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Research Article

An evaluation of seed spacing accuracy of a vacuum type precision metering unit based on theoretical considerations and experiments

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Abstract: Currently the most widely used machine for precision seeding of cotton and maize seed is vacuum type. The capture of seeds by vacuum plate and the release of seeds from the vacuum plate should be performed precisely without missing or doubling. The physical phenomena should be clarified theoretically to understand how the precision seeding mechanism works. To solve these problems, an attempt was made to develop a nomogram using equations describing the technical characteristics of the seeder used in this study and to describe the seed capture mechanism relying on basic principles of fluid mechanics and aerodynamic properties of seeds. Seed spacing accuracy tests were performed to test the theory on a sticky belt in the laboratory. Quality of feed index, miss and multiple indices, and precision have been taken as a set of criteria for seed spacing accuracy. The regression models developed using the data obtained via sticky band tests showed that 16 seeds s^{-1} was the upper limit of seed release frequency (SRF) for cotton and maize seeds. The upper limit of vacuum plate peripheral speed was found to be 0.34 m s^{-1}. The use of 72 holes instead of 26 holes in the vacuum plate at 6.3 kPa created a vacuum band in the width of 10 mm around holes and this increased the multiple index and caused a reduction in seeding performance. For this reason, the use of vacuum plates with 60 or 52 holes is recommended for cotton seed. The forward speed of either 1.0 or 1.5 m s^{-1} was found to be acceptable for the seed spacing of 0.05 and 0.10 m, respectively. Aerodynamic calculations verified that widely used vacuum plates with 26 holes were the appropriate ones for seeding maize seeds. The performance indices, namely the quality of feed, and miss and multiple indices, reduced significantly for cotton and maize seeding when the precision metering unit was run at 20% (11°) slope to the right as compared to the no slope condition.

Key words: Precision seeding, seeding performance, vacuum plate

Teorik ve deneysel verilere dayalı olarak vakumlu tek dane ekim ünitesinin tohum aralığı düzgünlüğünün değerlendirilmesi

Özet: Günümüzde pamuk ve mısır tohumlarının tek dane ekiminde yaygın olarak kullanılan makine pnömatik tiptedir. Tohumun vakum plakası tarafından yakalanması ve plakadan çiziye bırakılması, boşluk ve ikizlenme olmadan hassas bir şekilde yapılabilmelidir. Tek dane ekim mekanizmasının nasıl çalıştığının anlaşılabilmesi için, teorik olarak fiziksel olayların açıklığa kavuşturulması gereklidir. Bu sorunu çözebilmek için, deneme materyali tek dane ekim ünitesinin teknik karakteristiklerini açıklayan eşitliklerden yararlanarak bir nomogram geliştirilmiş; temel akışkanlar mekaniği prensiplerine ve tohumların aerodinamik özelliklerine dayalı olarak, tohumların vakum plakası tarafından yakalanma mekanizması tanımlanmıştır. Teoriyi test edebilmek için, laboratuvarda yapışkan bant üzerinde tohum

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aralığı düzgünlüğü denemeleri yapılmıştır. Tek dane ekim ünitesinin yapışkan bant üzerindeki sıra üzeri tohum aralığı düzgünlüğünü tanımlamak için, kabul edilebilir tohum aralığı indeksi, boşluk indeksi, ikizleme indeksi ve hassasiyet kriterleri kullanılmıştır. Yapışkan bant test sonuçlarından elde edilen model eşitlikleri, pamuk ve mısır tohumları için dane atım frekansı (DAF)'nın izin verilen üst sınır değerinin 16 tohum s^{-1} olduğunu göstermiştir. Vakum plakası çevre hızının üst sınır değeri 0,34 m s^{-1} olarak bulunmuştur. 6,3 kPa vakum basıncında, 72 delikli yerine 26 delikli vakum plakasının kullanılması halinde, delik yörüngesi üzerinde 10 mm genişliğinde bir vakum bandı oluşmuş, bu da ekim performansının azalmasına neden olan ikizlenme indeksini arttırmıştır. Bu nedenle, pamuk tohumu için delik sayısı 60 veya 52 olan vakum plakası önerilmiştir. Pamuk tohumu için, 0,05 ve 0,10 m tohum aralıklarında, sırasıyla, 1,0 ve 1,5 m s^{-1} ilerleme hızları uygun bulunmuştur. Aerodinamik hesaplamalar, mısır tohumu ekiminde yaygın olarak kullanılan 26 delikli vakum plakasının seçiminin uygun olduğunu doğrulamaktadır. Tek dane ekim ünitesi % 20 (11°) sağa yanal meyilde çalıştırıldığında, pamuk ve mısır tohumları için besleme kalitesi, boşluk ve ikizlenme indeksi gibi performans değerleri düzde çalışmaya göre belirgin bir şekilde azalmıştır.

Anahtar sözcükler: Ekim performansı, tek dane ekim, vakum plakası

Introduction

From the point of precision seeding technique and for meeting agro-technical needs, maize seeds should be sown precisely without causing doubling and missing during field operations. Doubling and missing in the row are unwanted since doubling affects yield and dry matter while missing causes a reduction in yield (Rintelen 1971; Demmel et al. 2000). The graded maize seeds were used in mechanical types of metering units in the past (Wenner et al. 1980) but in the 1970s pneumatic type of precision seeders were started to be used and became widespread since they are not much affected by ungraded seed use and provide an even distribution during the metering process.

The studies conducted in the past on plant population and its effect on plant morphology and lint quality in cotton production revealed important knowledge for researchers in the field of agricultural mechanization and seeder design. Published research contains no consensus regarding the relation of spacing uniformity to yield. By defining the fundamental engineering principles of precision seeding of cotton seeds with and without thinning process, Önal (1981) concluded that cotton plants can adapt to the differences in plant densities and this may help agricultural engineers for reducing or totally removing the labor for in-row hoeing operations. According to Corley et al. (1959) the effect of increased seed spacing accuracy on seed cotton yield is not very evident. However, in a study that revealed contradictory findings to this, Wanjura (1980) found that plant spacing uniformity had some positive influence on cotton lint yield.

The performance of the vacuum type metering unit was the main interest in many studies conducted by Önal (1981) and Bayat et al. (1993), in both of which delinted cotton seeds were used while Önal (1987) also used sunflower and maize seeds. Stieger (1974) focused on constructional principles of 4 different types of pneumatic metering units and used graded maize seeds. These metering units were: I - Pneumatic metering unit with blower (positive pressure range used: 1.77 and 1.37 kPa); II - Vacuum type metering unit (vacuum range used: 5.9-8.8 kPa); III - Vacuum type metering unit with a single seed plate with double row holes (vacuum range used: 5.9-8.8 kPa); IV - Vacuum type metering unit with lugs (vacuum range used: 5.9-8.8 kPa). The performance of the metering unit IV was found to be less affected by the graded maize seeds. On the other hand, the capture of seeds by holes in the vacuum plate was better for the metering unit IV due to the availability of small lugs as compared to the other metering units. There is no study concerned with the number of holes in a vacuum plate for different seeds although there are many studies in the literature conducted on the effects of hole shape (circle, square, triangle, and oblong), hole diameter, vacuum level, and seed variety on precision metering unit performance in terms of seed spacing accuracy (Önal 1987; Barut 1996; Moody et al. 2003; Singh et al. 2005; Önal 2006a; Önal et al. 2009; Yazgı 2010; Yazgı et al. 2010). ISO (1984) recommends testing of precision metering units at slope conditions and the determination of the slope effect on seed spacing accuracy. Irla (1982) investigated the effects of slope conditions on seed rate and seed spacing accuracy for pneumatic and mechanical type seeders; however, to the best of our knowledge, there is no published report on the effects of slope conditions on precision seeder performance.

The objectives of this study were: to obtain the technical characteristics of a vacuum type precision metering unit, to develop a nomogram using equations that are commonly used during the design process, to find out the upper limit of the number of holes in a vacuum plate, to test the cotton and maize seed spacing accuracy at no-slope and slope position of the seed metering unit in the sticky belt test stand, and to interpret the results based on theoretical considerations presented in this study.

Materials and methods

Seeds and vacuum-type precision metering unit

Hybrid maize (AG 9241) and delinted cotton seeds (Deltapine 388) were used in this study. The physical properties of these seeds are given in Table 1.

In the experiments, a vacuum-type precision seeder unit with a ground-driven wheel with 0.64 m diameter that transfers the motion to the vertical vacuum plate with a combination of gears was used (Figure 1). The height of the seed drop was 0.10 m, and the holes were drilled in a circle with a 0.19 m diameter in a vacuum plate. The vacuum plates with 4.5 and 3.5 mm holes were used for seeding maize and cotton seeds, respectively. Seeds from the vacuum plate are released at an angle of 60° from the horizontal and the vacuum pressure applied was 6.3 kPa.

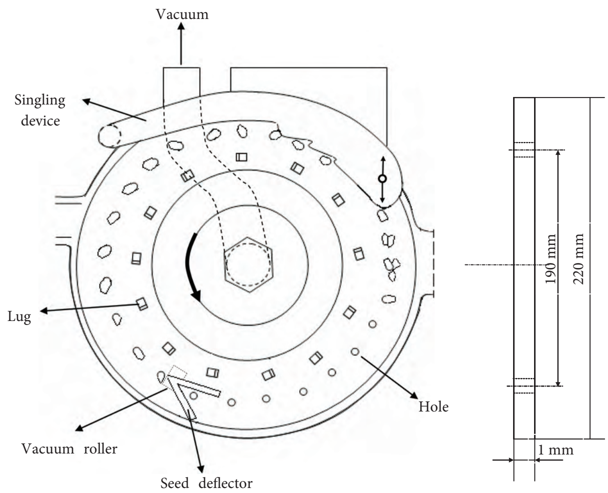

Figure 1. Metering unit of the vacuum type precision seeder and dimensions of the vacuum plate.

Theory of capture of seeds by vacuum plate

Precision seeding is such a phenomenon that 2 processes have to be performed and the objective is to precisely place seeds at the required seed spacing. The first process is the capture of seeds by the vacuum plate and this should be done without missing, doubling, or seed damage. The second process is the release of seeds from the vacuum plate and the placement of seeds into the soil. Capturing seeds by holes in the vacuum plate is of importance for successful seeding and the theory that is relevant to this is as follows.

Air flows through a hole in the radial direction and air stream lines form a semi-sphere envelope (Figure 2) and air velocity increases as the radius

Table 1. Dimensions (mean ± SEM) and test weight of seeds used in this study.

Seeds	Seed dimensions, mm			Sphericity* (s), %	1000-seed weight (g)
	Length (a)	Width (b)	Thickness (c)		
Hybrid maize (AG 9241)	11.5 ± 0.18	8.6 ± 0.18	6.9 ± 0.15	76.6	437.0
Delinted cotton seed (Deltapine 388)	8.5 ± 0.11	4.9 ± 0.11	4.3 ± 0.07	66.1	74.2

*) $s = (a.\ b.\ c)^{1/3}/a$ (Mohsenin 1970)

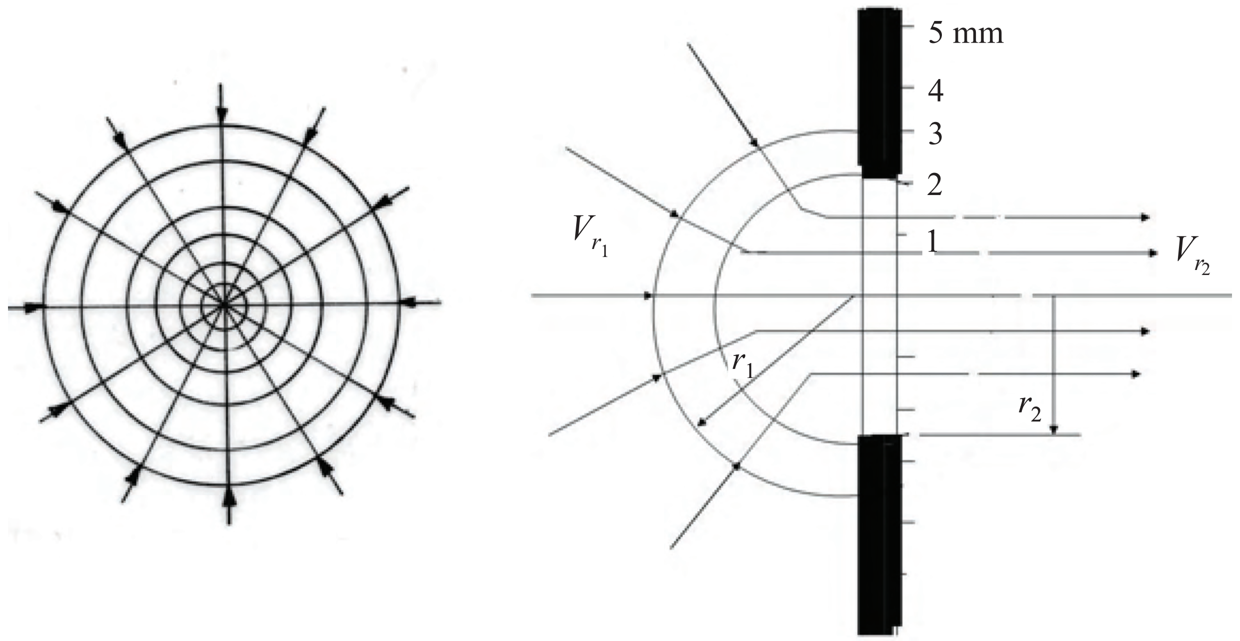

Figure 2. Suction of air through a hole.

of the envelope goes down. The air velocity, V_{r_1}, at r_1 distance from the center of holes is calculated by Equation 1.

$$V_{r_1} = \frac{r_2^2}{r_1^2} \cdot \frac{\alpha \sqrt{\frac{2\,g\,p}{\gamma}}}{2} \qquad (1)$$

where r_2, is the hole radius on the vacuum plate, *a*, is the flow coefficient (assumed to be 0.7), γ is the specific weight of air (11.2 N m^{-3} at 20 °C and 96 kPa), *p* is the vacuum pressure in N m^{-2}, and *g* is acceleration due to gravity (Jogwick 1975; Önal 2006a),

According to Eck (1958), the air velocity in the center of the hole, V_{r_2}, can be calculated by Equation 2.

$$V_{r_2} = \alpha \sqrt{\frac{2\,g\,p}{\gamma}} \qquad (2)$$

The terminal velocity of seeds in the air stream has to be known prior to the design of vacuum type precision seeders and these values were found to be 7.8 m s^{-1} for cotton (Tabak and Wolf 1998) and 11.8 m s^{-1} for maize (Gorial and O'Callaghan 1990).

The peripheral speed of the vacuum plate V_p and the forward speed of the seeder V_f can be calculated from Equations 3 and 4.

$$V_p = \frac{\pi\, d\, n_p}{60} \qquad (3)$$

$$V_f = \frac{n_p}{60}\, k\, Z_t \qquad (4)$$

where *d* is the pitch diameter of holes (vacuum plate diameter) in m (Figure 3), n_p is the rpm of the vacuum plate in min^{-1}, *k* is the number of holes in the vacuum plate, and Z_t is the theoretical seed spacing in m. Substituting $k = \pi\, d / l$ into Equation 3, the ratio of V_f / V_p can be expressed as in Equation 5.

$$\frac{V_f}{V_p} = \frac{Z_t}{l} = m \qquad (5)$$

where *l* is the arc distance between 2 holes and *m* is the velocity ratio.

Seed releasing frequency, *SRF*, is the number of seeds released from the metering unit in 1 s. At specific theoretical seed spacing, the *SRF* and the forward speed relationship is shown as in Equation 6.

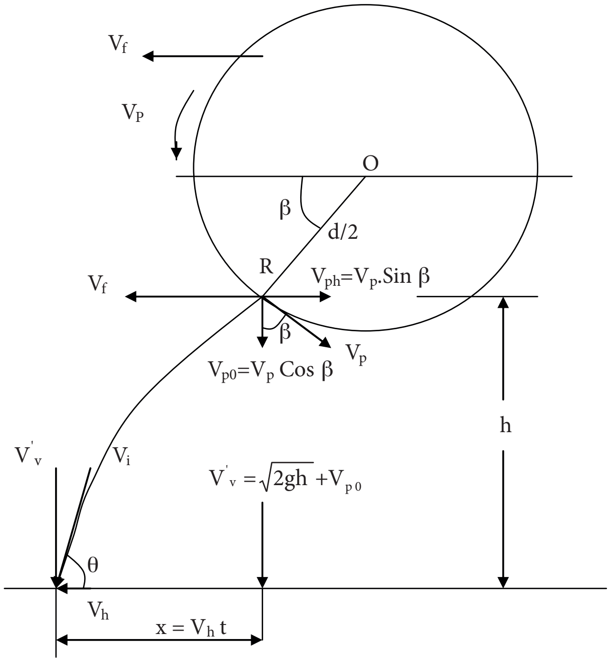

Figure 3. Kinematics of vacuum type metering unit.

$$Z_t = \frac{V_f}{SRF} \quad (6)$$

Forward speed (V_f) is equal to peripheral speed of the ground wheel (V_w) in no-slippage conditions. Finally, the theoretical seed spacing (Z_t) is calculated from Equation 7 as a function of the diameter of the ground wheel (*D*), transmission ratio (*i*), and the number of holes in the vacuum plate (*k*).

$$Z_t = \frac{\pi D}{i\,k} \quad (7)$$

Seed spacing accuracy tests and evaluation

A sticky belt test stand was used to measure the seed spacing in the laboratory. In order to facilitate this study, seed spacing measurements and its evaluations were made using a computerized measurement system (CMS) on a sticky belt test stand (Önal and Önal 2009). The program developed as part of the study analyzes the information and provides output results in numerical and graphical form (Figure 4).

Three different seed spacing groups according to Z_t are classified as shown in Figure 4, and these 3 indices are defined as:

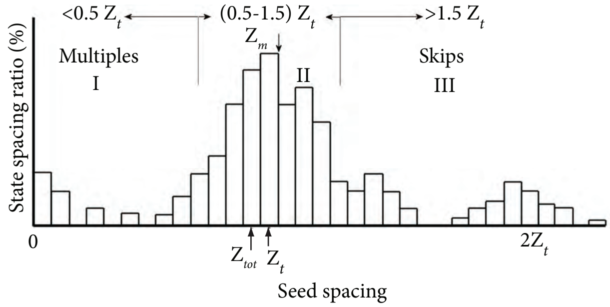

Figure 4. Frequency histogram of seed spacing distribution.

I. The multiple index indicates the percentage of multiple seed drops (0 to ≤ 0.5 Z_t), Z_t is the theoretical seed spacing,

II. Quality of feed index indicates the percentages of single seed drops in the range of >0.5 Z_t to ≤1.5 Z_t.

III. The miss index indicates the percentage of missed seed locations or 'skips' (>1.5 Z_t).

Seed spacing uniformity of the main seed distribution (II), called precision, is expressed by the coefficient of variation (CV_m, %) as shown in Equation 8.

$$CV_m = \frac{S}{Z_m} 100 \quad (8)$$

where *S* is the standard deviation of the main seed distribution and Z_m is the mean seed spacing of the main seed distribution curve (II). Z_{tot} in Figure 4 indicates the mean seed spacing of the total seed distribution curve (I + II + III).

As reported by Kachman and Smith (1995), the precision value (CV_m) is preferred to be less than 29%-30%. On the other hand, Önal (2006b) proposed 4.75% for the upper limit of miss- and multiple index values. Irla (1982) and Irla and Heuser (1991) stated that the quality of feed index of less than 90% could be considered as an insufficient seeding performance.

The sticky belt tests were performed at 0.10 and 0.20 m seed spacings for maize while the seed spacing for cotton was 0.05 and 0.10 m at forward speeds of 1.0, 1.5, and 2.0 m s^{-1}. The sticky belt tests were conducted with randomized complete block design with 3 replications both at level and slope positions of seed metering unit. Each replication had 250 seed spacings. The slope tests were performed at 1.5 m s^{-1} at 20% slope to the right (vacuum plate inclined 11° to the right; angle of inclination α = 11°). The effects of slope on seed spacing accuracy were determined by variance analysis. The relationships between *SRF* values vs. seed spacing accuracy indices were defined by regression models.

Results

Theoretical calculations for cotton and maize seeds

The air velocity calculations based on Equation 2 at r_1 = 0 and different distances from the hole center such as 2, 3, and 4 mm and at the edge of the hole were calculated using Equation 1. The results obtained from calculations are tabulated in Table 2.

In precision seeding using a vacuum, the capturing process of seeds at the presumed vacuum pressure and hole diameter could be possible once the air velocity at the semi-sphere suction zone is greater than the terminal velocity values of the seed considered for precision seeding. Once the results given in Table 3 are examined by assuming a terminal velocity of 7.8 and 11.6 m s^{-1} for cotton and maize, respectively, it can be said that the capturing process could be performed at a distance of approximately 4 mm or less from the center of the hole.

If the circumference of the semi-circle at a distance of 4 mm away from the center of the hole is assumed to be 10 mm, the number of holes to be drilled in a vacuum plate with a pitch diameter of 0.19 and a circumference of 0.5966 m can be approximately 60. This means that a vacuum plate with 60 holes will provide the necessary vacuum zone to capture seeds and a vacuum plate with more than 60 holes may not be capable of achieving the expected performance.

The nomogram that describes the technical characteristics of the precision seeder unit used in this study was obtained by using the theoretical Equations 3-7. Different options, where $V_p \leq 0.25$ m s^{-1} condition is met, can be easily found from Figure 5.

These options and the results from the application of the above written equations for cotton seeds are expressed below.

There should be 60 holes in the vacuum plate once 8.5 mm long Deltapine 388 variety cotton seeds were considered for precision seeding. The precision seeder was tested using plates with 72 holes since it is provided to farmers by default.

The seeding operation can be performed at a theoretical seed spacing of 0.05 m at a forward speed of 1.25 m s^{-1} using a vacuum plate with 72 holes at a *SRF* of 25 seeds s^{-1}. Once the forward speed of 2.5 m s^{-1} is required then the seed spacing of 0.10 m should be selected and the use of vacuum plate with 72 holes is needed. Both distances are appropriate for cotton seeding with or without thinning operation after the emergence in the field (Figure 5). At a theoretical seed spacing of 0.05 m, if V_f is 1.25 m s^{-1}, k is 72 and at a *SRF* of 25 seeds s^{-1} then m (V_f / V_p) would be 6.03.

The *SRF* values obtained from the use of vacuum plates with 36 and 52 holes by meeting the condition of $V_p \leq 0.25$ m s^{-1} are 15 and 20 seeds s^{-1}, respectively. At a *SRF* of 20 seeds s^{-1}, the forward speed should be 1 m s^{-1} for a seed spacing of 0.05 m and similarly at

Table 2. Air velocities at different distances from the center of a hole at 6.3 kPa vacuum pressure.

Hole diameter (d_0), mm	Terminal velocity, m s^{-1}	Distances from the center of a hole (r_1), mm					
		0	at the hole edge	2	3	4	5
		Air velocity (V_{r_1}) m s^{-1}					
3.5 (cotton)	7.8	73.49	36.74*	28.13	12.50	7.03	4.50
4.5 (maize)	11.6	73.49	36.74**	-	20.67	11.63	7.44

*) r_1=1.75 mm
**) r_1 = 2.25 mm

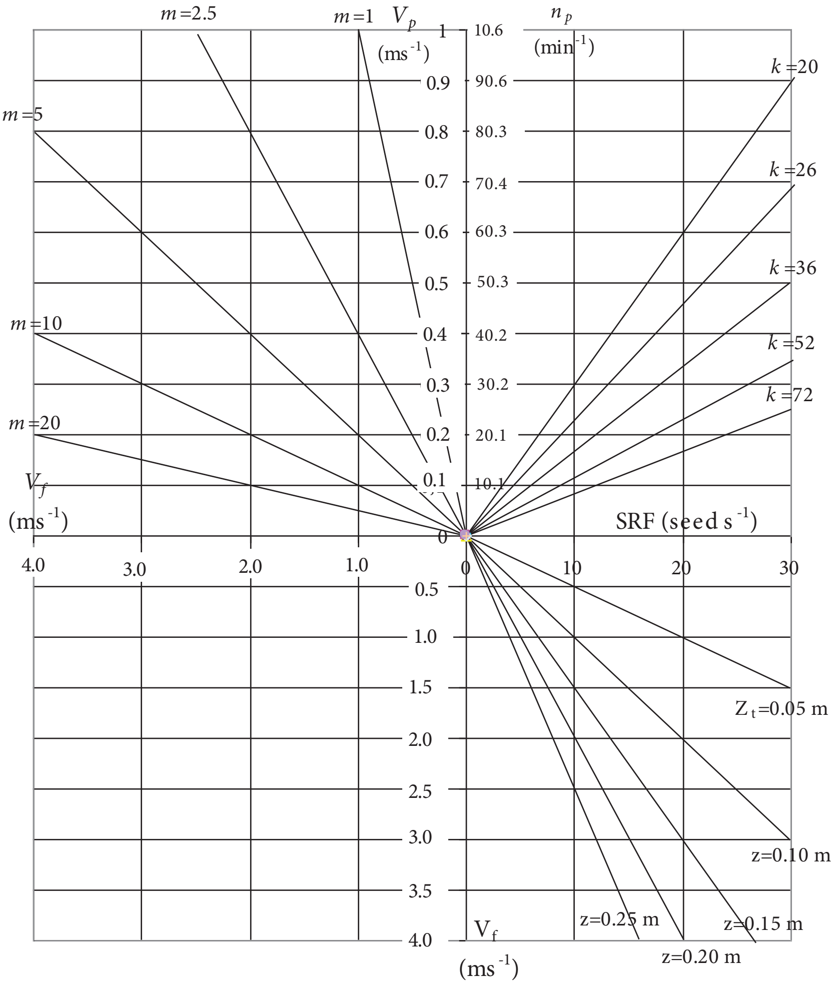

Figure 5. Nomogram developed for finding the technical characteristics of the precision seeder (D = 0.64 m, d = 0.19 m).

the same SRF value the seed spacing should be 0.10 m at a forward speed of 2 m s^{-1}. When the vacuum plate with 52 holes is used at a seed spacing of 0.05 m, the construction related parameters V_f and m at a *SRF* of 20 seeds s^{-1} and a peripheral speed of 0.23 m s^{-1} would be 1.0 and 4.358, respectively (Figure 5). The use of a vacuum plate with 36 holes at 0.05 and 0.10 m seed spacing requires forward speeds of 0.75 and 1.5 m s^{-1}, respectively (Figure 5).

At a seed spacing of 0.10 m, which is a planting to a stand type seeding operation, the use of a vacuum plate with 72 holes at a peripheral speed of 0.166 m s^{-1} and *SRF* of 20 seeds s^{-1}, the velocity ratio (m) would be 12.07 (Figure 5). The performance of the soil engaging components of the seeder are of importance due to a high velocity ratio, reduced impact angle, and increased impact velocity of the seed to soil.

When the seeding operation is performed using a vacuum plate with 52 holes at a seed spacing of 0.10 m, the peripheral speed of the vacuum plate at 2 m s^{-1} forward speed would be 0.23 m s^{-1} (Figure 5).

The results obtained from the theoretical equations as they are applied for seeding maize are given below.

The maximum number of holes in a vacuum plate would be 48 once a vacuum plate with a diameter of 0.19 m for 12.5 mm long maize seeds is considered. Hence, the use of vacuum plates with 20, 26, and 36 holes seems to be appropriate. However, the selection and use of a vacuum plate with 26 holes is thought to prevent the vacuum band on the vacuum plate and will provide better capturing in holes and a steeper fall trajectory for seeds.

The peripheral speed of the vacuum plate and *SRF* become 0.469 m s^{-1} and 20, respectively, if the seeding process with a vacuum plate with 26 holes is performed at 2 m s^{-1} forward speed and a theoretical seed spacing of 0.10 m (Figure 5). There seems to be a problem in this case as it was verified by the tests carried out in the laboratory. Once the forward speed is reduced to 1.5 m s^{-1} then the *SRF*, the peripheral speed of the vacuum plate, and velocity ratio would be 15, 0.344 m s^{-1}, and 4.358, respectively (Figure 5). In this case, it is recommended not to carry out seeding process at forward speeds higher than 1.5 m s^{-1}.

Seeding maize at a theoretical seed spacing of 0.20 m, the condition that meets $V_p \leq 0.25$ m s^{-1}, is to work at 2 m s^{-1} forward speed with a vacuum plate with 26 holes. In this case, the *SRF* would be 10 seeds s^{-1} (Figure 5).

Increasing the seed spacing allows working at reduced *SRF* values and provides higher field work rate by increasing the forward speed (Figure 5).

To work at 0.20 m seed spacing and 2 m s^{-1} forward speed using a vacuum plate with 26 holes means a peripheral speed of 0.23 m s^{-1} and velocity ratio of 8.715 (Figure 5). These conditions make the soil engaging components more important due to the risk of seed rolling, bouncing, and displacement in the row.

Sticky belt test results

The results from sticky belt tests were tabulated for maize and cotton and from these values the regression models were developed and depicted in Figures 6-8. As seen in Figures 6a-c, the performance indicators, such as the quality of feed as well as miss and multiple indices, evaluated based on the criteria given in this study as "seed spacing accuracy tests and evaluation" are insufficient for seeding cotton at a seed spacing of 0.05 m. This could be explained as a result of using a vacuum plate with 72 holes where a continuous vacuum band occurs and also the *SRF* values of 20,

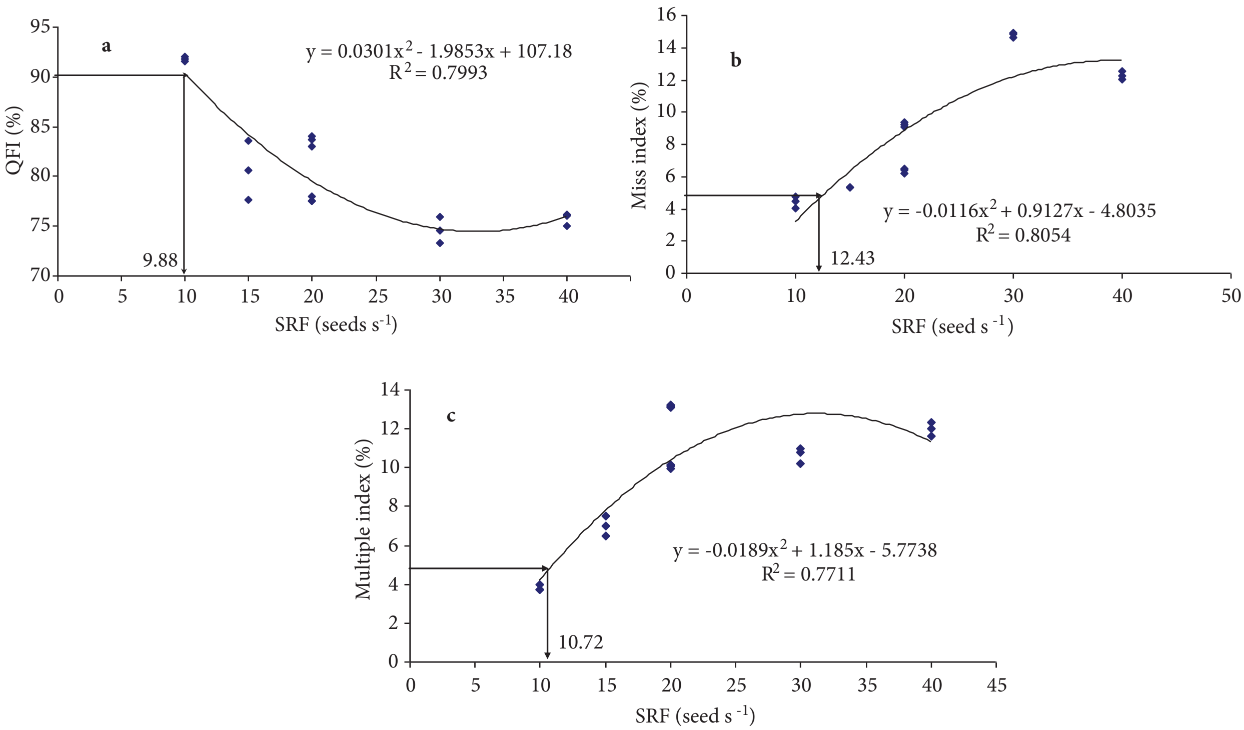

Figure 6. a) QFI vs SRF relationship for cotton seeds (k = 72), b) miss index vs SRF relationship for cotton seeds (k = 72) and c) multiple index vs. SRF relationship for cotton seeds (k = 72).

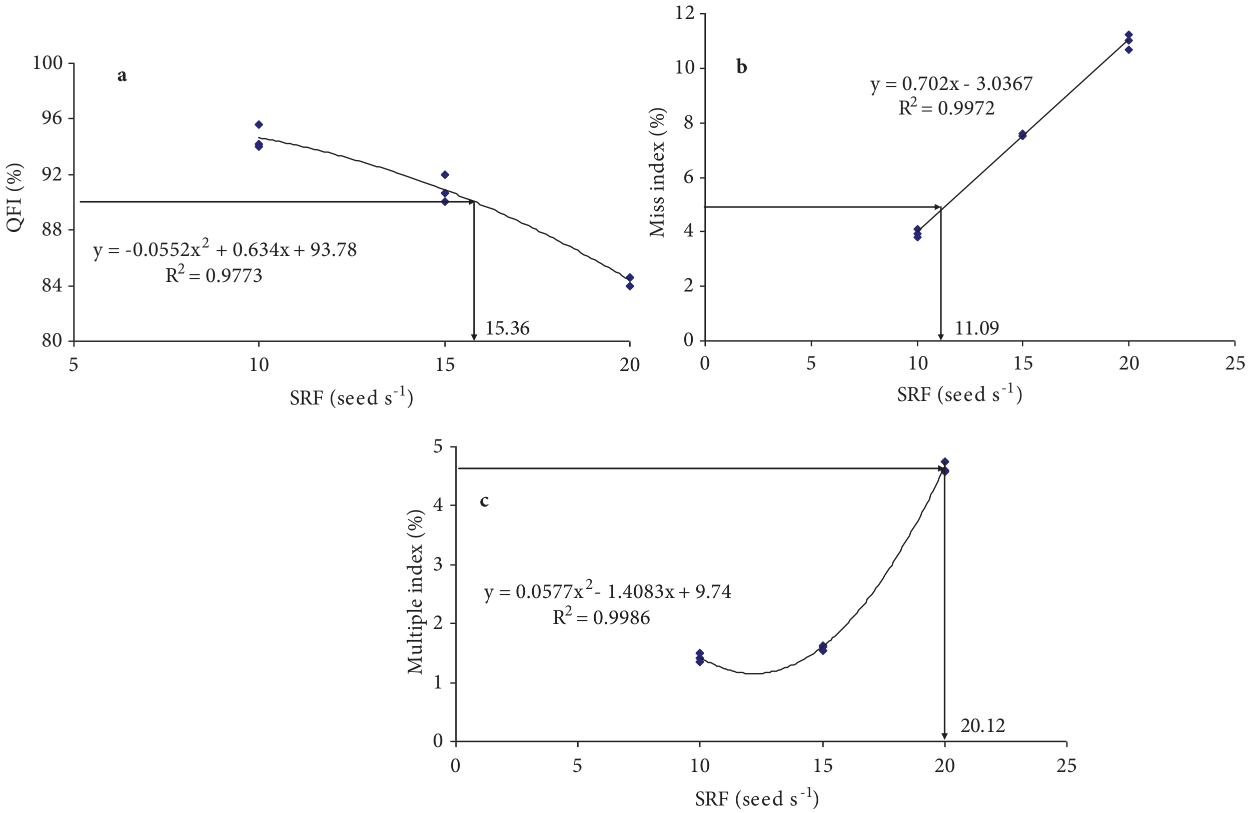

Figure 7. a) QFI vs SRF relationship for cotton seeds (k = 26), b) miss index vs SRF relationship for cotton seeds (k = 26) and c) multiple index vs. SRF relationship for cotton seeds (k = 26).

30, and 40 seeds s^{-1} at 1.0, 1.5, and 2.0 m s^{-1} forward speeds are high. On the other hand, performance values at 20 seeds s^{-1} are better than the higher *SRF* values due to a lower peripheral speed of the vacuum plate (0.17 m s^{-1}) (Figures 5, 6a-c).

The performance of the seeder for a plant to stand type seeding is classified as a good level of seeding when seeding was performed at 1.0 and 1.5 m s^{-1} forward speed as they correspond to *SRF* values of 10 and 15 s^{-1} (Figures 5, 7a-c). At 1.0 m s^{-1} forward speed, the quality of feed index is at a moderate level while multiple and miss index values are at a good and moderate level, respectively. Seeding at 1.5 m s^{-1} forward speed provides a moderate level of quality of feed index, good level of multiples index, but an unacceptable level of miss index. The performance values of quality of feed, miss, and multiples indices go down to an unacceptable level at 2 m s^{-1} forward speed when the seed spacing of 0.10 m and a vacuum plate with 26 holes are used (Figures 7a-c).

Cotton seeds can be sown accurately at the forward speed of 1.0 and 1.5 m s^{-1} for seed spacing of 0.10 m if a vacuum plate with 26 holes is used while the speed can only be 1.0 m s^{-1} if a vacuum plate with 72 holes is used (Figures 6 and 7). The results obtained from the sticky belt tests seem to be verifying the results obtained from the theoretical evaluations. The maximum acceptable peripheral speed of the vacuum plate and the *SRF* values chosen from Figures 6-8 are 0.34 m s^{-1} and 16 seeds s^{-1}, respectively.

The sticky belt tests that used maize seeds showed a better performance at a seed spacing of 0.20 m as compared to 0.10 m (Figures 5, 8a-c). The performance of the seeder at 0.20 m seed spacing is classified as excellent in terms of multiples index and the quality of feed index at 1.0 m s^{-1} forward speed while the miss index is at a good level. The same indices are at a good level at the forward speed of 1.5 and 2.0 m s^{-1}.

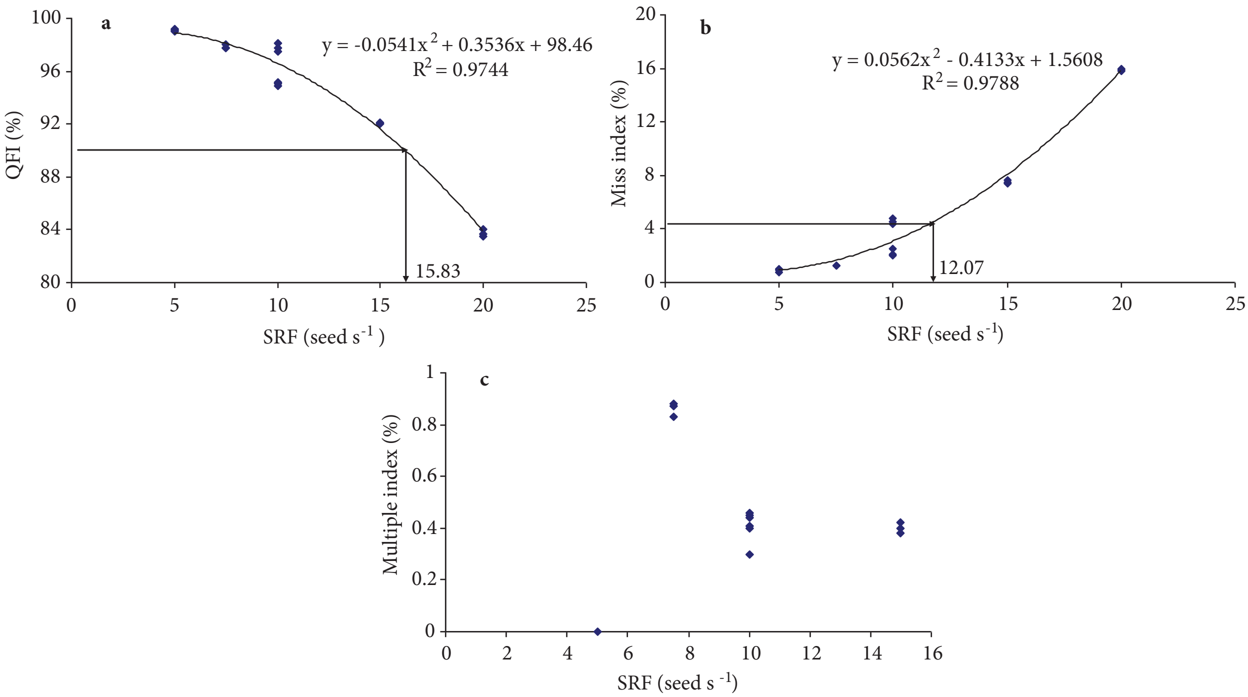

Figure 8. a) QFI vs SRF relationship for maize seeds (k = 26), b) miss index vs SRF relationship for maize seeds (k = 26) and c) multiple index vs. SRF relationship for maize seeds (k = 26).

The performance of the seeder at a theoretical seed spacing of 0.10 m and the forward speed of 1.0 m s^{-1} in terms of miss, multiple, and quality of feed index is at moderate, excellent, and good level, respectively. At 1.5 m s^{-1} forward speed, the miss index is at an unacceptable level while multiple index is excellent, and quality of feed index is at a moderate level. The performance of the seeder at a theoretical seed spacing of 0.10 m and 2.0 m s^{-1} forward speed is at an unacceptable level (Figures, 5, 8a, 8b).

The tests performed for cotton and maize seeds at 20% slope indicated a significantly lower seeding performance at 0.05, 0.10, and 0.20 m seed spacing as compared to no-slope conditions (Table 3).

Discussion

Sticky belt test results obtained in this research indicated that 16 seeds s^{-1} was the upper limit of *SRF* for cotton and maize seeds (Figures 6a, 7a, 8a). The permissible upper limit of vacuum plate peripheral speed was found to be 0.34 m s^{-1} (Figure 5). For the same type of seed metering unit, Stieger (1974) reported the single seed capture ratio (SSCR) for maize seeds as 98.9% at 0.35 m s^{-1} peripheral speed. Schön et al (1998) reported that the upper limit of *SRF* values for sugar beet and maize seeds was 20-25 and 15 seeds s^{-1}, respectively. At 15 seeds s^{-1} *SRF* value, 10 and 15 cm of maize seed spacings were recommended for 1.53 and 2.22 m s^{-1} forward speed, respectively. Önal (1987) recommended the upper limits of *SRF* values for sunflower, maize, and cotton seeds as 17-19, 20, and 17 seeds s^{-1}, respectively. A nomogram that can be used for the design of a precision metering was developed by using Equations 3-7. Using this original monogram, the selection of seed spacing, forward speed, and the number of holes on a vacuum plate can be made while the *SRF* and V_p values are kept within the limits.

The condition required for the determination of the maximum number of holes on a vacuum plate is the alignment of seeds longitudinally within the vacuum envelope on hole and intermittent vacuum band in the motion trajectory. The number of 10 mm long cotton seeds that can be aligned longitudinally around 190 mm vacuum envelope diameter is 60. The

Table 3. Sticky belt test results (mean ± SEM) for cotton and maize seeds at level and lateral slope conditions.

Seed	Seed spacing m	Hole number k	Slope^{+} %	Forward Speed $m\ s^{-1}$	Seed release frequency seeds s^{-1}	Vacuum plate peripheral speed $m\ s^{-1}$	Quality of feed index %	Multiple index %	Miss index %	Precision (CV_m) %
Cotton	0.05	72	0	1.5	30	0.25	74.60 ± 0.75	10.66 ± 0.24	14.77 ± 0.09	29.14 ± 0.20
			20^{+}				73.24 ± 0.12	9.73 ± 0.12	17.03 ± 0.10	29.32 ± 0.36
				P			ns	ns	**	ns
	0.10	72	0	1.5	15	0.124	87.68 ± 0.31	7.00 ± 0.32	5.34 ± 0.02	20.60 ± 0.25
			20^{+}				86.12 ± 0.06	12.26 ± 0.13	1.62 ± 0.01	21.43 ± 0.20
				P			*	**	**	**
		26	0	1.5	15	0.34	90.87 ± 0.57	1.59 ± 0.02	7.54 ± 0.03	23.72 ± 0.12
			20^{+}				89.17 ± 0.97	4.77 ± 0.02	6.06 ± 0.05	28.06 ± 0.14
				P			ns	**	ns	**
Maize	0.10	26	0	1.5	15	0.34	92.05 ± 0.05	0.40 ± 0.01	7.53 ± 0.03	21.77 ± 0.11
			20^{+}				78.27 ± 0.19	3.91 ± 0.05	17.81 ± 0.01	24.01 ± 0.18
				P			**	**	**	*
	0.20	26	0	1.5	7.5	0.17	97.85 ± 0.09	0.86 ± 0.02	1.29 ± 0.01	11.04 ± 0.13
			20^{+}				85.52 ± 0.25	3.07 ± 0.02	11.40 ± 0.03	10.75 ± 0.09
				P			**	**	**	ns

$^{+}$) Slope to the right
* $P < 0.05$, ** $P < 0.01$, ns= non-significant

number of holes that can create a continuous vacuum band is 72 as seen in Table 3. The findings from cotton seeding experiments using a vacuum plate with 72 holes on sticky belt tests and aerodynamic evaluations indicated an increased multiple index value as seen in Figures 6 and 7. For this reason, the use of vacuum plates with 52 or 60 holes is recommended. The forward speed of either 1.0 or 1.5 $m\ s^{-1}$ is recommended for the seed spacing of 0.05 and 0.10 m, respectively.

The maximum number of holes on a vacuum plate would be 48 once the vacuum plate with a diameter of 0.19 m and 12.5 mm long maize seeds is considered. Hence, the use of 20, 26, 32, and 36 hole vacuum plates seems to be appropriate. Stieger (1974) used a vacuum plate with 32 holes for different graded maize seeds. Aerodynamic calculations verified that the widely used vacuum plates with 26 holes are the appropriate ones for seeding maize seeds. It was found that the performance of the precision seeder while seeding maize seeds at a seed spacing of 0.10 m and forward speed of 1.5 $m\ s^{-1}$ was classified as excellent. Seeding at an excellent quality at seed spacing of 0.20 m was possible at the forward speed of 2.0 $m\ s^{-1}$.

As seen in Table 3, increases in seed spacing improved the performance values of miss, multiple, and quality of feed indices and precision.

The tests conducted at 20% slope ($\alpha = 11°$) to the right for cotton and maize seeds showed a lower performance than the no-slope conditions at 0.05, 0.10, and 0.20 m seed spacings considered in this study. The reason for this can be attributed to the reduced force ($W \times sin\alpha$) on seed mass (W) at slope conditions. New performance models that include the effect of slope and less sensitivity to slope position should be developed in future studies. The slope effect on the seed spacing accuracy was greater for maize seeds since 1000-seed mass of maize is much greater than cotton seeds (Table 3).

Reduced *SRF* means higher QFI, lower miss, and multiple indices (Figures 6-8). In contrast, lower forward speed means lower field capacity. In order to increase the forward speed, especially at lower seed spacing, twin disk or cylindrical vacuum seeding unit with proper soil engaging components could be recommended to improve seeding performance. It is thought that the results obtained from theoretical considerations and experiments in this study will help designers to design seeders that will meet the seeding requirements for better performance with an innovative approach.

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