Furrow design for improving crop establishment of two-wheel tractor operated strip tillage planters in loam and clay loam soils

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Abstract: Conservation agriculture (CA) based production systems may help in achieving more sustainable intensification of cropping systems that use less labour and energy and have higher profit margins, in addition to soil conservation and environmental impact mitigation advantages. But these objectives can only be achieved when the right mechanization options, including appropriate crop establishment equipment, are in place to assist in timely field operations. An urgent need exists, therefore, to fine tune and re-adjust the existing two-wheel tractor (2WT) operated seed drills, with specific reference to the design of blade and furrow openers, while at the same time considering performance in different soil types and environments. To this end, experiments were conducted during 2013-2014 and 2014-2015 at two BARI Regional Agricultural Research Stations in Jamalpur and Barisal, Bangladesh, on a loam and clay loam soil, respectively, to evaluate five types of furrow opener for strip tillage. Shoe and modified shoe-type furrow openers were tested and compared with three inverted-T furrow openers with rake angles of 75°, 65° and 55°. The newly designed inverted-T furrow openers were narrower than the shoe-type openers; they also had a longer, hollow shanks and provided better options for adjustment to achieve the desired seeding depth and line spacing. Compared to shoe-type openers, better seeding depth, uniformity and higher degree of seed coverage were recorded with use of the inverted-T furrow opener with a 65° rake angle. This resulted in better seed coverage in the furrow, a higher emergence rate index, and the highest emergence percentage of maize and mung bean. Our research findings can be generalized to smallholder production systems on loam and clay loam soils where farmers utilize 2WT operated seed drills for crop establishment in both traditional and conservation agriculture-based planting systems.

Keywords: two-wheel tractor, strip tillage planter, inverted-T furrow opener, rake angle, conservation agriculture, emergence percentage

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1 Introduction

Over the last forty years, a process of transformation has been underway in Bangladesh agriculture, from the use of animal-drawn land preparation to two-wheel tractor (2WT)-based mechanized land preparation and crop establishment approaches. In 2020, more than 95% farmland is prepared mechanically, a change relative to twenty years ago that affects the country's high level of crop intensification[1,2]. More than 700 000 2WTs (also known as power tillers) – imported mainly from China – can be found operating in Bangladesh. Their use is multipurpose, but predominantly for land preparation and the transportation of agricultural products and goods[1-3]. However, current agricultural production systems are relatively energy inefficient and rely on multiple tillage events for land preparation. In some crops, such as maize, this is followed by labour intensive manual crop establishment[4,5]. From 2019 forward, the Government of Bangladesh (GOB) has increased attention and support for small-scale and appropriate agriculture mechanization (from planting through to processing) including incentive programs to address labour shortages encountered during peak portions of the crop season, and to reduce the turn-around time between successive crops[6,7]. Scale-appropriate mechanization can have additional 'knock-on' benefits including the provision of tools and techniques to build resilience climatic stresses by enabling them to complete operations in a timely manner before heat stress or extreme rainfall events can reduce yields and damage crops intensive rice-based rotational farming systems with multiple alternative crops[1].

During the last decade, market development efforts have been put into place to facilitate the commercial availability of predominantly imported power tiller operated seeders (PTOS) as an attachment for 2WTs. The common model of PTOS mounted on a 2WT is characterized by its high speed (500 r/min) shallow rotary tillage, with 48 'C type' (C shaped) blades on a rotor and comprising a fluted seed metering system with shoe-type furrow openers for seeding crops in a single pass. The small shank shoe-type furrow openers align with the imported PTOS, facilitating an airdrop seeding mechanism and simultaneous

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covering with a laddering operation. This configuration however leads to poor crop germination and establishment, due to poor seed to soil contact and coverage, and quick drying of top soil[8]. The imported seeders are fabricated with a fluted roller-type seeding mechanism, which accommodates small-to-medium seed for continuous seeding, but not for precise planting.

Conservation agriculture (CA) based practices can, when properly implemented, assist in crop productivity and profitability gains, while also optimizing use of limited input resources (such as labor, energy and water). Recently (2015 onwards), Bangladesh has seen a research priority shift towards mechanized crop production, from seeding to processing including conservation agriculture in particularly 2WT operated strip tillage and crop establishment. Based on experience with the Chinese seeder, the Bangladesh Agricultural Research Institute (BARI) designed and developed an inclined plate seeding mechanism for planting multi-crops, including small and large seeds[9].

As practiced in South Asia, strip tillage is a form of minimum tillage in which small 5-6 cm wide strips are tilled into which seeds are deposited and covered with soil. The inter-row space remains undisturbed in order to meet the principles of conservation agriculture (CA), which is slowly getting momentum in Bangladesh, especially for 2WT operated planters[9,10]. The existing PTOS can be modified as a strip tillage planter by reducing in number and introducing specialized soil cutting blades attached to the PTOS rotovator. The number of blades used depends on the row-to-row crop spacing. The modified PTOS also has press wheels behind the seeding line to ensure proper furrow closure and, as a result, better soil-to-seed contact for improved moisture retention and supply during seed germination[11]. Use of an appropriate seeding mechanism is important for crop establishment performance; placing and distributing seed at the right depth and spacing is key to achieve the desired level of crop density[12,13]. This is possible only when each component part of the machine is designed appropriately, and functions effectively in the field.

The furrow opener is a key component for ensuring proper seed placement at the right depth with proper seed soil coverage in the seeding furrow. In general, a furrow opener cuts the soil, makes a furrow and allows the seeds to be deposited before they are partially covered with soil. The type of furrow opener used depends on soil type, texture, soil moisture, field operating conditions (such as no-till, tilled, and the quantity of crop residue on the soil surface) and crop[14]. Furrow openers commonly used for minimum and no tillage systems are the inverted-T and disc types[13,15]. Disc-type furrow openers are recommended and highly suitable for large planters, which in turn are most suited to large farms with high horsepower and heavy tractors. Disks are less suitable for small and lightweight tractor configurations; similarly, large and heavy tractors are less manurable the small field sizes that prevail in Bangladesh.

Less costly and lighter strip/no-till type-based seed drills are therefore likely to be more appropriate and for effective operation in small fields, using either two- or four-wheel light weight tractors with smaller horsepower (12-40 hp) as found in Bangladesh and eastern India[14,16,17]. Inverted-T furrow openers also perform better under no-till/minimum-till when compared to traditional types of furrow openers (such as shoe, hoe, chisel, wing chisel types) in respect to power requirement, soil disturbance, seed coverage, and rate of plant emergence, all of which interact to affect crop establishment performance[18]. The use of shoe-type openers (that is, the type of furrow opener regularly supplied with a PTOS) have the disadvantage of resulting in a higher rate of soil moisture loss due to the greater soil disturbance and excavation of soil from the furrow that they produce[19]. With improved seed-to-soil contact through proper soil coverage at effective depth, appropriate levels of soil moisture can be retained to aid in seed imbibition water vapour intendency within the furrow-groove micro-environment[20]. Shoe-type furrow openers found on most manufacturer PTOS are however unable to cover the seed properly during strip tillage because they are designed for use with an air-seed dropping mechanism[10,16]. Field evaluation of the seeder using inverted-T furrow openers for both conventional and zero tillage systems showed a higher plant emergence when compared to traditional practice[21,22]. Soil disturbance was less in the case of the inverted-T furrow opener than with shoe and shovel-type furrow openers[23].

Ideal furrow quality parameters (such as cross-sectional area, furrow backfill, moisture content, bulk density and penetration resistance) can be achieved through the appropriate structural design (including type, thickness, cutting edge angle and thickness, rake angle) of the furrow opener[11,13]. These parameters can also be changed with the forward speed of tractor during planting and presence of crop stubble. A greater forward speed of tractor increases the displacement of soil, and crop stubble may lead to poor soil backfill and influence the other parameters[24]. In Bangladesh, 2WT operated seeders are mainly operated as walk-behind machines during field operation with a forward moving rate of approximately 3.0±0.5 km/h; as such, soil displacement should – at least theoretically – not be considered an influencing factor[8,9]. The greater and smaller rake angles of the different openers significantly influence soil movement within the furrow, penetration ability, soil furrow backfill, and optimum rake angle suggested in the previous study was 45°-60° as this created the lowest soil disturbance. Use of an appropriate opener with appropriate rank angle (45°-60°) leads to improved furrow backfill by reducing the portion of rake angle that lifts the soil compared to larger rake angles[14].

The depth of sowing is influenced by the depth of furrow tilling and opener penetration[25]. Research indicates that the seedbed should extend downwards only to the seeding depth, as working to greater depths is costly and can bring about unnecessary loss of soil moisture[8]. The optimum seed furrow depth is also governed by crop requirements (e.g. coleoptile length), and seedling emergence can be seriously affected by either deeper or shallower depths[26]. To facilitate deeper seeding depth, the imported shoe-type furrow opener was modified in by the Wheat Research Centre, Bangladesh Agricultural Research Institute, in Dinajpur Bangladesh[12]. These modified shoe type furrow openers were tested for both full tillage and strip tillage. However, the larger width of these openers was found to reduce soil backfill in the furrow. To improve soil backfill and ensure proper seed placement in the narrow strip, a narrower furrow opener was desired. Inverted-T furrow openers tend to be narrower and capable of placing seed and fertilizer at the desired depth when used with a 4WT zero-till planter[27], although designs for lightweight 2WT equipment are less common. The geometry of an opener also affects the characteristics of the furrow and pattern of soil movement[28]; moreover, the type of furrow opener used may need to be varied according to soil type and operating conditions (although research into the performance of different types of furrow opener for use with the 2WT operated seeder is very limited in Bangladesh). As such, an inverted-T furrow opener was developed in this study by scaling down these large openers to a design compatible for use with a PTOS.

In response, this study evaluates strip tillage and crop establishment performance for different furrow geometries and assesses which combination ensures the best seed placement.

2 Materials and methods

2.1 Experimental site and treatment design

Experiments were conducted at the Regional Agricultural Research Station (RARS) under the Bangladesh Agricultural Research Institute (BARI), in two locations in Bangladesh (Jamalpur and Barishal) for two one-year periods in 2013-2014 and 2014-2015. Geographically, the study areas of Barishal and Jamalpur were located at 22°47'22.2432"N, 90°17'23.7228"E and 24°56'30.6844"N, 89°55'40.3882"E, respectively. The soils of Jamalpur and Barishal are loam and clay loam, respectively (Table 1). Soil moisture and bulk density in the topsoil (0-15 cm) at Jamalpur and Barisal were 24.0% and 1.42 g/cm^3 and 26.3% and 1.33 g/cm^3, respectively, at the time of sowing.

Table 1 Soil properties of the two experimental locations

Soil properties	Location	
	Jamalpur	Barisal
Sand/%	47.28	40.25
Silt/%	30	24.75
Clay/%	22.72	35
Textural class	Loam	Clay loam
Soil moisture content in Year 1/%	24.5	25.31
Soil moisture content in Year 2/%	23.47	27.01
Soil bulk density in Year 1/g·cm^{-3}	1.42	1.33
Soil bulk density in Year 2/g·cm^{-3}	1.42	1.32

The experiments used a PTOS consisting of an inclined plate seed metering device and a fluted roller for fertilizer metering. Five different types of furrow opener were fitted on bars attached to the PTOS to enable the sowing of maize and mung bean seed using strip tillage in the presence of 20-25 cm standing height of anchored crop residue from the preceding rice crop that was established in approximately 20 cm×15 cm hill-to-hill spacing. (Figures 1 and 2). The furrow openers were: F_1 = a shoe-type furrow opener, generally supplied with the Chinese PTOS and with an airdrop seed mechanism under full tillage; F_2 = a modified shoe-type furrow opener, generally supplied with the inclined plate planter designed by the Wheat Research Center (WRC), BARI; F_3 = an inverted-T furrow opener with a 75° rake angle; F_4 = an inverted-T furrow opener with a 65° rake angle, and F_5 = an inverted-T furrow opener with a 55° rake angle.

A randomized complete block design with three replications was used. The PTOS was operated using a modified blade design with a 15° tip angle and rotary shaft operating at 480 r/min. In this study, we used the 2WT operated walk-behind strip tillage seeder (commercially available PTOS generally lack a seating arrangement) and maintained a forward speed of 3.0 km/h during planting to eliminate any possible speed variation effect on furrow opener performance. The experiment was conducted with two crops, namely, maize and mung bean, both sown after harvest of the preceding rice crop, of the varieties NK40 and BARI Mung 6, respectively. The individual testing plot size was 50 m^2 (10 m× 5 m) across the two years, crops and locations, and four running passes were executed in each plot, maintaining 2 and 4 rows in each pass for maize and mung bean, respectively. Multiple tractors were used to execute the planting operations in order to minimize the planting time difference among the treatments. Each tractor was a Dongfeng 16 hp power tiller with the PTOS attached, configured in identical fashion to eliminate any differences between crop establishment equipment. Sowing was conducted before noon at each site in both years, though the date of planting differed between locations in respect of crop species. Both crops were sown on 10 November in 2013 and November in 2014 (Jamalpur and Barisal), and on 5 April in 2013 and 10 March 2014 (sowing was delayed in the second session, due to field access only being possible in February because of prolonged excess soil moisture following the retreat of the monsoon).

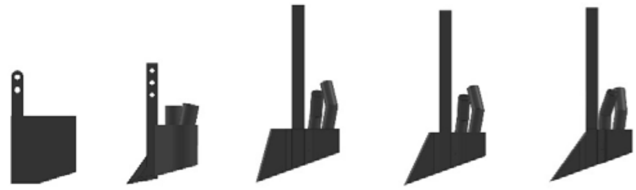


Figure 1 Isometric 3D views of different furrow openers used in this study

2.2 Characteristics of furrow openers

Comparative parameters of different furrow openers were used as different treatments, summarized in Table 2. The length of the shoe-type furrow opener (F_1) was 175 mm which was the shortest; however, the length of the original furrow opener, which came with the imported PTOS, was even shorter, at 155 mm. The length of the modified shoe-type furrow opener (F_2) was 200 mm; the length of the inverted-T furrow openers (F_3-F_5) with rake angles of 55°, 65° and 75° was 325 mm. The width of the Chinese shoe-type opener was 36 mm, 60% of the tilling strip width (60 mm). The width of the modified shoe furrow opener was 60.92 mm, slightly wider than tilling strip width. The width of the newly designed inverted-T furrow opener model was 25 mm; in comparison, much narrower (by 42%) than the tilling strip width. The shank of the shoe-type and modified openers was solid, and the dimensions ($w\times b\times l$) were 20 mm × 10 mm × 175 mm and 18 mm × 75 mm × 200 mm, respectively. In contrast, the shank of the inverted-T furrow opener model was hollow, and the dimensions were 25.40 mm × 15.24 mm × 305 mm. The shoe and modified shoe-type openers were attached to the planter by three bolts and sliding-type clamps with limited fixed 2-3 cm depth small adjustment options. The inverted-T furrow openers were fitted on with a universal-type single bolt clamp, able to be adjusted in a two-way direction to achieve the desired depth of seeding and line spacing (Figure 2).

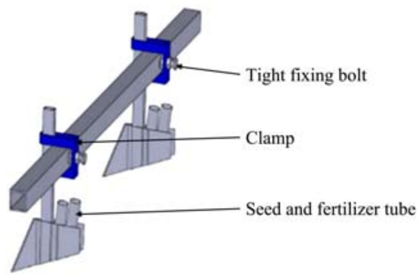


Figure 2 Inverted-T type furrow opener attaching system used in this study

Table 2 Detailed characteristics of different furrow openers

Parameters	Treatments				
	F_1	F_2	F_3	F_4	F_5
Rake angle/(°)	-	-	75	65	55
Length of furrow opener with shank/mm	175	200	325	325	325
Width of strip/mm	60	60	60	60	60
Width of furrow opener/mm	36.00	60.92	25	25	25
Shank type	solid	Solid	hollow	hollow	hollow
Shank dimensions (w × b)/mm	20×10	18×75	25×15	25×15	25×15
Options for changing depth	two	Three	any depth	any depth	any depth
Weight of the furrow opener/g	925	850	820	525	475
Attaching clamp	Sliding clamp	Sliding clamp	2-way movable clamp	2-way movable clamp	2-way movable clamp
Attaching bolts	3	3	1	1	1

2.3 Crop management and data collection

The inter-row and plant spacing for maize and mung bean were 60 cm×20 cm and 30 cm×6 cm, respectively. Five days before planting, a pre-plant herbicide roundup (Glyphosate) was applied at 3.7 L/hm^2 (1.0 kg/hm^2 active ingredient) using 320-400 L/hm^2 of water and a three-nozzle flat-fan spray boom. Urea at 0.15-0.2 kg/hm^2 was mixed in the sprayer tank to increase the efficiency of the herbicide by increasing plant absorption. The recommended basal dose of fertilizer was applied in all treatments in both locations. Diammonium phosphate (DAP) fertilizer was drilled in at the rate of 95 kg/hm^2 with seed at the time of sowing. The remaining N and K fertilizers were applied manually as urea and muriate of potash in both locations for maize. The basal fertilizer dose per hectare in both locations for maize was 80 kg of N, 46 kg of P_2O_5 and 65 kg/hm^2 of K_2O.

Uncovered seeds were counted for both maize and mung bean from four random places just after seeding; for maize and mung bean, seeds were counted from a 10 m and 1 m row length, respectively. The number of seeds planted per linear meter strip was calculated from seed spacing and seed rates, which were 5 and 17 for maize and mung bean, respectively. The percentage of uncovered seed was calculated using the following equation:

$$U = \frac{N_u}{N_p} \times 100 \quad (1)$$

where, U is the percentage of uncovered seed; N_u is the number of uncovered seed observed per linear meter; and N_p is the number of seeds planted/sown per linear meter.

To measure plant depth uniformity, drilled seeds were irrigated gently and adequate time allowed for seedling emergence. Following emergence, seedlings were cut at the soil surface and the plant stem (from the soil surface to the seed remnants on the root) was taken out carefully with the seed and its length measured. An average of 20 samples was taken as depth of seed planted and average deviation of the depth of seeds planted from the pre-set planting depth was calculated. The coefficient of planting depth uniformity was then computed using the following equation[29,30]:

$$S_d = 100(1 - \frac{Y_d}{D_d}) \quad (2)$$

where, S_d is the coefficient of seeding depth uniformity, %; Y_d is the average numerical deviation of depth of seeds planted from pre-set planting depth; D_d is average depth of seeds planted. Observations of emergence were taken at 2 d-intervals from sowing onwards from a 2 m-long strip per plot. The mean emergence time (*MET*), emergence rate index (*ERI*), and seedling emergence rate (*ER*) were calculated using Equations (3)-(5)[31].

$$MET = \frac{(N_1T_1 + N_2T_2 + ... + N_nT_n)}{(N_1 + N_2 + ...N_n)} \quad (3)$$

$$ERI = \frac{Ste}{MET} \quad (4)$$

$$ER = \frac{Ste}{n} \times 100 \quad (5)$$

where, *MET* is the mean emergence time, d; *ERI* is the emergence rate index expressed in seedlings, d^{-1}; *ER* is the emergence rate, %; $N_1...n$ are the number of seedlings emerging since the previous count; $T_1...n$ are the number of days after sowing; *Ste* is the number of total emerged seedlings, m^{-2}; and n is the number of seeds sown per meter.

2.4 Data analysis

Analysis of the variance (ANOVA) was performed considering soil type and furrow opener design as factors, including replication as a fixed effect, and year as a random effect, as the furrow opener design × year interaction was found to be non-significant. As such, we pooled both years of data. All analysis was performed using JMP 8 software (SAS 9.4). Where significance was identified, means were separated using Tukey's Honestly Significant Difference *post-hoc* procedure. Bivariate Pearson's correlation coefficients and regression equations were computed along with PCA of the 6 furrow characteristics namely plant emergence rate (ER), mean emergence time (MET), emergence rate index (ERI), uncovered seed (US), seeding depth (SD), and seeding depth uniformity (SDU) to evaluate relationships between the response variables in reference to performance of the furrow designs.

3 Results and discussion

3.1 Effect of furrow openers on seed coverage

ANOVA results showed that soil type had no influence on maize seed coverage patterns, even though about 19% of the maize seeds were found uncovered in the 60 mm wide strip in both loam and clay loam soils (Table 3). The maize seed coverage pattern differed significantly ($p \leq 0.001$) between different furrow openers. The highest percentage of uncovered maize seeds was found with the shoe-type furrow opener (56%), followed by the modified shoe-type opener (37%). With inverted-T furrow openers (F3-F5), almost all the maize seeds were covered; at most only 1% seeds remained uncovered. Similar seed coverage patterns were observed among inverted-T furrow openers with a changing rake angle.

The mung bean seed coverage pattern was guided by soil type: clay loam soil had 3.5% higher uncovered mung bean seed compared to loam soil (Table 4). In clay loam soil, the higher uncovered seed percentage was due to (1) higher soil moisture content in the clay loam soil in both years (Table1), and (2) clay loam soils being more sticky in nature due to their high clay content and stronger particle bonds (this leads to the production of larger clods during strip tilling than with loam and sandy loam soils[32]). Seed coverage can be further improved by placing the press wheel behind the furrow openers in both soils[8,12].

Table 3 Effects of soil type, year and furrow opener types on mean emergence time (MET), emergence rate index (ERI), emergence rate (ER), uncover seed (US), seeding depth (SD) and seeding depth uniformity (SDU) on maize crop establishment in strip tillage

	US/%	*S*D/cm	*SDU*/%	*MET*/d	*ERI* /d^{-1}	*ER*/%
Soil type (soil)						
Clay loam	19.54	3.80	74.57	8.93a	0.44b	67.57
Loam	18.56	3.82	71.90	8.10b	0.51a	69.63
Furrow opener (FO)						
F1	55.51a	2.65c	54.97c	11.83a	0.13b	29.46c
F2	37.47b	2.80c	61.18b	10.83b	0.21b	44.08b
F3	1.25c	4.87a	82.08a	6.70c	0.67a	87.71a
F4	0.14c	4.57a	86.20a	6.54c	0.70a	91.83a
F5	0.22c	4.18b	81.75a	6.69c	0.67a	89.92a
Analysis of variance (*p* values)						
Soil	0.6312	0.8294	0.0984	0.0068*	0.0261*	0.2468
FO	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*
Soil × FO	0.2410	0.3433	0.2695	0.8913	0.6472	0.9110

Note: Within a column and not separated by factors, figures followed by the same/no letter are not significantly different using Tukey's HST test; the different furrow openers are: F1 = shoe-type furrow opener, F2 = modified shoe-type furrow opener, F3 = T-inverted furrow opener with 75° rake angle, F4 = T-inverted furrow opener with 65° rake angle, and F5 = T-inverted furrow opener with 55° rake angle. *p* value = the choice of significance level at $p<0.05$ levels.

Table 4 Effects of soil type, year and furrow opener types on mean emergence time (MET), emergence rate index (ERI), emergence rate (ER), uncover seed (US), seeding depth (SD) and seeding depth uniformity (SDU) on mung bean crop establishment in strip tillage

	US/%	*S*D/cm	*SDU*/%	*MET*/d	*ERI* /d^{-1}	*ER*/%
Soil type (soil)						
Clay loam	19.83a	2.07a	76.57b	5.91a	2.12	71.47a
Loam	16.37b	1.96b	78.81a	5.67b	2.01	66.91b
Furrow opener (FO)						
F1	41.23a	1.99b	66.07c	6.12a	1.32c	47.14c
F2	34.44b	1.98b	67.20c	6.05a	1.58b	56.03b
F3	4.94c	2.05a	83.41b	5.61b	2.44a	80.11a
F4	5.27c	2.02ab	86.82a	5.63b	2.50a	82.63a
F5	4.64c	2.03a	84.94ab	5.54b	2.48a	80.02a
Analysis of variance (*P* values)						
Soil	0.0009*	<0.0001*	0.0034*	0.0134*	0.1375	0.0231*
FO	<0.0001*	0.0070*	<0.0001*	0.0002*	<0.0001*	<0.0001*
Soil × FO	<0.0001*	0.0174*	0.0867	0.0013*	0.0945	0.3240

Note: Within a column, figures followed by the same letter/no letter are not significantly different (p=0.05) using Tukey's HST test; the different furrow opener are: F1 = shoe-type furrow opener, F2 = modified shoe type furrow opener, F3 = T-inverted furrow opener with a 75° rake angle, F4 = T-inverted furrow opener with a 65° rake angle, and F5 = T-inverted furrow opener with a 55° rake angle. P value = the choice of significance level at $p<0.05$ levels.

With mung bean, furrow openers followed the same trend as in maize seeding, with F1 (shoe-type) and F2 (modified shoe-type) seed coverage being poor, compared to F3, F4 and F5 (inverted T-type openers). The interaction effect of soil type and furrow opener on mung bean seed coverage pattern varied but was significant in all cases. The highest number of uncovered mung bean seed was found with the use of the shoe-type furrow opener in clay loam soil, followed by the modified shoe opener in clay loam soil. These findings are similar to those for mung bean seed sown in loam soil, using both the shoe and modified shoe furrow opener (Figure 3). The lowest rate of uncovered mung bean seed was found with inverted-T furrow openers for all rake angles in both the soils. The lower percentage of mung bean seed coverage using the shoe-type opener was as of designed for airdrop seeding for well-pulverised conventional till soils and under strip tillage, it could not penetrate up to desired depth as its shank length was short and not strong enough. In the case of the modified shoe type opener, although the shank length was longer than the shoe-type opener, the width was more than the standard strip width (60 mm). As a result, it was unable to penetrate the soil, or if it did penetrate it, it threw the tilled soil out of the furrow strip. Due to their long shank and narrower width (especially designed for no-till seeding), the inverted-T furrow openers were easily able to penetrate the tilled soil into the strip till furrow, to make furrows and place the seed at the desired depth, ensuring better seed coverage in the strip. This could also be attributed, in improved inverted furrow openers, to the cutting edge being thinner, with a concave edge providing better furrow backfill than the thicker, blunted cutting edge with a straighter cutting curve found in shoe type openers[33,14]. The number of uncovered seeds in shoe and modified shoe-type furrow openers was found to be lower for medium-sized seed (in this case, mung bean) than the large seed (in this case, maize). Small seeds need less soil coverage and have a greater chance to penetrate deeper within the pore space between soil particles.

3.2 Effect of furrow openers on seeding depth

Seeding depth did not vary between soil types for maize seed, but it did significantly vary for mung bean, which is a smaller sized seed. The seeding depth of mung bean was also deeper in clay loam than in loam soil (Table 4). The furrow openers significantly (p≤0.001 and 0.007*)* influenced seeding depth for both crops maize and mung bean, respectively at Jamalpur and Barisal. In general, as in the case of seed coverage, the inverted-T furrow openers maintained deeper seed placement than shoe (F1) and modified shoe (F2) openers in both crops. With maize, the inverted-T furrow openers maintained a 2 cm deeper seed placement than shoe and modified shoe furrow openers; this difference was minimal (but significant at p=0.007) for mung bean. Among the newly designed inverted-T furrow openers in maize seeding, those with 75° and 65° rake angles placed the seed deeper than the 55° rake angle; no difference was observed for mung bean among inverted-T furrow openers of every rake angle size.

The interaction effect of furrow opener and soil type on seeding depth did not vary significantly for maize, though it did for mung bean (at p=0.017; Figure 3). The combination of clay loam with the inverted-T furrow openers were shown to result in better seed placement than that of loam soil with the inverted-T furrow openers. The shallowest (1.93 cm) mung bean seed depth was observed in loam soil with the shoe-type (F1) furrow opener, closely followed by the modified shoe furrow opener (also with mung bean and in loam soil).

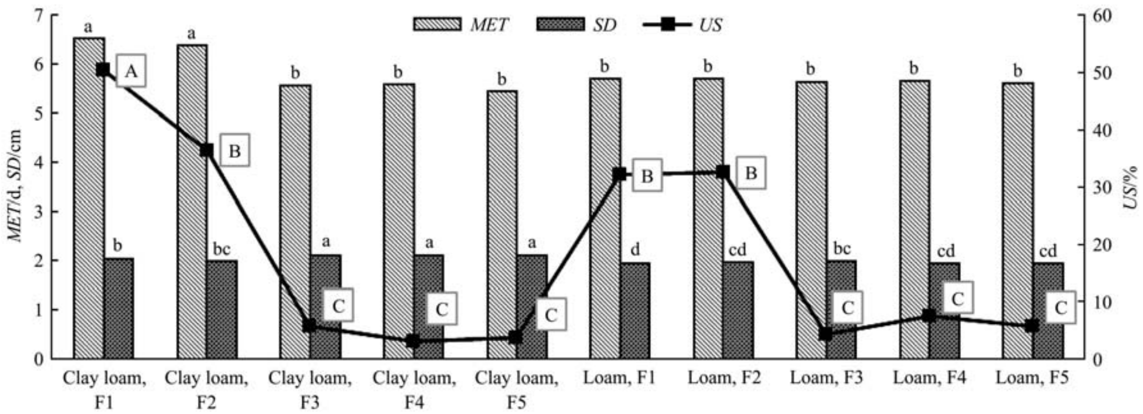


Figure 3 Interactive effects of soil type and furrow opener on mung bean mean emergence time (MET), seeding depth (SD) and uncovered seed (US) in strip tillage

Seeding depth and placement are influenced by factors such as crop, seed size, coleoptile length of the respective crop seed, ET losses, soil moisture and soil type[34]. In general, seed placement requires increasing seed depth with increasing seed size and in consideration of soil moisture status; small seeds required shallower depth in a range of 12-25 mm; medium-sized seeds such as mung bean typically require a depth in the range of 30-35 mm (but this is also related to their coleoptile length), and the depth of large seeds such as maize, chickpea, cotton and pea should be in the range of 50-80 mm (these depths all apply universally including in for Bangladesh[35]). Optimum seeding depth can also vary depending on the surface soil moisture condition at the time of sowing – deeper sowing is often recommended in dry soil conditions[8,36]. The improved inverted-T furrow opener is mounted on a separate frame with a single universal bolt clamp which allows flexibility for adjustment to any desired soil depth and spacing, depending on the seed size of different crops and soil moisture status. This is in contrast to shoe-type furrow openers, which have only limited options. Our findings clearly demonstrated that when the rotating blades were tilling and throwing soil particles out of the strip, these particles were thrown out from when they collided with the walls of a wider furrow, such as that formed by the modified shoe opener. In the case of the shoe-type furrow opener, some soil particles were thrown out from the strip due to the furrow's wider width, which created a barrier to soil back flow into the strip during tillage and before placing the seeds into the strip. Thus, the covering and placement of the seed was done with less precision. If seeds are placed before the soil aggregates, tended to be more fully covered by soil, but when they are placed on the soil aggregates themselves, they remain uncovered. However, the inverted-T furrow opener can minimize collision between soil particles and the opener body, due to its being less wide and, as a consequence, less soil is thrown out from the furrow. The present experiments thus produced better seed coverage with the inverted-T furrow opener, as it produced greater furrow backfill, resulting in the desired deeper seed depth.

An elliptical tool face produced less lateral soil throw and draught force compared to a blunt (flat) face[37]. Soil compaction at the seed level was shown to improve the emergence of crops, while compaction from the surface down may have the opposite effect[38]. Furrow compaction from the surface down to seed level is easier to implement, indicating that alternative methods of improving soil-seed contact which will not impair coleoptile and radicle development need to be devised[39]. According to this suggestion, the power tiller operated strip tillage planter with an inverted-T opener may be one of the best alternatives to current PTOS configurations. Here, strip tillage using rotating blades is followed by seeding with an inverted-T opener, assuring seed coverage with soil particles and subsequent moderate compaction through long laddering, contributing to an improvement in the emergence of crops. Furrow openers which produced subsurface shattering in zero tillage, such as inverted-T furrow openers, gave the best performance considering the rate of plant emergence and final plant stand due a more favorable and humid environment in the furrow opener groove[14]. Although this statement applies to zero tillage, it was observed similar results under strip tillage in this experiment, though additional research and careful soil moisture and water vapor measurements are needed to validate this hypothesis.

3.3 Seeding depth uniformity (SDU)

Seeding depth uniformity (SDU) followed the same trend as seeding depth and seed coverage, where larger seed (in this case, maize) was not influenced by soil type, but medium seed (mung bean) was found to be significant. Better SDU of mung bean was found in clay loam soil compared to loam soil (Table 4). Poor SDU of maize (54.97%) was recorded for the shoe-type furrow opener, and this was similar for the modified shoe opener (61.18%) (Table 3). The best SDU (86.20%) was recorded with the inverted-T furrow opener with a 65° rake angle, which was similar for all inverted-T openers when seeding maize. This also applied when seeding mung bean. Here, using the inverted-T furrow opener with a 65° rake angle, a higher SDU (>80%) was found to be more optimal than other treatments. This observation was similar to that found with the inverted-T furrow opener with 55° rake angle (Table 4). The lowest SDU was found with shoe types, and remained unchanged in the modified shoe-type furrow opener. Seeding depth uniformity for both maize and mung bean was not significant with the interaction effect of furrow openers and soil type.

Sowing depth is an important agronomic parameter affecting seed emergence[40] but must be uniform[26]. Lack of seed placement uniformity and failure to establish uniform plant stand are critical problems[41]. Our findings showed that depth of seed placement for the shoe and modified shoe-type furrow openers was poor, possibly due to reduced seed coverage capability and skips resulting from the airdrop seeding mechanism. However, for the inverted-T opener, depth of seeding was near the desired depth and SDU more uniform, possibly due to the better uniformity of soil backfill and seed coverage. Improved soil backfill and seed coverage obtained with inverted-T furrow openers is likely attributable to better controlled soil movement within the furrow, penetration ability, and soil furrow backfill due to the more optimum rake angle of 45° to 65° (which created the lowest soil disturbance because a smaller portion of rake angle lifted soil when pushed by the larger rake angle)[14].

3.4 Mean emergence time

The mean emergence time (MET) of both maize and mung bean varied significantly according to soil type, where a significant (p = 0.007 and 0.013) one-day delay was recorded in clay loam soil over loam soil. A higher MET was recorded with shoe and modified shoe-type furrow openers; 4.5 d and 1 d delays were observed for maize and mung bean, respectively, compared to when inverted-T furrow openers were used. Results for all inverted-T furrow openers remained unchanged for both maize and mung bean seed. The interaction effect of furrow openers and soil types on maize MET was not significant; mung bean MET was however influenced (p = 0.003) by furrow openers and soil type (Figure 3). The highest mung bean MET was found for the interaction of clay loam soil with the shoe and modified shoe-type furrow openers, compared to the rest of the interaction effects. Mean emergence time significantly increased (p = 0.003) with the depth of sowing[36]. Emergence time not only depends on seeding depth but also on SDU; poor SDU of the shoe-type opener was likely the reason for the greater MET. This is likely have occurred because deeply sown seed requires more time to emerge from the soil, while shallow placed seed requires more time to start the initiation of germination due to lack of moisture in the soil surface layers that result from higher evaporative losses. Seeding emergence after shoe and modified shoe-type opener use also lower (p≤0.001), a result of a greater percentage of uncovered seed (Table 4). Reduced or no tillage without proper soil cover resulted in poor crop establishment, which reduced crop yield[42].

3.5 Emergence rate index

The emergence rate index (ERI) of maize varied significantly (p = 0.026) by soil type, though no significant variation was observed with mung bean. A higher ERI was found in maize in clay loam soil than in loam soil. The ERI of maize (0.70-0.67 seedlings/d) was be higher with inverted-T furrow openers than with shoe and modified shoe type openers (Table 3). Mung bean ERI also changed according to type of furrow opener; it tended to be higher (2.50-2.44 seedlings/d) with inverted-T furrow openers than with shoe and modified shoe-type openers (Table 4). Using the shoe-type opener, mung bean ERI was higher than with the modified shoe-type opener. The greater ERI per day with the inverted T-type furrow opener was likely achieved through improved seed-to-soil contact, which in turn was influenced by better seed coverage and correct depth placement, with better seeding depth uniformity.

3.6 Emergence

The emergence rate (ER) of mung bean was significant (p= 0.023) according to soil type; this was however not the case with maize. Emergence of mung bean was higher in clay loam soil than in loam soil (Tables 3 and 4). The emergence of both maize and mung bean changed significantly with type of furrow opener, with a higher emergence rate of maize (89.92%) and mung bean (80.02%) observed with the use of inverted-T furrow openers than with shoe-type furrow openers. The lowest emergence of maize (29.46%) and mung bean (47.14%) was found with the shoe-type furrow opener; these were significantly ($p \leq 0.001$) lower by 15% and 9 % than with the modified shoe-type opener, respectively. Seed emergence of maize and mung bean was 91% and 82%, respectively for the inverted-T opener (Table 4). This variable was also improved in the case of inverted T-type furrow openers because of better seed coverage, SDU and seed placement, compared to the airdropping seed mechanism in shoe-type furrow openers. These results are likely due to the way in which this furrow opener improved placement of seeds in the zone where a more moist soil moisture environment prevails; it also opened a narrow furrow and seeds were properly covered by soil. The narrow opener point of 35 mm width demonstrated a better performance on sorghum early plant height than the wide point of 95 mm width[43]. The inverted-T furrow opener with right rake angle produced better furrow quality parameters (such as bulk density, penetration resistance, soil temperature, better soil furrow backfill with an optimum cross-sectional area) leading to better plant emergence[14,44].

3.7 Implications

In addition to a number of initiatives led by the private sector and agricultural research and extension organizations since 2012, the Government of Bangladesh recently launched a ‘mega-scheme’ in 2020 to promote agricultural mechanization. Its multiple goals include intensifying the country’s rice-based farming systems, addressing labor shortages in farms, and mitigating climatic shocks, among others[45,46]. Approximately 700 000 imported power tillers are working in the Bangladesh agricultural sector, used mainly for land preparation and agricultural goods transport[3]. Efforts have been made to diversify the uses of these existing power tillers to include mechanized seeding, harvesting and processing, using a separate attachment unit.

In response to these factors, Government of Bangladesh is encouraging wider use of the PTOS through a subsidized initiatives program; however, this appears to be partially influenced by China's business-oriented import policy. Most commercially imported Chinese PTOS seeders are supplied with less than ideal quality shoe-type furrow openers. While they may be appropriate on coarser textured soils, they are less suited to loam and clay loams that are common on Bangladesh's alluvial soils and in its deltaic environment. This can lead to poor crop establishment, as observed in our study, which suggests that these shoe-type furrow openers can result in <50% plant emergence (Tables 3 and 4). Because of these challenges, these furrow openers were re-engineered by WRC and BARI to provide a wider furrow cutting width, although this resulted in the same outcome[12]. Considering the current policies, there is an urgency to provide domestically produced seeder or re-attachable furrow opener equipment compatible with both conventional and CA-based mechanised seeding in Bangladesh. As such, this study highlights how an improved inverted-T furrow opener, which showed promising results for improved furrow quality parameters, can lead to significant improvements in crop establishment (Figure 4).

Greater plant emergence is the primary indicator of improved crop establishment. Our study clearly shows that plant emergence for maize had a negative correlation with MET (–0.87) and uncovered seed (–0.91) (in mung bean these were –0.54 and –0.85, respectively). At the same time, in both crops plant emergence was highly correlated with emergence rate index, seeding depth and seeding depth uniformity pattern (Table 5).

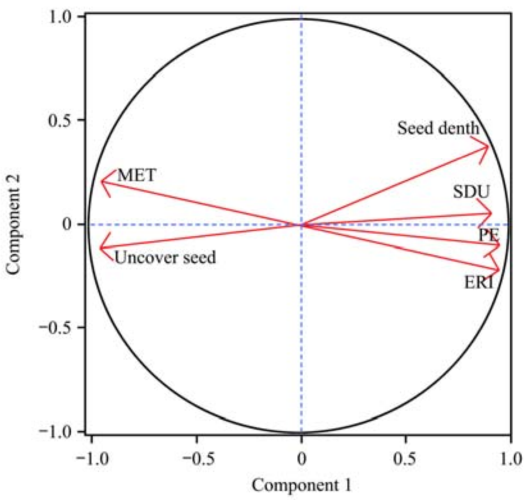
Figure 4 Types of furrow opener type and their respective crop establishment performance

Table 5 Correlation matrix of furrow quality parameters and seed emergence characteristics and principal component analysis

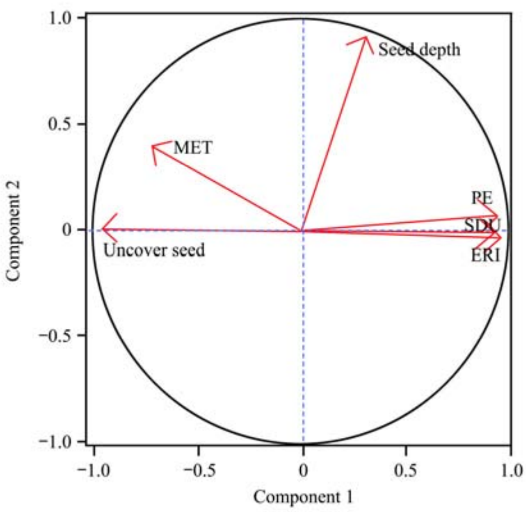
Parameter	PE	MET	ERI	Uncovered seed	Seed depth	SDU	PCA	Eigenvalue	% PCA
				Maize					
PE	1.00						1	5.27	87.79
MET	–0.87*	1.00					2	0.26	4.40
ERI	0.92*	–0.93*	1.00				3	0.18	3.09
Uncovered seed	–0.91*	0.86*	–0.87*	1.00			4	0.15	2.45
Depth	0.81*	–0.79*	0.80*	–0.86*	1.00		5	0.09	1.54
SDU	0.85*	–0.84*	0.83*	–0.85*	0.80	1.00	6	0.04	0.73
				Mung bean					
PE	1.00						1	4.15	69.26
MET	–0.54*	1.00					2	0.99	16.54
ERI	0.97*	–0.71*	1.00				3	0.52	8.73
Uncovered seed	–0.85*	0.58*	–0.85*	1.00			4	0.25	4.19
Depth	0.30	–0.02	0.27	–0.26	1.00		5	0.07	1.19
SDU	0.84*	–0.53*	0.82*	–0.92*	0.22	1.00	6	0.01	0.09

Note: * Indicates significance level at ∝=0.05. MET = mean emergence time, SDU = seeding depth uniformity, PE = plant emergence, ERI = emergence rate index

These findings indicate that better crop establishment is strongly influenced by furrow quality parameters, including furrow backfill, soil coverage of the seed, seed depth uniformity, and soil moisture in the furrow. The principle component analysis covering six variables for both quality parameters and seed emergence characteristics further confirmed the correlations, where plant emergence is highly negatively associated with uncovered seed and mean emergence rate (Figure 5). Plant emergence, seed depth uniformity, and emergence rate index were highly positive weighted variables in PCA1 contributing 88 % in maize and 70% in mung bean with high eigenvalues (Table 5). This supports the supposition that a newly designed, inverted-T furrow opener can improve PTOS operated multi-crop planters under both conventional and conservation agriculture conditions. Such multi-functionality is also likely to increase the interest of machinery service providers and local manufactures with potential business opportunities to develop new and high-performing equipment in Bangladesh and elsewhere.



a. Maize



b. Mung bean

Figure 5 Principal component plot of different furrow quality parameters and seedling emergence characteristics for maize and mung bean. MET = mean emergence time, SDU = seeding depth uniformity, PE = plant emergence, ERI = emergence rate index

4 Conclusions

Although initially designed for four-wheel zero-tillage equipment, in this study, the inverted-T furrow opener re-engineered for use with the 2WT based power-tiller operated seed drills. The new design the inverted-T furrow is narrower than commercially available shoe-type openers, which results in improved seed placement ensures the lowest uncovered seed rate for both maize and mung bean in loam and clay loam soils. The highest seeding depth and SDU was recorded in the inverted-T furrow opener with a 65° rake angle, which was reflected in improved MET and plant emergence rate for both crops. The reduced seeding depth with both shoe-type openers conversely resulted in poor MET because of uneven seeding depth and inadequate seed coverage for both crop species. These findings clearly suggest that all desirable crop establishment indicators were associated positively with inverted-T furrow openers; to achieve better crop establishment under strip tillage with a PTOS, it is therefore important to use the right furrow opener. This research also pointed to soil moisture and soil type as important factors in achieving adequate crop establishment with the studied tillage and seed drill configurations. Further research could perhaps focus more on diverse environments (soil textures and moisture levels) and different crops under both full tillage and conservation agriculture-based crop establishment to quantify the productivity, profitability and environmental benefits accrued by use of the improved furrow opener under different types of tillage and crop establishment. Furthermore, we hypothesize that the manufacturing and commercial availability of the inverted-T opener could make the PTOS more desirable and assist in facilitating the provision more agronomically precise custom hiring services by 2WT owners, a subject that could be studied through future research, perhaps though randomized control or large-scale on-farm agronomic research trials conducted in partnership with mechanized crop establishment service providers.

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