that was 2.34%, 9.91%, and 11.06% higher compared to TM, SSP, and SSM, respectively. On the other hand, both TMch and TM methods exhibited a higher coefficient of variation compared to the other two methods, promoting a better survival rate for the onion seedlings. Meanwhile, a lower depth of seed sowing might lead to a poor seedling survival rate due to insufficient moisture content, as documented in this study.

Table 5 Onion seedlings depth variation with different cultivation methods

Methods	TM			TMch			SSP			SSM		
	R_1	R_2	R_3	R_1	R_2	R_3	R_1	R_2	R_3	R_1	R_2	R_3
M_d/mm	29.5	26.0	28.5	28.5	30.5	27.0	25.5	26.0	24.5	24.5	27.0	25.0
SD	±1.47			±1.43			±0.62			±1.08		
CV/%	5.26			5.00			2.46			4.24		

SD: Standard deviation; CV: Coefficient of variation; R_i: R indicates row and i shows number of row, i.e. 1, 2, and 3.

3.3 Analysis of onion bulb weight

The mean weight of fresh onion bulb was found to be 129.2±63.68 g (Mean±SD) in TMch treatment, followed by TM, SSP, and SSM as 125.4±54.10, 31.87±18.20, and 12.93±10.23 g respectively, as given in Table 6. After onion harvesting, de-topping was done and left for 15 d for curing purposes, leading to significant loss of water from selected onion samples to be collected under different cultivation techniques. However, the curing had reduced the weight of fresh onion bulb to 122.13±53.56, 115±48.75, 28.67±16.47, and 9.8±5.37 g in TMch, TM, SSP, and SSM respectively, which is consistent with the findings of Bahnasawy et al.[56]. Average water lost from the sample was recorded as 6.2%, 5.47%, 10.04%, and 24.20% for TM, TMch, SSP, and SSM methods, respectively. It revealed that large size onion bulb offers more resistance to loss of water from the onion skin under respiration process, which happened due to large onion layer thickness. It signifies the good growth of the onion bulb with large average weight, which was attained under TM and TMch methods.

Table 6 Average weight of fresh onion bulb

Methods	TM	TMch	SSP	SSM
M_{wfb}/g	125.4	129.2	31.87	12.93
SD	±53.19	±62.61	±17.90	±10.06
W_l/%	5.47	6.20	10.04	24.20

M_{wfb}: Mean weight of fresh bulb; SD: Standard deviation; W_l: Water loss after curing.

In addition, the mean weight of fresh onion bulb under TMch method was recorded as 3.03% lesser than that of TM, which is not a considerable level, while 74.54% and 89.67% higher than that of SSP and SSM, respectively.

Statistical analysis was conducted to comprehend the importance of diverse growing cultivation techniques on the average weight of the onion bulb. The analysis revealed that there is a significant difference between the effects of different cultivation techniques on the average weight of bulb at 5% level of significance, as presented in Table 7.

Table 7 ANOVA for average weight of cured onion bulb

	SS	*df*	MS	F_{cal}	F_{tab}
Between groups	335 713.97	3	111 904.66	60.35	2.68
Within groups	215 099.33	116	1854.31		
Total	550 813.30	119			

SS: Sum of square; MS: Mean sum of square; *df*: Degree of freedom.

Under the post-hoc test, Tukey HSD test was performed to determine which pair of onion cultivation practices had a significant effect on the average weight of the onion bulb. Multiple pairwise comparison tests were performed by using the Tukey test to compare the average weight of the onion bulbs under a specific cultivation method with the remaining three methods, as shown in Table 8. When comparing average weight, TMch was found to have no significant difference with TM, but showed a significant difference with SSP and SSM methods at a 5% level of significance, as depicted in Table 8. The average weight of onion bulbs under the SSP was not significantly different from the SSM. Nonetheless, a significant difference was observed when comparing it to both the TMch and TM, with a significance level of 5%.

Table 8 Multiple comparison test for average weight of cured onion bulb (g)

(I)	(J)	Mean difference (I−J)
TMch	TM	−3.80
	SSP	97.33*
	SSM	116.27*
TM	TMch	3.80
	SSP	−93.53*
	SSM	−112.47*
SSP	TM	93.53*
	TMch	97.33*
	SSM	−18.93
SSM	TM	112.46*
	TMch	116.267*
	SSP	18.93

* Depicts the significant difference in average weight to that of other corresponding treatments.

The positive mean difference under a specific cultivation method showed that its average weight of onion bulb is higher than that of the rest of the cultivation practices and vice–versa. Under the

TMch method, the mean difference for the average weight of onion bulb was observed positive as compared with both SSP and SSM, while a negative mean difference was observed with TM method without any significant difference. This highlighted that the TMch method is the best onion cultivation method for average weight in comparison to both SSM and SSP with considerable difference, while it provided more or less similar results to TM with respect to average onion bulb weight.

3.4 Analysis of onion size distribution

As per AGMARK standard 2011 guideline in APEDA report, whole fresh onion samples for each cultivation technique were segmented into four groups, i.e. small, medium, large, and extra-large, on the basis of the equatorial diameter of the onion bulb. However, TM and TMch were provided with only two kinds of onion size categories, i.e. large (TM: 53.33%; TMch: 56.76%) and extra-large onion size (TM: 46.67%; TMch: 43.24%) as shown in Figure 12; while in SSP three categories were included, excepting the extra-large size, and SSM only contained small and medium onion size. The study found that both the SSP and SSM methods lacked extra-large onion segments. This clearly signified the impact of poor spacing between seedlings, thus limiting the soil nutrients and hindering the growth of onion seedlings. It highlights the significance of maintaining uniform seedling-to-seedling spacing to be required in onion cultivation, leading to better onion productivity with minimum onion seeds. Similar findings were reported by Demisie and Tolessa[57] that the disclosing equatorial diameter growth was increased by increasing the intra-row spacing.

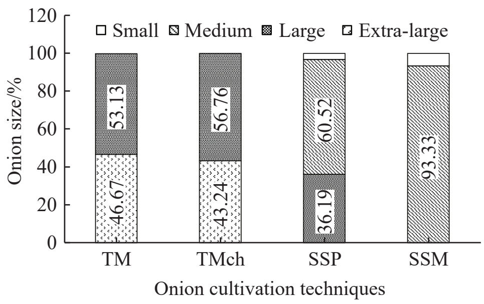


Figure 12 Onion size distribution for TM, TMch, SSP, and SSM

3.5 Overall comparison between different onion cultivation techniques

The mechanical transplanter ensured higher survival rate of onion seedlings close to manual transplanting, which gives higher onion productivity and better bulb growth assurance due to uniform plant spacing, appropriate planting depth, and adequate availability of soil nutrients. In addition, survival rates (%) for both SSP and SSM methods were not estimated and reported because it is very difficult to find out how many seeds dropped in each row, and vigorous germination of multiple seeds occurred at one particular point; as a result, thinning operation was carried out for onion bulb growth. However, the mechanical transplanter registered only 200 labor requirement units to transplant onion seedling per hectare (Table 9), which saves 118% labor requirement as compared to manual transplanting method. This signifies the potential application of a developed mechanical transplanter to replace manual transplanting for onion sowing without significant loss of onion productivity. Meanwhile, both SSP and SSM methods have a significant advantage over mechanical transplanter in total labor requirement per hectare, but they provided poor management of uniform seed spacing, affecting overall growth of onion bulb and leading to low onion productivity.

Table 9 Comparison between performances of different onion cultivation techniques

Techniques	TM	TMch	SSP	SSM
Labor requirement, man-h/ha	436	200	3	150
Survival rate, %	94	92	-	-
Effective field capacity, ha/h	0.002	0.012	0.120	0.003

The effective field capacity varied from 0.002 to 0.12 hm^2/h among the four onion cultivation techniques. However, the mechanical transplanter registered 83.33% and 75.00% higher field capacity as compared to field capacity of TM and SSM, respectively. This shows that the mechanical transplanter has incredible potential to meet labor demands during onion transplanting sessions with considerable field capacity.

4 Discussion

The accuracy and reliability of the developed mechanical transplanter can be analyzed on the basis of its effective performance to achieve uniform seedling spacing, appropriate depth, better survival rate, and high field capacity as much as possible. All these parameters finally affect onion productivity. In this study, seedling spacing achieved by the developed mechanical transplanter coincides with that of manual transplanting, which ensures appropriate available nutrients to every onion seedling, leads to better onion bulb growth, and avoids the need for thinning operation. Furthermore, this demonstrates the improved efficacy of the designed mechanical transplanter, which enables seedling transplantation comparable to the manual transplantation method. In contrast, the SSP and SSM methods fail to maintain standard seedling spacing, resulting in congested seedlings within rows. This, in turn, negatively impacts the growth of onion bulbs and productivity, and leads to wastage of costly onion seedlings with more labor requirement for thinning operations. Several studies reported the impact of spacing on the onion morphological growth and yield[58,59]. Khan et al.[58] assessed the effect of different plant spacing impact on the growth and the morphology of onion (Variety BARI Piaz-1) and revealed that the maximum yield of onion was noted where the close spacing (7.5 cm×7.5 cm) was considered for cultivation, while the wider spacing (20 cm×10 cm) gave lesser yield. The most economical and highest yield was recorded with 10 cm plant spacing and 15 cm row-to-row spacing. These findings are consistent with results of a different study performed by varying row-to-row (20-30 cm) and plant-to-plant spacing (10-20 cm)[60], and reported significant differences in the morphological growth and yield of onion (Nasik Red) in plant-to-plant spacing variation. From all these research works, it can be concluded that the adequate plant-to-plant or seed-to-seed spacing is very crucial for achieving higher onion yield, which is highly dependent on what type of cultivation techniques to be adopted. This is because the size of onion seed is very fine (1.93-2.48 mm)[61] and difficult to regulate in the working condition. Additionally, the developed onion transplanter is highly capable to resolve the above issue with minimal seed input and ensure higher onion production.

Sowing depth plays a significant role in the development of onion bulb and also affects the seed germination. Therefore, in this research, sowing depth was taken as an output parameter and used for the purpose of comparison among the various onion cultivation techniques. A very shallow sowing depth may adversely affect the germination of onion seeds or seedlings due to insufficient soil moisture and nutrient availability. At the same time, higher sowing depth offers poor onion production, because the onion seed may not grow due to high soil pressure or the onion bulb may not develop well due to poor soil aeration and high compaction. In the present study, depth of seedling transplanting with TM and TMch technique registered slightly higher than the results with SSP and SSM techniques. Additionally, transplanting results of the developed mechanism were found to be in line with the results quoted by Pandirwar et al.[23], while the mechanical transplanting (for plug seedling) outperformed and compared with traditional transplanting method. Depth of placement varied from 29-32 mm and 17-21 mm, for mechanical and traditional transplanting respectively, which fulfill the essential depth needed for successful survival of onion seedlings and onion bulbs in field. However, in the planting aspect, the combined influence of spacing and planting depth was shown to be significant on the majority of the growth and yield of onion, as reported in the study[59]. Researchers compared the growth of onion planting by varying the depth (2-4 cm) along with spacing[59] and observed a significant impact on morphological growth and yield. Therefore, appropriate sowing depth is a prerequisite for the good germination, better survival rate, and better growth of onion bulb.

The average bulb weight of onion under both TMch and TM methods showed similar results with no significant difference. However, the average bulb weight under TMch differed significantly from that observed under SSP and SSM. This might be due to poor seedling spacing and inappropriate sowing depth to be traced with these methods (SSP and SSM). In Ethopia, Ketema et al.[62] experimented on three onion cultivation methods (seeding, transplanting, and set type planting) on the basis of growth parameters and reported that the planting method found a highly significant (p<0.001) effect on dry bulb weight during the whole growing season. As compared to onion seeding method, significantly higher bulb weight was reported in transplanting and set type planting method. In Indian conditions, a significant difference in the growth of onion and yield was traced by Jeevitha et al.[63], who compared the cultivation method of transplanting and seed drilling of onion over two consecutive years. The study revealed that average onion bulb weight under transplanting method was 64 g, which was 11 g more than the average onion weight observed under seed drill method. Therefore, it can be said that the transplanting method (like TMch) is a more reliable and more accurate onion cultivation method than the others. However, the results of the present study were confined to one season, but its results are highly in line with several above-mentioned studies' findings, where onion transplanters were tested in more than one season.

Both TMch and TM methods lead to identical findings in terms of onion size distribution, with no significant differences, which confirms better onion bulb quality, characterized by a larger bulb diameter, among the onion cultivation techniques. It shows the potential reduction in precious time, ease of processing operation, and saving on processing cost of the obtained different onion size distribution. These findings are also supported by other researchers[62,64], who compared transplanting method with onion seed sowing and set planting. When compared to transplanting, the significantly (p<0.001) lower bulb diameter was attained using the seed sowing approach. Similar type attributes were exhibited in the present research, indicating a substantial difference in outcomes of onion size distribution with TMch and TM methods as opposed to those of SSP and SSM, which exhibit poor quality of onion production (smaller onion bulb).

The TMch shows better results than other methods in terms of effective field capacity (FC) and compatibility, with the exception of the SSP, which has a high seedling survival rate. The higher field capacity ensures the timely sowing of the onion crop, which contributes to economic field operation with lower environmental degradation without sacrificing onion production and productivity. These findings are consistent with the study conducted by other researchers[22,23,27]. Researchers developed automatic[27] and semi-automatic[23] transplanters having higher FC than the developed mechanical transplanter (TMch) due to their multi-row system, and their FC varied from 0.054 to 0.071. Nonetheless, the proposed system also showed potential for effectively dealing with bare-root seedlings, and its field capacity might be increased even more by upgrading the developed mechanism into a multiple-row system. In the onion transplanting area, most of the researchers had developed the transplanters either for dealing with plug type[23] or pot type seedlings[27], and these systems required manual delivery of onion seedling-pot. However, few efforts had been made for the development of the semi-automatic onion transplanters, which can deal with bare-root onion seedlings[18,22], but require additional labor for feeding of onion seedlings to each row. Among all above-mentioned systems, it is clear that human interference is essential for feeding of onion seedling, which might be a potential cause for human hazard under working conditions. Additionally, seedling spacing uniformity also becomes a cause of concern because humans have limited feeding capability and activity on these machines, which may negatively influence the overall onion production. On the other hand, the proposed transplanter has the potential to eliminate labor over the machine under working conditions by the use of a well-designed magazine, which accommodates sufficient onion seedlings, and drops seedling automatically with a cut-off mechanism. Thus, it removes dependency on the human skill required for onion seedling feeding and maintains uniform seedling-to-seedling spacing. The research findings under TMch method confirmed that the developed novel mechanical onion transplanter is ideally compatible with other onion cultivation methods in dealing with every aspect of bare-root onion seedlings. Moreover, the developed system showed leverage over other cultivation techniques by offering greater performance compared to the manual transplanting along with high field capacity. It also shows a great potential to increase the onion production and productivity with high quality of onion by ensuring uniform seedling spacing and appropriate soil-nutritional space for each onion seedling.

For future perspective, this automated mechanism may be transformed into a multi-crop transplanting system and used for the transplanting of the pot seedlings of vegetable and horticultural crops like chilli, pea, brinjal, and similar crops. The conveyor belt and vertical conveyor rollers can be driven by electric motor to regulate the forward speed of the magazine, which can facilitate variable rate planting. With certain magazine, shoe design modification, and proper adjustment of gear ratio as per agronomically recommended planting requirements, it can be adopted for multi-crop transplanting applications under diversified field conditions. It can be upgraded for multi-row systems, which will not only improve its field capacity and efficiency, but will also contribute to lower carbon emissions and save precious time, ultimately leading to lower cost of production. Additionally, a sensor-based choking detection system can be embedded within the developed transplanter for each row, which will give a choked shoe alert to the driver on the screen during working conditions. Finally, it can improve crop productivity by timely ensuring smooth and uniform transplanting in the field.

5 Conclusions

This study confirmed that the developed mechanical onion transplanter was highly reliable for accurate placement of bare-root seedling, maintained proper seedling space and uniform sowing depth, and led to a favorable micro-climate for overall onion bulb development in comparison to other onion cultivation techniques. Study results revealed that high quality of onion bulb, i.e. large and extra-large bulb size, was observed under TMch and TM techniques, which might positively influence the onion processing industries. Under both TMch and TM methods, higher average weight of onion bulb and >90% seedling survival rate was observed, which might assure higher onion productivity and production. The proposed system (TMch) might meet seasonal labor demand with higher field capacity and save considerable costly onion seeds as compared to that of the TM, and even prevent human hazard by eliminating human involvement in feeding of onion seedling. The field capacity of the developed system might be further scaled up by upgrading it into a multi-row system and automation unit.

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[References]

[1] Serkara A, Pokluda R, Vacchio L D, Somma S, Caruso G. Interactions among genotype, environment and agronomic practices on production and quality of storage onion (*Allium cepa* L.) – A review. Horticultural Science, 2017; 44(1): 21–42.

[2] Joy P P, Thomas J, Mathew S, Skaria B P. Medicinal plants. In: Bose T K, Kabir J, Das P, Joy P P, editors. Tropical Horticulture, Vol. 2. Calcutta: Naya Prokash, 2001; 449–632.

[3] Jangandi S, Berker R D, Nageshkumar T. Development and evaluation of tractor operated onion seed drill. In: International Conference on Role of Agricultural Engineering toward Global Food Security, Bengaluru, India, April 11–13, 2019.

[4] Grewal R S. Development and evaluation of tractor operated planter for onion crop. M. Tech thesis. Ludhiana: Punjab Agricultural University, 2014.

[5] Panjab Agricultural University. Report of the All India Coordinated Research Project on Farm Implement and Machinery. Ludhiana: Panjab Agricultural University, 2004.

[6] Turbatmath P A, Bhatt Y C, Kadam P B. Development and field evaluation of tractor operated onion transplanter. International Journal of Agricultural Engineering, 2011; 4(1): 52–55.

[7] Verma K, Thakur S S, Khurana R, Narang M K. Design and development of onion drum seeder for direct sowing of onion (*Allium cepa* L.) seeds. Journal of Krishi Vigyan, 2021; 9(2): 40–45.

[8] Grewal R S, Khurana R, Manes G S, Dixit A, Verma A. Development and evaluation of tractor operated inclined plate metering device for onion seed planting. Agricultural Engineering International: CIGR Journal, 2015; 17(2): 31–38.

[9] Annamalai S, Vignesh K, Vikneswaran N. Design and fabrication of onion seed sowing machine. International Journal of Scientific Research in Science, Engineering and Technology, 2019; 6(2): 447–450.

[10] Mahapatra J, Tiwari P S, Singh K P, Nandede B M, Sahni R K, Pagare V, et al. An adjustable pneumatic planter with reduced source vibration for better precision in field seeding. Sensors, 2024; 24(11): 3399.

[11] Mahapatra J, Tiwari P S, Singh K P, Nandede B M, Singh J, Sahni R K. Flexible orifice seed metering plate to address variability in seed shape, size and orientation enhances field performance of a pneumatic planter. Discover Applied Sciences, 2024; 6(11): 609.

[12] Mahapatra J, Tiwari P S, Singh K P, Nandede B M, Sahni R K, Singh J, Pagare V. Optimization of operational parameters for pneumatic planting of cotton seeds using a standard metering plate. Scientific Reports, 2025; 15(1): 33746.

[13] Mahapatra J, Sahni R K, Pagare V, Singh J, Tiwari P S, Singh K P, Nandede B M. An analytical procedure in pneumatic seed meter design for enhanced performance validated through development and evaluation. Ain Shams Eng J, 2026; 17(2): 104001.

[14] Kumar S, Pal S, Joshi P K. Vegetable sector in India: An overview. In: National Seminar on Impact of Vegetable Research in India, National Centre for Agricultural Economics and Policy Research, New Delhi, India, March 1–2, 2002.

[15] Kumar G V P, Raheman H. Vegetable transplanters for use in developing countries: a review. International Journal of Vegetable Science, 2008; 14(3): 232–255.

[16] Kulhariya S K, Naik R K, Singh S, Diwan P, Kumar A, Hemshanker. Design of power tiller operated vegetable transplanter. The Pharma Innovation Journal, 2021; 10(12): 2010–2014.

[17] Pandirwar A, Kumar A, Mani I, Islam S. Biometric properties of onion seedlings relevant to the development of onion seedling transplanter. Journal of Applied and Natural Science, 2015; 7(2): 768–773.

[18] Turbatmath P A. Development and performance evaluation of tractor operated onion transplanter. PhD dissertation. Udaipur: Maharana Pratap University of Agriculture and Technology (MPUAT), 2011.

[19] Singh S. Research highlight. Report of all India coordinated research project on farm implements and machinery. Bhopal, India: Central Institute of Agricultural Engineering, 2008.

[20] Magar A P, Nalawade S M, Walunj A A, Gaikwad B B, Shelke G N, Khadatkar A, Modi R U. Development and optimization of an automatic transplanting device for plug tray vegetable seedlings using embedded system. Scientific Reports, 2025; 15(1): 22483.

[21] Li G, Xu Y, Han C, Liang J, Luo Y, Mao H, Cao G. Design and experiment of the follow-up seedling picking and depositing mechanism for the pepper plug seedling transplanter. Agriculture, 2025; 15(19): 2026.

[22] More P S. Tractor drawn onion transplanter. Available at: www.nif.org.in. 2008. Indian Patent Applied (No. 2353/MUM/2008).

[23] Pandirwar A, Kumar A, Singh J K, Mani I, Bhowmik A. Development and evaluation of semi-automatic six row onion seedlings transplanter. Agricultural Mechanization in Asia, Africa and Latin America, 2019; 50(1): 29–35.

[24] Pandirwar A. Design and development of mechanical transplanter for onion seedlings. PhD dissertation. New Delhi: Indian Agricultural Research Institute, 2016; 22.

[25] Kumawat L, Raheman H. Determination of engineering properties of onion crop required for designing an onion harvester. Cogent Engineering, 2023; 10. DOI: 10.1080/23311916.2023.2191404.

[26] Zhou M, Sun H, Xu X, Yang J, Wang G, Wei Z, Yin J. Study on the method and mechanism of seedling picking for pepper (*Capsicum annuum* L.) plug seedlings. Agriculture, 2023; 14(1): 11.

[27] Kumawat L, Raheman H, Singh V. Design and development of a tractor drawn automatic onion transplanter. International Journal of Current Microbiology and Applied Sciences, 2020; 9: 2020.

[28] Onion (*Allium cepa*). Available at: https://vikaspedia.in/agriculture/crop-production/package-of-practices/vegetables-1/onion-allium-cepa. Accessed on [2024-02-28].

[29] Chaudhari D, Singh V V, Dubey A K. Refinement and adoption of mechanical vegetable transplanter for Indian condition. Agricultural Engineering Today, 2002; 26(5-6): 11–20.

[30] Nandede B M, Carpenter G, Chillur R, Jadhav M L. Development of a low cost manually operated two row vegetable transplanter. International Journal of Tropical Agriculture, 2017; 35(4): 1047–1055.

[31] Khadatkar A, Mathur S M, Gaikwad B B, Pandirwar A, Shrinivas D J. Biometric properties of plug vegetable seedlings relevant to the design of vegetable transplanter. Journal of Agricultural Engineering, 2020; 57(1): 16–24.

[32] Pagare V, Din M, Mehta C R, Nandede B M, Kumar M. Morphological and mechanical characteristics of onion seedlings insight to mechanized transplantation. Indian Journal of Agricultural Research, 2022. DOI: 10.18805/IJARe.A-5844.

[33] Singh J, Din M, Agrawal K N, Jyoti B, Roul A K, Kumar M, et al. Estimation of leaf area and leaf area density for design optimization of a recycling tunnel sprayer. Journal of Scientific & Industrial Research, 2022; 81(2): 173–179.

[34] Singh J, Din M, Agrawal K N, Jyoti B, Roul A K, Pagare V. Assessment of morphological attributes of guava tree for design of a novel tunnel spraying system. Environment Conservation Journal, 2024; 25(1): 1–9.

[35] Singh J, Din M, Agrawal K N, Jyoti B, Roul A K, Mahapatra J, et al. Enhancing tunnel sprayer performance through optimization of constructional parameters. Scientific Reports, 2025; 15(1): 20349.

[36] Singh J, Din M, Mahapatra J, Pagare V, Agrawal K N, Jyoti B. Optimization of spray control parameters for improving performance of the tunnel sprayer. Results in Engineering, 2026; 29: 109190.

[37] Misra A D, Kumar A, Meitei W I. Effect of spacing and planting time on growth and yield of onion var. N-53 under Manipur Himalayas. Indian J Hortic, 2014; 71(2): 207–210.

[38] Shah K P. Construction and maintenance of belt conveyors for coal and bulk material handling plants. 2018; 269p.

[39] DKT Engineering Enterprises. Difference between PVC conveyor belts and polyurethane belts. 2024. https://www.dktee.com/pvc-conveyor-belt-vs-pu-belt/

[40] Turner A, Jones K, Filella M. The density of virgin, consumer and environmental plastics: An investigation using gas displacement pycnometry. Sci Total Environ, 2025; 979: 179457.

[41] Daniyan I A, Omokhuale A M, Aderoba A A, Ikumapayi O M, Adaramola B A. Development and performance evaluation of organic fertilizer machinery. Cogent Engineering, 2017; 4(1): 1364044.

[42] Omari S, Majidi A H, Amiri A F. Effect of nitrogen and plant spacing on the growth and yield of onion (*Allium cepa* L.) in Afghanistan. Plant Physiology and Soil Chemistry, 2023; 3(2): 99–106.

[43] Alemu D, Kitila C, Garedew W, Jule L, Badassa B, Nagaprasad N, Seenivasan V, Saka A, Ramaswamy K. Growth, yield, and yield variables of onion (*Allium cepa* L.) varieties as influenced by plant spacing at Dambi Dollo, Western Ethiopia. Scientific Reports, 2022; 12. doi: 10.1038/s41598-022-24993-x

[44] Matin M A, Hossain M I, Gathala M K, Timsina J, Krupnik T J. Optimal design and setting of rotary strip-tiller blades to intensify dry season cropping in Asian wet clay soil conditions. Soil & Tillage Research, 2020; 104854. doi: 10.1016/j.still.2020.104854.

[45] Hoque M A, Hossain M M, Ziauddin A T M, Krupnik T J, Gathala M K. Furrow design for improving crop establishment of two-wheel tractor operated strip tillage planters in loam and clay loam soils. Int J Agric & Biol Eng, 2021; 14(3): 130–139.

[46] Verma A K, Dewangan M L, Singh V V, Das V. Mechanical consideration for design and development of furrow openers for seed-cum-fertilizer drill. Agricultural Mechanization in Asia, Africa and Latin America, 2007; 38(2): 74.

[47] Khurmi R S, Gupta J K. A textbook of machine design. 14th ed. New Delhi: Eurasia Publishing House, 2008.

[48] Singh J, Kumar A, Singh L. Design, development and evaluation of transplanting mechanism of single row prototype for rice seedlings. The Pharma Innovation, 2021; 10(4): 282–287.

[49] BARI. BARI technology hand book. Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh, 2016.

[50] Agricultural and Processed Food Products Export Development Authority (APEDA). Commodity profile on onion. New Delhi: Government of India, 2024; 10–12. Available at: https://agmarknet.gov.in/Others/Onion.pdf.

[51] Karayel D, Haciyusufoğlu A F, Çanakci M, Topakci M. Performance of a large seed vacuum planter for bare and pelleted onion seeds. Mediterranean Agricultural Sciences, 2020; 33(2): 253–258.

[52] Celik A, Ozturk I, Way T R. Effects of various planters on emergence and seed distribution uniformity of sunflower. Applied Engineering in Agriculture, 2007; 23(1): 57–61.

[53] Pagare V, Din M, Nandede B M, Yadav D, Mehta C R, Kumar M, Singh K. A comparison of onion seedling growth under various environmental conditions, with an emphasis on mechanical transplanting. Journal of Applied Horticulture, 2022; 24(1): 36–41.

[54] Ozmerzi A, Karayel D, Topakci M. Effect of sowing depth on precision seeder uniformity. Biosystems Engineering, 2002; 82(2): 227–230.

[55] Kavitha R, Duriasamy V M. Development and evaluation of semi-automatic vegetable transplanter for plug seedlings. In: International Agricultural Engineering Conference, Bangkok, Thailand, December 3–6, 2007.

[56] Bahnasawy A H, El-Haddad Z A, El-Ansary M Y, Sorour H M. Physical and mechanical properties of some Egyptian onion cultivars. Journal of Food Engineering, 2004; 62(3): 255–261.

[57] Demisie R, Tolessa K. Growth and bulb yield of onion (*Allium cepa* L.) in response to plant density and variety in Jimma, South Western Ethiopia. Advances in Crop Science and Technology, 2018; 6(2): 2–6.

[58] Khan M A, Hasan M K, Miah M A J, Alam M M, Masum A S M H. Effect of plant spacing on the growth and yield of different varieties of onion. Pakistan Journal of Biological Sciences, 2003; 6(18): 1582–1585.

[59] Sikder M, Mondal F, Mohammed D, Alam M S, Amin M B. Effect of spacing and depth of planting on growth and yield of onion. Journal of Agroforestry and Environment, 2010; 4(2): 105–108.

[60] Ngullie R, Biswas P K. Effect of plant and row spacing on growth and yield of onion under Mokokchung district of Nagaland. International Journal of Plant Sciences, 2017; 12(1): 28–35.

[61] Pandiselvam R, Pragalyaashree M M, Kailappan R, Thirupathi V, Krishnakumar P. Moisture dependent engineering properties of onion seeds. Journal of Agricultural Engineering, 2014; 51(2): 36–43.

[62] Ketema S, Dessalegn L, Tesfaye B. Effect of planting methods on growth of onion (*Allium cepa var. cepa*). Advances in Applied Physiology, 2018; 3(1): 8–13.

[63] Jeevitha D, Chimmalagi U, Adishesha K, Hosamani G B, Vinay V T, Dharmatti P R. Influence of planting methods on growth, yield and storage of onion (*Allium cepa* L.) var. Bhima Shakti. Indian Journal of Agricultural Research, 2024; 58(5): 885–888.

[64] Ketema S, Dessalegn L, Tesfaye B. Effect of planting methods on maturity and yield of onion (*Allium cepa var. cepa*) in the Central Rift Valley of Ethiopia. Ethiopian Journal of Agricultural Sciences, 2013; 24(1): 45–55.