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Mathematical Modelling and Optimization of the Performance of a Metering Unit for Precision Corn Seeding*

Arzu YAZGI[1], Adnan DEĞİRMENCİOĞLU[1], İsmet ÖNAL[1], Emine BAYRAM[2]
[1]Ege University, Faculty of Agriculture, Department of Agricultural Machinery,
35100-Bornova-İzmir/Turkey
[2]Ege University, Faculty of Agriculture, Department of Field Crops, 35100 Bornova-İzmir/Turkey
arzu.yazgi@ege.edu.tr

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Abstract: The objective of this study was to develop mathematical functions and to optimize the performance of a vacuum type precision seeder for metering corn seeds. The variables considered in the study were the seed hole diameter, peripheral speed of the vacuum plate and vacuum on vacuum plate. The experimental study was conducted in the laboratory on a sticky belt and the seed distribution in a row was investigated based on Multiple Index, Miss Index, Quality of Feed Index, Root Mean Square Error (E_{rms}) and the Coefficient of Precision (CP3). For the experiments, the level of the peripheral speed of the plate was 0.053, 0.08, 0.12, 0.16 and 0.19 m/s corresponding forward speed of the seeder was 0.52, 0.8, 1.2, 1.6 and 1.87 m/s), the diameter of the holes drilled on the vacuum plate was selected to be 2.32, 3, 4, 5 and 5.68 mm, five levels of the vacuum pressure were 26.4, 40, 60, 80 and 93.6 mbar. Response Surface Methodology was applied to optimize the performance of the seeder and the experiments were conducted using Central Composite Design (CCD). The results obtained from the experiments based on CCD that use five different levels for each variable were used to develop a polynomial function in quadratic form for corn seeds. From these mathematical functions, the optimum level of each variable was obtained in the study. The optimum level of the peripheral speed of the vacuum plate (0.068 m/s), hole diameter (3.77 mm) and vacuum pressure (76.75 mbar) were verified in the lab and under field conditions.

Key words: Response Surface Methodology, precision seeding, seeder

INTRODUCTION

The use of pneumatic precision seeders has an increasing trend in our country since the number of the seeders reached 22919 in 2008 while it was 15770 in 2002 (TUİK, 2010). These types of seeders are expected to serve in plant productions for many years and be the most common type among many different types. The one of the desired and the most important features expected from this type of seeders is to incorporate seeds into the soil at theoretical seed spacing without causing the multiples and misses. On the other hand there are some problems related to the performance of this type of seeder and adaptation of them for planting different types of seeds. One of the main problems is to know the peripheral speeds of the vacuum plate as corresponds to the traveling speed linearly, hole diameter and vacuum applied on vacuum plate.

Seeders should be operated at a performance that meets the expected agro-technical needs and this makes the studies be focused on the constructional, seed and operational related parameters. Systematical examination in order to determine the effects of the above mentioned parameters may require full factorial designs and use of these designs require time, finance and labor. But, the tool such as Response Surface Methodology (RSM) as used in this study is a methodological approach and an alternative to the full factorial designs and reduces the number of experiments. As a result it causes a significant reduction in less labor, finance and time.

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The examples of RSM applications to agricultural machinery related problems are limited but there are some studies on seeding optimization. One of them in the literature was conducted by Singh et al (2005) on cotton. Karayel et al. (2004) tried to develop mathematical models to determine the vacuum need for different seeds.

The common point of many studies on seeding was the assumption of hole diameter on vacuum plate. But the study carried out by Yazgi and Degirmencioglu (2007) indicated that the hole diameter was the most important variable that affected the seeding phenomena. Yazgi and Degirmencioglu (2007) found that the hole diameter of 3 mm and a vacuum of 5.5 kPa are the optimum points that provided a quality of feed index of 99.67 %.

Hence an optimization based study was conducted and the objective of this study was to develop mathematical performance functions that included the peripheral speed of the vacuum plate, vacuum pressure and hole diameter and to optimize the seeding performance of a metering unit for planting corn seeds and to verify the optimum levels of the variables.

MATERIALS and METHOD

Materials

The precision seeder used in the experiments was a four-row vacuum type seeder consisting of a vertically operating vacuum plate. The vacuum plate that separates seed hopper and vacuum cell from each other had 36 holes drilled on a pitch diameter of 185 mm. Vacuum pressure at a range of 0-100 mbar was provided by an electronically controlled fan and there were two adjustable singulation devices on each metering unit of the seeder (Figure 1).

The vacuum plate during the experiments was driven separately by an electronically controlled system and the theoretical seed spacing was adjusted to 11.8 cm by using appropriate gears. Five different vacuum plates were used in the experiments and the determination of the range for hole diameter was made upon the physical properties of the corn seeds (Table 1). The holes on vacuum plates were drilled on a laser cutting machine with an accuracy of ± 0.1 mm.

Figure 1. Test stand of seeder

Table 1. Physical properties of corn seeds

Corn variety	**Length** *(l, mm)*	**Width** *(w, mm)*	**Thickness** *(t, mm)*	**Sphericity** *(Φ*,%)*	**Thousand seed mass (g)**
Sele (MAY)	10.7±0.98	7.8±0.63	6.2±0.57	75.0	343.75

$$\phi = \frac{(lwt)^{1/3}}{a} * 100$$

Seed spacing accuracy tests were achieved on sticky belt and for this purpose, 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 by means of a computerized measurement system, CMS, (Onal and Onal, 2009). For this reason, a sticky belt test stand was equipped with a computerized measurement system. CMS hardware consists of a high precision optical mouse coupled with laser pointer and a notebook computer. The software of the CMS stores coordinate data of the seeds using a simple user interface and sends to Microsoft Excel for further statistical analysis. The developed program analyzes the information and output results in numerical (ISO Standard indexes of quality-of- feed index, miss index, and precision) and graphical (histogram of seed spacing) forms. Sticky belt test stand is 0.15 m wide and 11 m long horizontal viewing surface. The measurement of seed distances was carried out at a distance of 7-8 m approximately for each test. The sticky belt stand was equipped with a multi-speed drive arrangement and grease oil was smeared on the top surface of the belt to capture the seed as it was released from the seeder without rolling or bouncing of the seed on the belt surface.

Method

In an ideal precision seeding process, no multiples and skips occur and the quality of feed index is 100%. This means that seeds are planted into the soil at equal distances. But in practical conditions this may not be achieved.

Performance of the seeders is determined as the quality of feed index, multiple and miss indexes. So for a better performance, the quality of feed index should be maximized while the multiple and miss indexes are minimized. Seed dispersions for precision seeding were determined according to Table 2 (Önal, 1995) and evaluated based on the criteria given in Table 3 (Anonymous, 1999).

Table 2. Definition of the seed/plant spacing distribution indexes (Önal, 1995)

Seed spacing	Definition
< 0.5 Z	Multiple Index
(0.5-1.5) Z	Quality of feed index
(1.5-2.5) Z	Miss index
(2.5-3.5) Z	Miss index
> 3.5 Z	Miss index

Table 3. Performance criteria based on main seed distribution for precision seeding (Anonymous, 1999)

Quality of feed index (I_{qf} %)	Multiple index (I_{mult}%)	Total miss index (I_{miss}, %)	Classification
> 98.6	< 0.7	< 0.7	Very good
> 90.4 – ≤ 98.6	≥ 0.7 – < 4.8	≥ 0.7 – < 4.8	Good
≥ 82.3 –≤ 90.4	≥ 4.8 – ≤ 7.7	≥ 4.8 – ≤ 10	Moderate
< 82.3	> 7.7	> 10	Insufficient

Seed spacings obtained from experiments were classified by the computerized measurement system at a theoretical seed spacing of 11.8 cm and the percentage of indexes; multiple index, quality of feed index and miss index (Kachman and Smith, 1995) were calculated. Multiple index is the percentage of spacings that are less than or equal to half of the theoretical spacing (≤5.9 cm), quality of feed index is the percentage of spacings that are more than half but no more than 1.5 times (5.9-17.7 cm) the theoretical spacing, miss index is the percentage of spacings greater than 1.5 times (≥17.7 cm) the theoretical spacing. As well as the above mentioned performance indicators available in literature, an another performance criterion called root-mean-square deviation from the theoretical seed spacing, E_{rms} as proposed by Yazgı and Degirmencioglu (2007) was calculated. This definition is expected be zero in ideal cases and it is defined as in the following.

$$E_{rms} = \sqrt{\frac{\sum_{i=1}^{N}(x_i - Z)^2}{N}} \quad \text{..............................} \quad [1]$$

where; Z is theoretical seed spacing in cm; x_i is the measured seed spacing in cm; and N is the number of measurements. It should be noted that this definition is different from the well-known standard deviation.

The other performance criterion on precision seeding is coefficient of precision (CP3). It is required in this criteria that if seed spacing is greater than 10 cm, deviations of seed spacings (Z, 2Z,...nZ) should be ±2.5 cm. In the laboratory this value should be ±1.5 cm (Önal, 1987). For example, if the seed spacing is 11.8 cm, distance for two seeds or plants should be minimum 9.3 cm, maximum 14.3 cm in the field. In the laboratory, these values changes as 10.3 cm and 13.3 cm.

As an optimization tool, Response surface methodology was used and experiments were conducted based on this methodology.

The RSM designs are not primarily used for understanding the mechanism of the underlying system and assessing treatment main effects and interactions, but to determine, within some limits, the optimum operating conditions of a system (Myers, 1971). It is less laborious and time-consuming than other approaches and is an effective technique for optimizing complex processes since it reduces the number of experiments needed to evaluate multiple parameters and their interactions (Lee et al., 2006). The response surface problem usually centres on an interest in some response Y, which is a function of k independent variables ξ_i, ξ_j, ...,ξ_k , that is,

$$Y = f(\xi_i, \xi_j, \ldots\ldots, \xi_k) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [2]$$

and response surface can take the different forms according to the function types of response and usually response function is defined in the quadratic polynomial form as follows

$$Y = \beta_0 + \sum_{t=1}^{k} \beta_i X_i + \sum \beta_{li} X_i^2 + \sum_{i} \sum_{j} \beta_{ij} X_i X_j + \varepsilon, \quad i \leq j \qquad [3]$$

where Y is the response; β_0 is the intercept; β_i, β_{ii}, β_{ij} are the regression coefficients; X_i X_j are the coded variables; and ε is the error. The coding of independent variables into X_i is expressed by the following equation:

$$X_i = \frac{\xi_i \quad \xi^*}{d_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [4]$$

where ξ_i is the actual value in original units; ξ^* is the mean value (centre point); and d_s is the step value. For a better understanding and detailed theoretical knowledge on RSM, the reader is referred to read the textbook written by Box and Draper (1987).

One of the RSM designs used in this study is a rotatable CCD and it requires five levels for each independent variable. These levels were coded as -1.682, -1,0, +1 and +1.682.

In the experiments, the peripheral speed of the vacuum plate, hole diameter and vacuum pressure were considered to be the independent variables that affect seeding performance.

The seeder was operated at five levels of peripheral speed of vacuum plate (X_1), hole diameter (X_2), and vacuum pressure (X_3). The values chosen for independent variables in the experiment were 0.053, 0.08, 0.12, 0.16 and 0.19 m/s (0.52, 0.8, 1.2, 1.6, 1.87 m/s forward speed) as peripheral speeds of the vacuum plate, 2.32, 3, 4, 5, 5.68 mm as hole diameters and 26.4, 40, 60, 80 and 93.6 mbar as vacuum pressures.

The independent variables considered in this study and their coded levels are tabulated in Table 4. The coding of independent variables X_1, X_2 and X_3 are expressed by the following equations:

$$X_1 = \frac{X - 0.12}{0.04}, \quad X_2 = \frac{X - 4.0}{1.0}, \quad X_3 = \frac{X - 60}{20} \qquad [5]$$

The determination of the centre point for each independent variable was based on field conditions and the physical properties of the corn seeds used since for the design of such experiments, a special care has to be given for the selection of centre point as well as the minimum and maximum levels in order to construct polynomial functions from which the optimum levels of the independent variables are to be calculated.

The centre point of peripheral speed of the vacuum plate was chosen 0.12 m/s and the step value of 0.04 m/s was used while the centre point of the hole diameter was determined as 4 mm and step value was determined as 1 mm. The centre point of the vacuum pressure was assumed to be 60 mbar and a step value of 20 mbar was chosen.

Table 4. Central composite design (CCD) with coded and uncoded independent variables

Run no	**Independent Variables**					
	Peripheral speed (X_1, *V*)		**Hole Diameter (X_2, *d*)**		**Vacuum pressure (X_3, *P*)**	
	Coded	**Uncoded (m/s)**	**Coded**	**Uncoded (mm)**	**Coded**	**Uncoded (mbar)**
1	-1	0.08	-1	3	-1	40
2	-1	0.08	1	5	-1	40
3	1	0.16	-1	3	-1	40
4	1	0.16	1	5	-1	40
5	-1	0.08	-1	3	1	80
6	-1	0.08	1	5	1	80
7	1	0.16	-1	3	1	80
8	1	0.16	1	5	1	80
9	-1.682	0.053	0	4	0	60
10	1.682	0.19	0	4	0	60
11	0	0.12	-1.682	2.318	0	60
12	0	0.12	1.682	5.682	0	60
13	0	0.12	0	4	-1.682	26.4
14	0	0.12	0	4	1.682	93.6
15	0	0.12	0	4	0	60
16	0	0.12	0	4	0	60
17	0	0.12	0	4	0	60
18	0	0.12	0	4	0	60
19	0	0.12	0	4	0	60
20	0	0.12	0	4	0	60

Each test was triplicated and the quality of feed index, multiple and miss indexes, root mean square error and coefficient of precision were found and treated as dependent variables.

Minitab was used for the development of polynomial functions and stepwise regression analysis was achieved at the probability level of 99%.

RESULTS and DISCUSSION

The results obtained from the experiments are given in Table 5. As seen from the table, the precision metering unit performance changes as the independent variables are varied.

Data given in Table 5 were evaluated in Minitab Statistical package program to construct polynomial functions for all dependent variables as considered to be the quality of feed index, multiple and miss indexes, root mean square error and coefficient of precision. Only a significant polynomial function was developed for the quality of feed index from the data once arcsin transformation was applied as given below.

$$y_m = \arcsin(\sqrt{\frac{I_{qf}}{100}}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[6]$$

Quality of feed index model;

$$y_m = 1.351 - 0.089\,X_1 + 0.0721\,X_2 + 0.0459\,X_3 + 0.0546\,X_1X_2 - 0.048\,X_2X_3 - 0.0391\,X_1^2 - 0.0837\,X_2^2 - 0.0341\,X_3^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[7]$$

Table 5. Experimental data for precision seeding of corn seeds

	Independent Variables			Dependent Variables				
Run No	**Peripheral Speed (X_1)**	**Hole Diameter (X_2)**	**Vacuum Pressure (X_3)**	**Quality of Feed Index (%)**	**Miss Index (%)**	**Multiple Index (%)**	**Root Mean Square Error, E_{rms} (%)**	**Coefficiant of Precision, CP3 (%)**
1	-1	-1	-1	83.40	3.62	12.98	4.47	25.59
2	-1	1	-1	93.21	6.79	0.00	3.10	42.57
3	1	-1	-1	59.85	1.76	38.40	11.41	29.52
4	1	1	-1	93.13	3.08	3.79	4.24	36.70
5	-1	-1	1	93.29	1.56	5.15	3.19	42.76
6	-1	1	1	93.86	5.16	0.98	3.29	41.03
7	1	-1	1	74.65	5.48	19.87	6.61	26.06
8	1	1	1	88.59	5.67	5.75	3.79	29.66
9	-1.682	0	0	97.50	0.49	2.01	2.59	46.88
10	1.682	0	0	76.63	2.10	21.27	6.54	27.72
11	0	-1.682	0	75.36	1.89	22.75	7.83	31.87
12	0	1.682	0	85.24	8.72	6.03	4.14	33.93
13	0	0	-1.682	82.75	0.00	17.25	5.76	50.40
14	0	0	1.682	95.76	2.08	2.16	2.86	46.95
15	0	0	0	93.90	1.16	4.94	3.13	54.39
16	0	0	0	95.94	0.56	3.50	3.39	55.03
17	0	0	0	95.56	2.19	2.26	2.73	55.30
18	0	0	0	95.02	0.55	4.43	2.77	56.08
19	0	0	0	95.08	1.64	3.28	2.54	60.11
20	0	0	0	95.63	0.56	3.82	2.76	56.74

(Values are given as the average of three replications of the machine performance obtained. Source: Yazgı, 2010)

The results from the regression analysis are tabulated and the variables included in the model are given in the order they entered into the model in Table 6.

As seen from table 6, the first variable entered to model is peripheral speed of the vacuum plate called X_1, the second and third variables are the hole diameter related variables, X_2^2 and X_2, respectively. The first variable peripheral speed accounts for approximately 27% of the variation in the quality of feed index. The second and third terms account for almost an additional 40% variation in the quality of feed index. As seen from the above written model, the vacuum pressure is also included in the model as an important variable.

Table 6. Results from the stepwise regression analysis for the quality of feed index model for corn

Step No	Variable	Constant	Standart deviation	R^2 (%)
-	Model constant	1.351	-	-
1	X_1	-0.089	0.124	26.82
2	X_2^2	-0.0837	0.105	48.43
3	X_2	0.0721	0.0857	66.01
4	X_3	0.0459	0.0769	73.15
5	X_1X_2	0.0546	0.0686	79.05
6	X_1^2	0.0391	0.0611	83.64
7	X_2X_3	-0.048	0.0524	88.21
8	X_3^2	-0.0341	0.0426	92.35

If the model is viewed in terms of interaction terms, it is seen that X_1X_3 interaction isn't in the model. This means that the peripheral speed and vacuum pressure interaction does not contribute to model at the 99% probability level. If the model is examined in terms of quadratic terms, it is seen that the model includes quadratic effects of all variables. But it is clearly seen that the most effective variable for system is the hole diameter at a quadratic form. The models are valid for the following conditions;

$$0.053 \text{ m/s} \geq v \geq 0.19 \text{ m/s}$$
$$2.32 \text{ mm} \geq d \geq 5.68 \text{ mm}$$
$$26.4 \text{ mbar} \geq P \geq 93.6 \text{ mbar}$$

In order to obtain the optimum level of the variables, mathematical software called Maple was used and a special code was written and the Equation

7 in polynomial form was submitted to the software and the function was tried to be maximized. The coded optimum values of independent variables were calculated as X_1=-1.3015, X_2=-0.2339 and X_3=0.8377.

The variables in their original dimensions are found as in the flowing if the coded values are converted to uncoded values,

$$\frac{X_1-0.12}{0.04}=-1.3015 \Rightarrow X_1=0.068\,m/s \qquad \text{[8]}$$

$$\frac{X_2-4}{1}=-0.2339 \Rightarrow X_2=3.77\,mm \qquad \text{[9]}$$

$$\frac{X_3-60}{20}=0.8377 \Rightarrow X_3=76.75\,mbar \qquad \text{[10]}$$

Some typical views from the response surface functions are depicted in figure 2 thru 4.

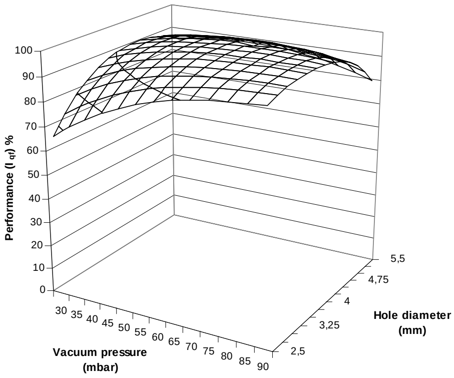

Figure 2. Quality of feed index as a function of vacuum pressure and hole diameter as 3D view (peripheral speed of vacuum plate:0.068 m/s)

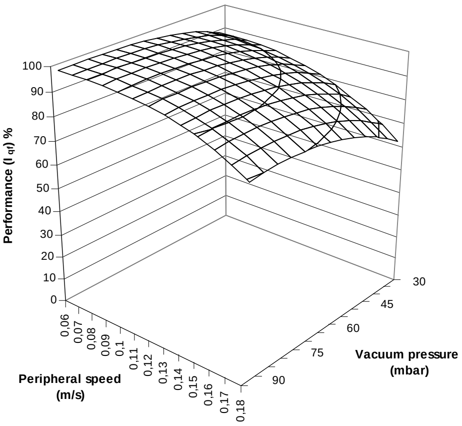

Figure 3. Quality of feed index as a function of vacuum pressure and peripheral speed of vacuum plate (hole diameter : 3.77 mm)

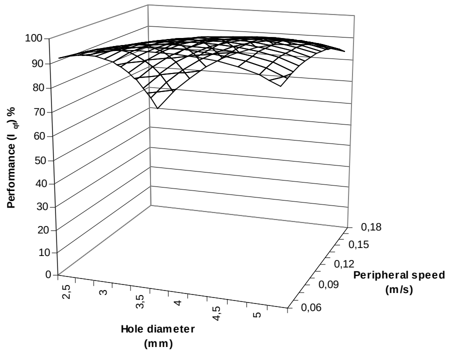

Figure 4. Quality of feed index as a function of hole diameter and peripheral speed of vacuum plate (vacuum pressure: 76.75 mbar)

Sensitivity analysis

Sensitivity analysis is the best way to show the harmony between predicted and measured values and this was depicted in figure 5. As seen from the figure, the data are scattered around the diagonal line and this shows a good correlation (96.8 %) between the measured and predicted quality of feed index data.

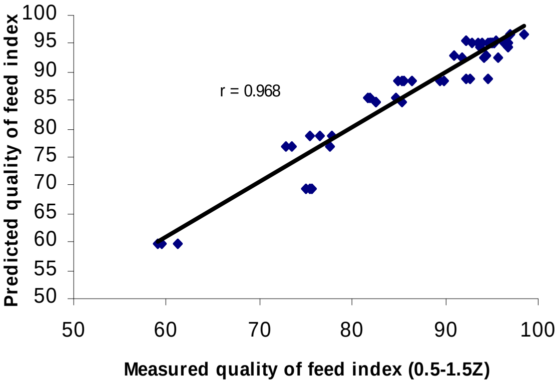

Figure 5. Comparison of predicted and measured quality of feed index

Results from the verification tests achieved at optimum level of the variables

If the optimum levels of the variables in coded form are substituted in equation 7, an arcsin value of 1.4197 as associated with a quality of feed index of 96.34 % (using equation 6) is obtained.

These optimum values were tested in the laboratory and in order to carry out the verification tests, the seeder was operated using optimum values of peripheral speed, hole diameter and vacuum pressure. Three verification tests carried out at a peripheral speed of 0.07 m/s, 3.8 mm of hole diameter and a vacuum pressure of 77 mbar (as they are close to the optimum level of the variables) were carried out and an average value of 99.48% was obtained.

Verification tests were also carried out in the field at the same level of the variables and resulted in a quality of feed index of 97.0% as an average of three replications. The performance of the machine in the field conditions was lower than the greased belt experiments and this was an expected situation since some other factors may affect seeding phenomena in the field.

It can be thought that the optimum peripheral speed of 0.068 m/s as corresponds to a forward speed of 0.68 m/s determined is very low while it makes the field work rate low. But it should be kept in mind that these optimum values obtained are the values which maximize the performance of the machine.

In order to increase the field work rate while the performance of the machine is kept at an acceptable level, the value of 0.15 m/s peripheral speed (1.5 m/s forward speed) entered into model equation in a coded form (+0.75) and the performance of the machine was calculated to be 92.27% (good) at a vacuum of 77 mbar and a hole diameter of 3.8 mm.

CONCLUSIONS

Response surface methodology is a useful tool and provides a means of optimizing the performance of a precision seeder. The equation developed may be used for estimating the quality of feed index for a similar type seeder as used in this study within the boundaries as indicated in the study. Based on the results obtained from this study, the followings can be drawn:

- The performance of a metering unit is mostly affected by the hole diameter on the vacuum plate. The optimum level of the hole diameter is about 3.8 mm and this is expected to vary depending upon the physical properties of corn seeds.
- The level of vacuum pressure is of importance and interacts with hole diameter and the selection of its appropriate level is again based on the physical properties of the corn seeds and the optimum level is about 77 mbar.

The peripheral speed as it is associates with the forward speed affects the seed spacing performance of a metering unit and it is approximately 0.07 m/s for planting corn seeds. This speed should be considered as a low value since the forward speed of 0.7 m/s should result in a low field work rate (field capacity). In order to increase the field work rate, the peripheral speed of 0.15 m/s (1.5 m/s forward speed) should be used. In this case the field work rate (field capacity) will increase but the quality of feed index will be reduced down to 92 %.

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