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Graphite action on the longitudinal distribution of soybean seeds in mechanical and pneumatic feeders

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ABSTRACT. The use of powdered graphite as a solid lubricant to reduce friction among soybean seeds during mechanical sowing aims to facilitate the seed flow into the seed reservoir, while reducing mechanical damage to the seed. The objective of this study was to evaluate the influence of graphite on the longitudinal deposition of soybean seeds using mechanical and pneumatic feeders at different distribution velocities. The experiment was performed on a static simulation-test bench, with a completely randomized design with two varying factors: graphite dose (0, 1, 2, 4, and 8 g kg^{-1} seed) and distribution velocity (5, 7, 9, and 11 km h^{-1} for the pneumatic feeder; and 3, 5, 7, and 9 km h^{-1} for the mechanical feeder). To assess the homogeneity of seed distribution, the frequency of parameters such as double, flawed, and acceptable spacings, coefficient of variation, and precision index were evaluated from five repetitions of 250 spacing each. For the pneumatic feeder, the optimal values to maximize precision of seed deposition were 4.6 g kg^{-1} and 6.7 km h^{-1} of graphite dose and distribution velocity, respectively. In turn, the optimal values to minimize undesirable spacing while maximizing accuracy with the mechanical feeder were 4.9±0.6 g kg^{-1} and 4.9±0.3 km h^{-1}. Overall, regardless of feeding mechanism, the use of graphite promoted greater efficiency in the distribution of seeds owing to the higher level of fluidity inside the reservoir; however, high doses can cause the opposite effect. In addition, an excessive increase in speed influenced seed distribution negatively.

Keywords: precision; resting angle; solid lubricant; seeder.

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Introduction

The evaluation of the performance of seed longitudinal distribution measured from consecutive spacings is essential to determine the efficiency of a sowing operation. Further, feeder mechanisms are regularly assessed under laboratory conditions, such as to eliminate potential negative interference from external factors (Okopnik & Falate, 2014).

The homogeneous deposition of seeds is important in the establishment of the crop, and any interference with it can cause significant losses in productivity (Tourino, Rezende, & Salvador, 2002). Thus, the improvement of sowing has been widely studied to promote higher levels of homogeneity of seed deposition, and ultimately, to achieve greater productivity (Cay, Kocabiyik, Karaaslan, May, & Khurelbaatar, 2017; Kumar & Rahema, 2018; Savi, Kmiecik, Strapasson Neto, Silva, & Jasper, 2020). Among the various components of a seeder (which can be either mechanical or pneumatic), the dosage unit is considered the most decisive factor determining the precision of seed deposition.

Mechanical feeders dispose seeds horizontally under the reservoir, from which the seeds are housed in their wells by gravity and dosed individually by the rotation movement of the delivering mechanism. Pneumatic feeders, on the other hand, have a disc located vertically, capturing the seeds by air suction and retaining them until they are positioned at the release site, where the absence of a differential pressure allows to dispense them into the conductive tube for deposition in the sowing groove (Dias, Alonço, Carpes, Veit, & Souza, 2014).

Efficiency of seed distribution is assessed by the frequency of double and flawed spacings in the sowing groove. Double spacing occurs when the deposition of consecutive seeds does not reach 0.5 × the desired spacing, while a flaw is said to occur when seeds are deposited 1.5 times above the desired spacing (ISO 7256/1, 1984). In addition to measuring the spacing, it is necessary to evaluate the dispersion in relation to the mean, determined by the coefficient of variation (CV), and how close the deposition varies depending on the theoretical distribution, expressed by the precision index (IP) (Cay, Kocabiyik, & May, 2018).

The resting angle is directly influenced by the roughness of the surface of the seeds and reflects their degree of fluidity (Al-Hashemi & Al-Amoudi, 2018). Seed fluidity influences the distribution efficiency, requiring the adoption of graphite as a solid lubricant to the reduce friction coefficient of the seeds and between them and the feeder, thereby promoting greater fluidity in the reservoir (Hentschke, 2002; Sidhu, Monono, Bora, & Wiesenborn, 2017).

The short time interval of the sowing window determined by the risks associated with climatic variables, forces farmers to obtain larger and more technically advanced seeders, aiming at a good distribution in the shortest possible time. This goal often makes the operator work at a higher speed than indicated, directly impairing the efficiency of the longitudinal distribution of seeds (Mangus, Sharda, Flippo, Strasser, & Griffin, 2017). The increase in the working regime results in an increase in the peripheral speed of the dosing discs, causing less regularity in the longitudinal distribution of the seed (Carpes et al., 2016).

Based on the foregoing discussion, the objective of this study was to evaluate the influence of different doses of graphite on the longitudinal deposition of soybean seeds distributed by mechanical or pneumatic feeders at different sowing velocities.

Material and methods

The tests were performed at the Agricultural Tractor Adequacy Laboratory (LATA) of the Federal University of Paraná (UFPR), Curitiba, Paraná State, Brazil.

Test bench characterization

The homogeneity of seed deposition was evaluated using a static sowing bench to determine the efficiency of the seed feeders under different graphite doses and operational speeds. This bench simulates the longitudinal distribution of seeds within the sowing groove with different feeder mechanisms, whose components and settings can be calibrated within a wide range of operational speeds and sowing densities. The mechanism is activated using a 0.25 kW gearmotor (Sew Eurodrive Inc., Bruchsal, Germany) managed by a CFW300 frequency inverter (Weg Inc., Santa Catarina State, Brazil).

The mechanical horizontal-disk feeder used was the Titanium model (J. Assy Inc., Goiás State, Brazil), which was maintained level and equipped with a 90-hole (9.0 mm) RampFlow disk over a 3-mm recessed ring. The seeds were deposited from a conducting tube with an 18° parabolic inclination and a 540-mm length. In turn, the pneumatic feeder mechanism used was the vSet model (Precision Planting Inc., IL, USA), equipped with an 80-hole soybean seed disk and the corresponding seed singulator and ejector. For the deposition of the seeds, a conducting pipe with a parabolic inclination of 17° and a 460-mm length was used. This mechanism was operated with a vacuum setting of 4.98 kPa, generated from a radial compressor CR-3 IBRAM (Brazilian Machinery Industry Ltd., São Paulo State, Brazil), with a maximum flow capacity of 0.022 $m^3\ s^{-1}$ and a maximum vacuum of 12.75 kPa.

The evaluation of the seed distribution dynamics was performed using an optical infrared-count sensor located at the end portion of the conductive mat. During the passage of each seed through the sensor, the light beam between the emitting element and the detector was interrupted, thereby resulting in a change in the output voltage and, consequently, the identification of the exact time of seed drop (Karimi, Navid, Besharati, Behfar, & Eskandari, 2017). Another infrared sensor was positioned on the sprocket (16 teeth) present in the roller driving the mat to measure the simulated velocity. Finally, the test bench had a printed circuit board data-acquisition system with acquisition frequency linked to seed passage, measured by optical sensors connected to this system. The data were transferred and stored on a hard disk (Jasper, Bueno, Laskoski, Langhinotti, & Parize, 2016).

Experimental design

Two experiments were conducted using a completely randomized double-factorial design. The first factor evaluated was the dose of graphite (0, 1, 2, 4, and 8 g kg^{-1} of seed); the second was the distribution velocity during the operation of the pneumatic (5, 7, 9, and 11 km h^{-1}) or mechanical (3, 5, 7, and 9 km h^{-1}) feeders.

These velocity ranges were compatible with each mechanism. It is noteworthy that these velocities were assigned to assess the influence of graphite on seed distribution by each feeder separately, and not to compare them. For each treatment, five repetitions of 250 consecutive seed-deposition events were performed, for a total of 100 experimental units for each feeder evaluation (i.e., five doses of graphite, four distribution velocities and five repetitions).

The collection period for each treatment using the acquisition system of the static sowing bench corresponded to the deposition of 2,000 seeds, of which, each repetition was taken from the median portion of the collection for further statistical analysis.

For a constant planting density, at different simulated velocities, the deposition rate was altered with an increase in rotational speed of both feeder discs. Calibration was performed by correlating the electrical frequency provided by the frequency inverter and the number of seeds deposited per second (R^2=1 for both feeders). The increment of 1 Hz promoted the deposition of 1.15 and 1.12 seeds per second for mechanical and pneumatic feeders, respectively, during distribution.

Soybean seeds of cultivar NA 5909 RG showed a minimum purity and germination rate of 99% and 80%, respectively. During the tests, the adopted planting density was 277,777 seeds ha^{-1}, spaced at 0.08 m within rows and 0.45 m between rows. Table 1 shows the physical characteristics of the soybean seeds used. The dimensional characteristics (length, diameter, thickness, and sphericity) were measured according to the methodology proposed by Soyoye, Ademosun, and Agbetoye (2018) and assessed from 100 sample units using a digital caliper (1×10^{-4} m accuracy). The 1,000-grain weight was determined by weighing three samples of 300 seeds each in a semi-analytical balance BK-5002 (Gehaka Ltda., São Paulo State, Brazil). The break index (IB) of pre-existing seeds was assessed visually from three 100-g samples, and the breaks generated during the feeding and deposition processes were evaluated from the absolute sample of each treatment.

Table 1. Average physical characteristics of the soybean seeds used in the tests.

Length	Width	Thickness	Sphericity	1,000-grain weight	IB
-------------------------- (mm) --------------------------				(g)	(%)
6.87±0.06	5.84±0.04	6.53±0.07	93.20±0.03	171.79±0.47	0.10±0.03

The resting angle was established by the inverse tangent of the height due to the distance from the mass deposited on a flat surface with the increase in powdered graphite (Quimidrol Ltda., Santa Catarina State, Brazil), as described by Guo et al. (2014). Values of 27.47, 26.57, 25.74, 24.66, and 26.16° were arranged in ascending order according to the increase in graphite dose.

Evaluated parameters

The parameters analyzed to assess the distribution homogeneity included percent acceptable (SA), double (SD), and flawed (SF) spacings, CV, and IP. The performance indicators of the seeders were evaluated using the criteria listed in Table 2 (ISO 7256/1−1984 (E) Standard, 1984; Aykas, Yalçin, & Yazgi, 2013).

Table 2. Limiting values for classifying the performance of precision sowing.

Spacing (%)			Classification
SA	SD	SF	
>98.6	<0.7	<0.7	Excellent
>90.4 – 98.6	⩾0.7 – 4.8	⩾0.7 – 4.8	Good
⩾82.3 – 90.4	⩾4.8 – 7.7	⩾4.8 –10.0	Regular
<82.3	>7.7	>10.0	Unsatisfactory

According to Cay et al. (2018), IP indicates the variability of the distribution in relation to the theoretical spacing (Equation 1). By disregarding SD and SF, higher IP values are obtained, resulting in greater distribution unevenness with regard to the desired spacing. Furthermore, IP values must not exceed the upper limit of 29%, which is suggested for precision sowing (Nejadi & Raoufat, 2013). IP values were calculated using the following formula:

$$I_P = \left(\frac{\sigma_{S_A}}{S_E}\right)100 \qquad (1)$$

where IP is the precision index (%), σSA is the standard deviation of the acceptable spacing (m), and SE is the expected spacing according to the spacing between rows and plant stand (m).

Statistical analysis

The data were subjected to normality and homogeneity analysis of variance using the Shapiro-Wilk and Brown-Forsythe tests, respectively. Given these assumptions, the data were subjected to analysis of variance (ANOVA) and, if significant effects were detected, the Scott-Knott test was used on the isolated factors and the interaction between them was evaluated using SigmaPlot software (version 12.0; Systat Software Inc., CA, USA).

Results and discussion

Distribution of soybean seeds by the pneumatic feeder

Table 3 presents a statistical summary of the relationship between graphite dose and distribution velocity with the parameters used to assess the distribution homogeneity of the pneumatic feeder operation. Regarding the evaluated parameters, we can observe the significance of the independent factors and their interactions.

Table 3. Analysis of variance and means test for the deposition of soybean seeds distributed from a pneumatic feeder at different doses of graphite and velocities.

Analysis	Parameters				
	SA	SD	SF (%)	CV	IP
F-test					
Graphite	6.67**	2.65*	14.02**	3.51**	19.45**
Velocity	231.87**	166.12**	201.26**	346.28**	771.73**
Graphite x velocity	8.07**	4.92**	9.20**	19.08**	38.43**
CV (%)	2.79	27.49	25.07	6.83	4.41
Graphite (g kg^{-1})					
0	87.75 b	5.45 b	6.80 a	30.25 a	21.31 c
1	89.37 a	5.45 b	5.18 b	30.20 a	23.54 a
2	88.32 b	6.20 a	5.48 b	30.95 a	23.49 a
4	91.02 a	4.80 c	4.18 c	28.80 b	22.93 b
8	90.05 a	5.37 b	4.58 c	29.86 a	22.98 b
Velocity (km h^{-1})					
5	97.51 a	1.07 d	1.43 d	22.60 d	19.60 c
7	91.65 b	4.64 c	3.71 c	26.01 c	19.36 c
9	86.75 c	6.65 b	6.60 b	37.89 a	22.16 b
11	81.29 d	9.45 a	9.25 a	33. 54 b	30.27 a

Values followed by different lowercase letters within columns for each factor are significantly different (P<0.05). F-test: NS – not significant; * – P < 0.05; ** – P < 0.01. SA – acceptable spacing; SD – double spacing; SF – flaw spacing; CV – coefficient of variation; IP – precision index.

The analysis of the effect of graphite on seed distribution revealed a better performance in terms of SA, SD and SF at a dose of 4 g kg^{-1}, compared to the other graphite doses. Thus, precision was classified as "good" (Tables 2 and 3). For double spacings, 0, 1, and 8 g kg^{-1} were classified as "regular," and did not largely differ from each other. (Table 3). The highest occurrence of SD was observed when using a dose of 2 g kg^{-1}, which was 29% higher than at the 4 g kg^{-1} dose. Furthermore, the use of graphite promoted a significant reduction in SF levels, regardless of the graphite dose used, thus explaining the importance of treating seeds with graphite. When treated with the solid lubricant, the lowest SF values were observed at 4 and 8 g kg^{-1}, which reduced flawed spacings by 35% on average, whereby it was classified as "good." The results obtained corroborate those of Badua, Sharda, Strasser, Cockerline, and Ciampitti (2019), who determined that greater seed fluidity results in a reduction in SD and SF during seed distribution. These undesirables spacings directly affect individual plant and per unit area production of the soybean crop, as well as the degree of lodging and the mass of the harvested grain, which can contribute to significant reductions in crop productivity (Tourino, Rezende, & Salvador, 2002).

According to the CV for seed distribution, the best homogeneity of seed deposition was observed at a dose of 4 g kg^{-1}, in which case, the CV was 3.58% lower than the other doses, thus improving the efficiency of the pneumatic mechanism (Table 3). The distribution of IP was significantly higher at doses of 1 and 2 g kg^{-1} compared to 4 and 8 g kg^{-1}. However, none of the treatments exceeded the maximum limit of 29% for IP (Nejadi & Raoufat, 2013).

Graphite use at 4 g kg^{-1} resulted in the lowest values for SD, SF, and CV, in addition to the highest percentage of SA, relative to the other doses, thereby demonstrating that it was the best dose of graphite when operating with the pneumatic type of feeder. This resulted in a smaller measured resting angle (24.66°), and consequently, a higher seed fluidity in the reservoir of the feeding mechanism (Sidhu et al., 2017).

As for the effect of increasing simulated velocity on seed distribution, a concomitant increase in SD, SF, CV, and IP can be observed, that resulted in a reduction in the number of SA (Table 3). In this case, there was a proportional increase of 2.7% in undesirable spacings (i.e., 1.4% for SD and 1.3% for SF) and 1.82% of CV with an increase of 1.0 km h^{-1} in velocity. This can be explained by the increase in the centrifugal force of the seeds when they enter the conductive pipe, which results in more frequent collisions and jumps (Yazgi, 2016; Virk, Fulton, Porter, & Pate, 2020). Additionally, this reduction in the feeder efficiency with increasing distribution velocity is due to an increase in the number of seeds dosed per minute, which has an inverse relationship with the level of correct deposition (Mangus et al., 2017).

Regarding IP, an increase in velocity caused increased variation in the observed spacing in relation to the desired one. Additionally, it enhanced the occurrence of SD and SF. Thus, velocities of 5 and 7 km h^{-1} resulted in the lowest IP values and, therefore, greater accuracy of the dosing mechanism (Table 3). With a 1-km h^{-1} increase in velocity, an average increase of 1.19% occurred in IP, but only the highest speed exceeded the maximum limit of 29% for precision seeders (Nejadi & Raoufat, 2013), corroborating the results of Virk et al. (2020), who reported reduced levels of uniformity of spacing between plants with increasing operation velocity.

Considering the variation in SA, SD, and SF, there was an increase in distribution uniformity with increasing graphite dose and with lower target velocity (Table 4). Distributions were classified as "excellent" for SA and SD at 5-km h^{-1} velocity and 4-g kg^{-1} graphite dose (Tables 3 and 4). Additionally, at this velocity, graphite at 8 g kg^{-1} rendered an "excellent" distribution in terms of SD.

Table 4. Means comparison for soybean seed deposition by a pneumatic feeder at different graphite doses and distribution velocities.

Velocity (km h^{-1})	Graphite (g kg^{-1})				
	0	1	2	4	8
			SA (%)		
5	94.33 Ab	98.00 Aa	98.27 Aa	98.61 Aa	98.33 Aa
7	90.13 Bb	94.60 Ba	90.33 Bb	92.33 Ba	90.87 Bb
9	86.00 Cb	83.07 Cb	84.60 Cb	90.20 Ba	89.87 Ca
11	76.33 Dc	81.80 Cb	80.07 Db	87.13 Ca	81.13 Db
			SD (%)		
5	2.47 Da	0.87 Ca	1.00 Da	0.47 Ca	0.53 Ca
7	4.87 Ca	3.00 Bb	5.40 Ca	4.60 Ba	5.33 Ba
9	7.07 Ba	8.40 Aa	7.93 Ba	4.27 Bb	5.60 Bb
11	10.20 Aa	9.53 Aa	10.47 Aa	7.00 Ab	10.07 Aa
			SF (%)		
5	3.20 Da	1.13 Bb	0.73 Db	0.87 Ab	1.20 Cb
7	5.00 Ca	2.40 Bb	4.27 Ca	3.07 Bb	3.80 Ba
9	6.93 Ba	8.53 Aa	7.47 Ba	5.53 Cb	4.53 Bb
11	13.47 Aa	8.67 Ab	9.47 Ab	5.87 Cc	8.80 Ab
			CV (%)		
5	26.30 Ba	22.45 Cb	21.63 Db	20.68 Cb	21.96 Db
7	27.61 Ba	23.69 Cb	27.02 Ca	24.69 Bb	27.04 Ca
9	39.51 Ab	42.11 Aa	41.09 Aa	29.10 Ac	37.67 Ab
11	37.98 Aa	32.57 Bb	34.06 Bb	30.33 Ac	32.78 Bb
			IP (%)		
5	20.80 Ca	20.05 Ca	19.23 Cb	18.69 Bb	19.21 Cb
7	19.52 Da	19.23 Ca	19.77 Ca	18.48 Ba	19.81 Ca
9	22.84 Ba	22.36 Ba	22.79 Ba	22.04 Aa	20.80 Bb
11	32.50 Aa	32.52 Aa	32.16 Aa	22.06 Ab	32.12 Aa

Values followed by different uppercase letters within columns and by lowercase letters within rows, for each combination, are significantly different ($P<0.05$). SA – acceptable spacing; SD – double spacing; SF – flaw spacing; CV – coefficient of variation; IP – precision index.

The influence of graphite on SA was bolstered at 11 km h^{-1}, allowing an increase of up to 10.8% in SA when graphite was used at 4-g kg^{-1}. However, this increase was limited to 4.47% at other speeds. This might be explained by the greater need for seed fluidity in the reservoir when the mechanism operates at higher deposition rates on account of the increase in the number of individualized seeds per time interval and the shorter exposure period of the dosing disc to the seed in the reservoir. When the feeder mechanism operated at 5 km h^{-1}, the effect of using graphite was similar for all treatments, which only differed from 0 kg kg^{-1}; however, with the increase in speed, the dose of 4 g kg^{-1} yielded the lowest reduction in SA levels (-11.48%) in relation to the other doses (-17.4 ± 0.91%). This finding demonstrates the need for the correct use of graphite as a solid lubricant when operating at high working velocities, which makes it possible to improve operating performance without increasing operating width (Ivancan, Sito, & Fabijanić, 2004).

On average, increasing velocity of distribution had a negative effect on SD, irrespective of graphite dose (Table 4). Thus, we observed an increase of 1.40% in SD per unit velocity increase. However, when graphite was used at 4 g kg^{-1}, this increase was minimized to 1.09%, with a consequent reduction in the negative effect of velocity increase on distribution homogeneity. As for SF, Table 4 shows that graphite had a greater effect at 11 km h^{-1}, while a dose of 4 g kg^{-1} reduced SF levels by 7.6% in relation to the 0 g kg^{-1} graphite treatment, and by 3.11± 0.49% relative to the other doses. This is explained by the reduction in seed surface roughness and the friction inside the reservoir, with a consequent improvement in their adherence to the alveolus of the feeder disc and a reduction in the number of premature drops or failures.

With respect to SA, SD, and SF, we observed that at 5 km h^{-1}, seed distribution was impaired in the absence of graphite (Table 4). However, with increasing velocity, graphite doses have a differential effect, showing a greater uniformity of distribution at 4 g kg^{-1}, regardless of velocity. Furthermore, the effect of graphite can be emphasized by analyzing what happens at 11 km h^{-1}, at which velocity, graphite doses of 1 or 2 g kg^{-1}, do not provide the necessary seed fluidity for optimal operation of the seed distribution mechanism. Such lower seed fluidity may be due to the insufficiency of the volume necessary for the complete coating of the seeds, which would corroborate the findings of Alonço, Alonço, Moreira, Carpes, and Pires (2018), who pointed out that the negative effect of a lack of lubricant is aggravated by industrial chemical treatments of the seed. On the other hand, a dose of 8 g kg^{-1} compromises the distribution mechanisms, as the excess of graphite tends to segregate and deposit at the bottom of the reservoir, blocking seed drop.

Regarding spacing CV, the pneumatic feeder mechanism was more efficient in terms of uniform seed deposition at a velocity of 5 km h^{-1} and a graphite dose of 4 g kg^{-1}. However, efficiency obtained did not differ at doses of 1, 2, or 8 g kg^{-1} (Table 4). According to Kostic et al. (2018), CV increases with an increase in target velocity owing to the distortion of the path of consecutive seeds; however, this effect is 7.36% less with the use of graphite at a dose of 4 g kg^{-1}. It should be noted that the negative effect of any velocity increase was more evident when graphite was not used; however, it was observed that this effect was minimized with the use of a solid lubricant at a dose of 4 g kg^{-1}, thus demonstrating the need for a solid lubricant when operating at higher speeds. The effect of treating seeds with graphite is highlighted at the highest target velocities tested here (9 and 11 km h^{-1}). In either case, greater distribution homogeneity was observed with the use of 4 g kg^{-1}, and the value for CV observed at these velocities did not differ statistically from each other, thus making it possible to achieve higher levels of operating income without compromising distribution homogeneity.

Sidhu et al. (2017) reported that seed surface roughness was reduced with the use of solid lubricants and polymers, ensuring a strong seal with the hole in the dosing disc, thus preventing premature fall of the seeds. Moreover, monitoring the correct moment for seed ejection during operation of the dosing mechanism resulted in greater spacing uniformity and, consequently, a reduction in CV.

As shown by the behavior of IP in Table 4, seed distribution was more accurate when the feeding mechanism operated at higher velocity; however, the effect of velocity was lower when graphite was used at 4 g kg^{-1}. When operating at a velocity of 5 km h^{-1}, IP was different in relation to 0 and 1 g kg^{-1} graphite, which provided an increase of 1.38% in IP; however, at 7 km h^{-1}, there was no distinction between graphite doses. In turn, at 9 and 11 km h^{-1}, the highest levels of accuracy were obtained with the use of graphite at doses of 8 and 4 g kg^{-1}, respectively, demonstrating the need for higher dosages when operating at higher deposition rates. When operating at 11 km h^{-1}, IP values reached the maximum limit established by Nejadi and Raoufat (2013), except when using graphite at 4 g kg^{-1}.

These results corroborate those of Mantovani, Mantovani, Cruz, Mewes, and Oliveira (1999), who pointed out that, due to the resulting increase in seed fluidity, the use of graphite at the proper dose prevents the formation of empty spaces that in turn hampers feeding of the dosing disc. This increase in the efficiency of the feeding mechanism allows for greater levels of distribution homogeneity, which in turn has a direct effect on the uniformity of the stand.

Distribution of soybean seeds by a mechanical feeder

As with the pneumatic feeder, for the mechanical feeder there were also significant isolated and interactive effects among all parameters evaluated (Table 5).

Table 5. Analysis of variance and means test for the deposition of soybean seeds distributed from a mechanical feeder at different graphite doses and velocities.

Analysis	Parameters				
	SA	SD	SF (%)	CV	IP
F-test					
Graphite	95.34**	81.86**	55.70**	98.22**	55.12**
Velocity	84.73**	16.44**	128.54**	98.27**	117.34**
Graphite x velocity	4.59**	2.66**	5.71**	5.22**	5.48**
CV (%)	2.29	36.67	27.51	7.50	4.10
Graphite ($g\ kg^{-1}$)					
0	84.60 c	7.55 a	7.85 a	35.25 a	23.51 a
1	93.90 a	2.38 b	3.72 b	25.58 c	20.12 c
2	92.30 b	2.68 b	5.02 b	27.46 b	21.57 b
4	94.62 a	2.30 b	3.08 b	25.30 c	20.42 c
8	94.34 a	2.18 b	3.48 b	25.66 c	21.32 b
Velocity ($km\ h^{-1}$)					
3	93.82 b	2.73 b	3.45 c	26.72 b	21.62 b
5	94.96 a	2.83 b	2.21 d	24.18 c	19.71 d
7	92.10 c	3.37 b	4.53 b	27.37 b	20.51 c
9	86.93 d	4.75 a	8.32 a	33.13 a	23.71 a

Values followed by different lowercase letters within columns for each factor, are significantly different (P<0.05). F-test: NS – not significant; * – P < 0.05; ** – P < 0.01. SA – acceptable spacing; SD – double spacing; SF – flaw spacing; CV – coefficient of variation; IP – precision index.

When using graphite for the distribution of soybean seeds by a mechanical feeder, a “good” precision was observed regardless of graphite dose, whereas, in the absence pf graphite, a "regular" distribution for SA and SD parameters was recorded. For all graphite doses tested SF values were higher than when no solid lubricant was used; however, at 2 g kg^{-1} graphite caused 63% more failures than at 4 g kg^{-1} (Table 5). Moreover, on average, there was a 4.1% reduction in SF with solid lubrication, regardless of dose, in addition to the decrease in SD by 5.17%. According to Jasper, Janszen, Jasper, and Garcia (2006), the improvement in seed distribution upon treatment with graphite derives from the reduction of the internal friction inside the mechanism, thus facilitating seed adaptation to the holes of the feeding disc.

Regarding CV for seed distribution, greater homogeneity of deposition was observed at 1, 4, and 8 g kg^{-1} graphite, being, on average, 1.2% lower at 4 g kg^{-1} (Table 5). Not using graphite resulted in the highest CV, for seed distribution, which evidenced the difficulty of the mechanism in individualizing the seeds in the absence of graphite as a solid lubricant, which impaired the homogeneity of deposition.

The distribution of IP was significantly higher when graphite was not used, again, demonstrating a greater disparity in the spacing. However, when graphite was used at 2 and 8 g kg^{-1}, the accuracy achieved was greater (Table 5). As with the pneumatic feeder, none of the doses exceeded the maximum limit of 29% in this case (Nejadi & Raoufat, 2013).

As for distribution velocity, a better homogeneity ("good" precision level) was observed at 5 km h^{-1} for SA, SD, and SF (Tables 2 and 5). When the velocity of seed distribution was reduced to 3 km h^{-1}, SF increased by 56% (Table 5). This corroborates the findings of Dias et al. (2014), who verified a reduction in the regularity of seed distribution with an increase in the peripheral velocity of the feeding disk, independently of the seed dosing mechanism and culture. The increase in velocity caused an increase in SD levels; consequently, an increase of 1 km h^{-1} resulted in an average increase of 0.33% in SD; however, only the highest simulated velocity differed statistically from the other velocity treatments tested (Table 5).

In addition to undesirable spacing, the lowest CV was observed at 5 km h^{-1}, in which case, CV was 9.5% lower than at the lowest speed analyzed. The increase in peripheral velocity of the feeding disk reportedly increases the angle of seed impact against the conductor, generating a possibility of multiple paths during the fall and impairing the homogeneity of the distribution (Carpes et al., 2016).

With respect to IP, it appears that 5 km h^{-1} resulted in greater accuracy in the distribution, such that it was closest to the theoretical spacing. The increase in velocity from 5 to 7 and to 9 km h^{-1} reduced the level of hits in deposition, as evidenced by the increase of 0.8 and 4.0% in IP, respectively (Table 5). Notably, the reduction in velocity to 3 km h^{-1} increased the heterogeneity of SA in relation to 5 km h^{-1}.

Considering the behavior of parameters SA, SD, and SF for the factors analyzed, there was a gain in uniformity of seed distribution with an increase in graphite dose and a reduction in target velocity (Table 6).

Table 6. Means comparison for soybean seed deposition distributed by a mechanical feeder at different graphite doses and velocities.

Velocity (km h^{-1})	Graphite (g kg^{-1})				
	0	1	2	4	8
			SA (%)		
3	87.40 Ac	93.13 Bb	95.13 Ab	96.67 Aa	96.73 Aa
5	89.13 Ab	95.27 Aa	95.73 Aa	97.53 Aa	97.13 Aa
7	83.53 Bc	95.87 Aa	93.07 Ab	95.67 Aa	92.33 Bb
9	78.33 Cd	91.33 Ba	85.27 Bc	88.60 Bb	91.13 Ba
			SD (%)		
3	6.60 Ba	2.67 Ab	1.20 Bb	1.80 Bb	1.40 Bb
5	6.67 Ba	2.93 Ab	1.73 Bb	1.47 Bb	1.33 Bb
7	8.20 Aa	1.73 Ab	2.60 Bb	1.87 Bb	2.47 Ab
9	8.73 Aa	2.20 Ac	5.20 Ab	4.07 Ab	3.53 Ab
			SF (%)		
3	6.00 Ca	4.20 Bb	3.67 Bb	1.53 Bb	1.87 Bb
5	4.20 Da	1.80 Cb	2.53 Bb	1.00 Bb	1.53 Bb
7	8.27 Ba	2.40 Cc	4.33 Bb	2.47 Bc	5.20 Ab
9	12.93 Aa	6.47 Ac	9.53 Ab	7.33 Ac	5.33 Ad
			CV (%)		
3	32.99 Ca	27.20 Ab	25.80 Bb	24.20 Bc	23.39 Bc
5	30.36 Da	23.01 Bb	24.23 Bb	21.38 Bb	21.93 Bb
7	37.12 Ba	22.84 Bc	25.69 Bb	23.28 Bc	27.92 Ab
9	40.52 Aa	29.27 Ab	34.13 Aa	32.33 Aa	29.38 Ab
			IP (%)		
3	23.50 Da	21.52 Ab	21.21 Bb	21.16 Bb	20.70 Cb
5	21.49 Ca	18.89 Bc	20.32 Bb	18.73 Cc	19.14 Dc
7	22.96 Ba	18.27 Bc	20.77 Bb	19.30 Cb	21.94 Ba
9	26.08 Aa	21.78 Ad	24.68 Ab	22.52 Ac	23.49 Ac

Values followed by different uppercase letters within columns and lowercase letters within rows for each combination are significantly different ($p < 0.05$). SA – acceptable spacing; SD – double spacing; SF – flaw spacing; CV – coefficient of variation; IP – precision index.

As shown in Table 6, the highest percentage of SA (97.53%) was obtained when the feeder operated at 5 km h^{-1} and seed was treated with 4 g kg^{-1} graphite. This was classified as a “good” distribution (Table 2). Further, graphite doses of 1, 2, and 8 g kg^{-1} displayed the same capacity and this differed only relative to the 0 g kg^{-1} graphite treatment. The highest level of SA observed in our experiments corroborated data by Mantovani et al. (1999), who identified the same graphite dose to achieve greatest seed fluidity during pre-sowing of corn seeds.

The reduction of friction among seeds by the use of a solid lubricant generally caused a marked reduction in the levels of undesirable spacing, regardless of dosage, with an average of 236 ± 0.7% of SD and 116 ± 0.3% of SF (Table 6). Badua et al. (2019) reported that the use of solid lubricants increased singularization during seed distribution, in addition to minimizing abrasion with the components of the dosing mechanism, consequently reducing seed damage and prolonging the life of the measuring components. Furthermore, the velocity increase provided an increase in the frequency of SD and SF, particularly at 7 and 9 km h^{-1}. When graphite was used at doses of 2 and 4 g kg^{-1}, seed distribution at 3, 5, and 7 km h^{-1} did not differ statistically, demonstrating that the use of graphite can indeed minimize the negative effect of increased velocity on seed distribution. This observation can be demonstrated by the 7 km h^{-1} velocity having changed from "unsatisfactory" (SD) to "regular" (SF) performance for performances classified as "good" with any graphite treatment (Tables 2 and 6). For the 9 km h^{-1}-velocity, performances that were "unsatisfactory" for SD and SF, became "good" and "regular", respectively. In addition, the increase in velocity directly affected the levels of undesirable spacing due to insufficient (0 and 1 g kg^{-1}) or excess (8 g kg^{-1}) graphite used during seed treatment.

The reduction in the levels of undesirable spacings resulted in lower CV values, indicating greater homogeneity of seed distribution when the mechanism operated at 5 km h^{-1} and graphite was used at 4 g kg^{-1}. However, this graphite dose, CV did not differ between 7 and 3 km h^{-1}, suggesting the possibility of reaching higher values of operational efficiency without degrading the homogeneity of seed distribution (Ivančan et al., 2004).

The negative effect of a velocity increase was more evident when graphite was not used, with the effect being minimized by the use of the solid lubricant. This demonstrated the need to use graphite when operating at higher speeds. When operated with the use of graphite at a dose of 1 g kg^{-1}, the lowest CV levels were observed in the range of 5 to 7 km h^{-1}. However, doses of 2 and 4 g kg^{-1} resulted in similar seed distribution at 3, 5, and 7 km h^{-1}, making it possible to achieve higher levels of operational performance without causing a significant increase in the distribution of CV. When operated at a dose of 8 g kg^{-1}, this maintenance of homogeneity was observed up to 5 km h^{-1}, demonstrating the greater stability of spacing in the face of the variation of the operational speed when graphite is used at 4 g kg^{-1}, thus reducing CV during operation.

Owing to the effect of the interaction on IP, greater accuracy of the dosing mechanism was observed in individualizing and depositing the seeds when operated at 7 km h^{-1} and using a graphite dose of 1 g kg^{-1} (Table 6). At 3 km h^{-1}, IP differed only relative to the 0 g kg^{-1} graphite treatment; however, at other operation speeds, graphite doses differed from each other in their effects. Thus, when operating at 5 km h^{-1}, IP was slightly lower with graphite at 4 g kg^{-1}, although it did not differ from 1 or 8 g kg^{-1}; however, at 7 and 9 km h^{-1}, 1 g kg^{-1} graphite, IP was significantly lower than at other speeds, showing higher levels of accuracy in relation to the other doses of graphite. This emphasizes the need to adjust the operational velocity and graphite dosage to promote satisfactory levels of precision and uniformity in seed deposition.

Overall results

According to the results summarized and discussed herein, we found that the use of graphite reduced undesirable spacing (SD and SF) and increased the acceptable values (SA) in addition to providing greater precision (CV) and accuracy (IP) during individualization and seed deposition, regardless of feeder mechanism. It is noteworthy that the greatest uniformity in distribution was obtained with the use of a solid lubricant at 4 g kg^{-1}, which resulted in the highest level of seed fluidity observed during the characterization of resting angle among all evaluated dosages.

Several studies indicate that internal friction between the seeds in the reservoir is influenced by their physical characteristics, the chemical treatment used and the roughness of the surfaces involved in the process (Mantovani et al., 1999; Hentschke, 2002; Sidhu et al., 2017; Badua et al., 2019) Therefore, there is need to evaluate the lowest angle of rest for each specific seed condition and its treatments prior to sowing.

With respect to operating velocity, the limit for the mechanical feeder was 7 km h^{-1}, which, according to experimental conditions, corresponds to the deposition of 17 seeds per second. On the other hand, the pneumatic feeder proved to be more efficient in terms of operational velocity, making it possible to reach 9 km h^{-1}, which corresponds to the deposition of 31 seeds per second, without generating significant losses in distribution homogeneity. However, according to the results obtained, the pneumatic feeder allows seed sowing at a speed of 11 km h^{-1} if there is need to complete the operation in short sowing windows.

Conclusion

The use of graphite as a solid lubricant increases the efficiency of seed distribution, regardless of the seed dosing mechanism, thereby reducing the occurrence of double spacing, flaws, and variations, as well as increasing the acceptable spacing and precision of seed deposition. However, high doses of graphite can cause negative effects and reduce the homogeneity of seed distribution. The increase in seed deposition velocity negatively influenced seed distribution, regardless of the seed dosing mechanism. Thus, the highest levels of acceptable spacing were obtained at the lowest velocities of operation.

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