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CROP PRODUCTION

Planting speed and coinoculation in soybeans

Giovane Matias Burg[1], Matheus Martins Ferreira[1], Rosana Taschetto Vey[1], Joanei Cechin[2], Fernando Sintra Fulaneti[1], Glauber Monçon Fipke[3], Rafaela Leopoldina Silva Nunes[1] and Thomas Newton Martin[1*]

[1]Departamento de Fitotecnia, Universidade Federal de Santa Maria, Av. Roraima, 1000, Cidade Universitária, Camobi, 97105-900, Santa Maria, Rio Grande do Sul, Brazil. [2]Universidade Estadual de Ponta Grossa, Ponta Grossa, Paraná, Brazil. [3]Universidade Federal do Pampa, Campus Itaqui, Itaqui, Rio Grande do Sul, Brasil. *Author for correspondence. E-mail: martin.ufsm@gmail.com

ABSTRACT. Uniform seed distribution and an optimal plant stand are crucial for maximizing soybean yield. Additionally, a robust root system is essential for effective water and nutrient absorption through biological nitrogen fixation. This study investigated the impact of planting speed and coinoculation (*Bradyrhizobium japonicum* + *Azospirillum brasilense*) on plant distribution, nodulation, and soybean grain yield. Six field experiments were conducted during the 2018/19 and 2019/20 crop years in Santa Maria (two planting seasons per year) and Restinga Sêca, Brazil. The experiments utilized a randomized block design with four replications and treatments arranged in a 2 x 5 factorial design, assessing coinoculation (with and without) and five planting speeds. Results indicated that increasing planting speed reduced soil moisture and increased soil temperature, adversely affecting soybean nodulation and yield due to uneven plant distribution in the planting furrow. Planting speeds close to 4 km h^{-1} achieved the best uniformity in plant distribution, nodulation, and soybean yield. Coinoculation enhanced the number and dry mass of nodules and improved soybean grain yield.

Keywords: *Glycine max*; plantability; crop yield; intraspecific competition.

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Introduction

Soybean [*Glycine max* (L.) Merrill] cultivation plays a pivotal role in the Brazilian and global economies due to its versatility in grain usage for industrial purposes, protein sources, and biofuel production. As the world's leading producer and exporter, Brazil's soybean output surpassed 133.7 million tons during the 2020/21 harvest season, cultivated across 37.1 million hectares, generating over 125 billion dollars from exports (Companhia Nacional de Abastecimento [CONAB], 2021). Despite this significant production, soybean demand is expected to increase by 55% over the next 30 years to meet global consumer needs (Ray et al., 2013), underscoring the urgency for efficient agricultural practices to boost yield.

Large-scale soybean production can encounter several operational challenges, particularly during planting, directly interfering with grain yield. The narrow window for optimal planting, dictated by environmental conditions, often necessitates an increase in the number of machines used or the speed of planting to make up for time deficits. The displacement speed of tractor-seeders is crucial as it affects seed distribution and plant population density (Bortoli et al., 2021). Increasing planting speed can disrupt the uniformity of seed placement in furrows. Mechanical seeders with horizontal honeycomb discs are recommended to operate below 4 km h to prevent issues such as double spacing (Bortoli et al., 2021), ensuring optimal seed distribution and minimal soil disturbance for maximum soybean yield (Masino et al., 2018).

The interaction of the fixed elements in the seeder with the soil is directly proportional to planting speed, influencing seed positioning within furrows. The planting process involves straw cutting, furrow opening, fertilizer and seed deposition, furrow closing, and light soil compaction. Adequate planting speeds allow for equidistant seed deposition; however, deviations greater or less than 50% from the pre-established spacing can result in double or flawed spacings, respectively (Bruns, 2011).

Uniform seed distribution facilitates homogeneous germination and emergence, enhancing competitiveness against weeds and reducing intraspecific competition (Fatichin et al., 2013; Bertelli et al., 2016). The arrangement of plants within seeding rows can affect the photosynthetic rate, nodulation, and biological nitrogen fixation of soybeans (Luca & Hungria, 2014). Additionally, increased planting speeds may expose soil microorganisms to extreme temperatures and reduce surface moisture, negatively impacting bacterial survival and nodulation. However, strategies like coinoculation (simultaneous inoculation with *Bradyrhizobium* spp. and *A. brasilense*) can mitigate the adverse effects of soil temperature and moisture on microorganisms (Deak et al., 2019). *A. brasilense* promotes root system changes by producing phytohormones such as auxin, cytokinin, and gibberellin (Puente et al., 2018), enhancing the development of lateral and adventitious roots (Dobbelaere & Okon, 2007) and root hairs, which are crucial for effective bacterial infection and nodulation in soybeans (Hungria & Mendes, 2015).

Greater nodulation enhances soil exploration by the plants, leading to improved nutrient absorption and increased drought tolerance (Cohen et al., 2015). Nonetheless, the specific impacts of planting speed on soybean coinoculation remain unclear and are crucial for optimizing the crop's productive potential. Therefore, this research aims to evaluate the effects of planting speed and coinoculation (*Bradyrhizobium japonicum* + *Azospirillum brasilense*) on plant distribution, nodulation, structural components, and soybean grain yield.

Material and methods

Six field experiments were carried out in the municipalities of Santa Maria and Restinga Sêca, located in Rio Grande do Sul State, Brazil. According to the Köppen climate classification, both sites feature a Cfa climate type, characterized as subtropical with a rainy temperate climate (Alvarez et al., 2013). Rainfall and temperature data recorded during the experiments at these sites are detailed in Figure 1.

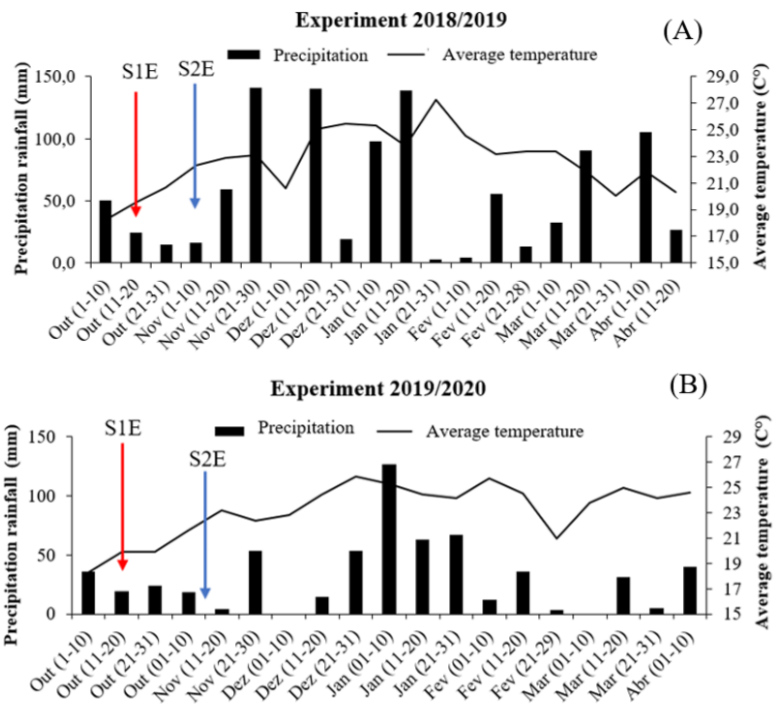

Figure 1. Average rainfall and temperature in the municipality of Santa Maria, Rio Grande do Sul State, Brazil during the 2018/19 crop year [1st season (planting 10/20/2018, flowering 01/04/2019, harvest 03/12/2019) and 2nd season (planting 12/13/2018, flowering 03/14/2019, harvest 04/20/2019)] and in the municipality of Restinga Sêca, Rio Grande do Sul State, Brazil (planting 11/16/2018, flowering 01/23/2019, harvesting 04/10/2019) (A). Average rainfall and temperature in the municipality of Santa Maria (RS) during the 2019/20 crop year [1st season (planting 10/16/2019, flowering 01/10/2020, harvesting 03/23/2020) and 2nd season (planting 12/07/2019, flowering 03/08/2020, harvest 04/07/2020)] and in the municipality of Restinga Sêca, Rio Grande do Sul State, Brazil (planting 11/12/2019, flowering 01/26/2020, harvesting 04/05/2020) (B).

Study conducted in Santa Maria, Rio Grande do Sul State, Brazil

The experiment was conducted at the Federal University of Santa Maria, located at geographic coordinates 29°42' S and 53°42' W, and at an altitude of 116 meters. The local soil is classified as a sandy dystrophic Red Argisol (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 2013), corresponding to Ultisol in the Soil Taxonomy Classification System (Soil Survey Staff [USDA], 2014). Soil chemical properties within the 0-10 cm depth layer included: pH = 5.5, organic matter (OM) = 2.2%, clay = 26%, P-Mehlich = 11.8 mg dm^{-3}, K = 0.164$cmol_c$ dm^{-3}, H + Al = 3.9 $cmol_c$ dm^{-3}, CEC_{pH7} = 12.2 $cmol_c$ dm^{-3}, and base saturation (BS) = 67.9%.

The experimental design was a randomized block with treatments arranged in a 2 x 5 factorial design, with four replications. Factor A pertains to the use or non-use of coinoculation, and factor D examines five planting speeds (2.2, 3.4, 4.8, 8.1, and 10.2 km h^{-1}). The seed distribution mechanism involved a mechanical system with horizontal honeycomb discs. The 2018/19 crop year planting occurred on October 20th, 2018 (first season), over oat straw, and on December 13th, 2018 (second season), in a native field area previously uncultivated with soybeans and with no history of coinoculation use. The 2019/20 crop year experiments were conducted on October 16th, 2019 (first season), and December 7th (second season). The soybean cultivar used was NS 5959 IPRO, with a planting density of 34 seeds per square meter.

Each experimental unit measured 7.75 m by 2.25 m, comprising five rows spaced 0.45 m apart, covering a total area of 17.4 m^2. Seed treatment before planting included Pyraclostrobin 25 g ai L^{-1}, Thiophanate-methyl 225 g ai L^{-1}, and Fipronil 250 g ai L^{-1} at a dosage of 2 mL per kg of seed. Base fertilization was applied at 375 kg ha^{-1} using an NPK blend (00-23-30). Coinoculation involved a liquid inoculant containing *Bradyrhizobium japonicum* at 7 x 10^9 CFU mL^{-1} at 6 mL per kg of seed and *Azospirillum brasilense* at 2 x 10^8 CFU mL^{-1} at 2.0 mL per kg of seed.

Soil samples were collected before planting and at harvest to quantify the resident bacterial population (*B. japonicum* and *A. brasilense*), with colony-forming units for both under 10^4. Soil moisture was determined using the oven-drying method, where soil samples were dried at 65°C for 72 hours, weighed after 96 hours, and the difference in mass between dry and moist soil established the upper water retention limit, i.e., 100% retention capacity (Wösten et al., 1999). Soil cover percentage was estimated using *ImageJ* software version 1.2.4 (RRID: SCR_003070), with an average calculated from four images per plot.

At the R_2 phenological stage (Fehr & Caviness, 1977), root nodules were counted from four plants randomly sampled per experimental unit. Each plant had a pre-established soil volume of 0.008 m^3 with dimensions of 0.2 m (L1) x 0.2 m (L2) x 0.2 m (H) collected using a cutting shovel. Nodules from the main and secondary roots were counted for each plant (NN, $plant^{-1}$), washed, and dried in a forced-air oven at 65°C for 48 hours. Then, nodule dry mass was determined for each plant (NDM, mg $plant^{-1}$).

Study conducted in Restinga Sêca, Rio Grande do Sul State, Brazil

The experiment was conducted in Restinga Sêca, Rio Grande do Sul State, Brazil, at geographical coordinates 29°44'27'' S and 53°29'56'' W, with an altitude of 85 meters. The local soil was classified as sandy dystrophic Red Argisol (EMBRAPA, 2013), corresponding to Ultisol in the Soil Taxonomy Classification System (USDA, 2014). The experimental design was a randomized block in split plots, with four replications. Treatments varied between coinoculation use and five planting speeds (1.2, 3.2, 4.3, 6.4, and 7.2 km h^{-1}). Seed distribution was managed through a mechanical system with horizontal honeycomb disks. Planting was executed using a seeder-fertilizer with six rows; coinoculation was applied to three rows, while the other three were left untreated.

Planting for the experiments took place on November 16th, 2018, and November 12th, 2019, both times on oat straw. The soybean cultivars used were Brasmax Garra for the 2018/2019 crop year and NEO 610IPRO for the 2019/2020 crop year. Each experimental plot measured 7.75 m in length and 1.35 m in width, incorporating three rows spaced 0.45 m apart, totalling an area of 10.4 m^2. Base fertilization was provided at 350 kg ha^{-1} using an NPK blend (02-30-15). Coinoculation involved a liquid inoculant comprising *Bradyrhizobium japonicum* at a concentration of 7 x 10^9 CFU mL^{-1} at a dose of 6 mL kg^{-1} of seeds and *Azospirillum brasilense* at 2 x 10^8 CFU mL^{-1} at a dose of 2 mL kg^{-1} of seeds.

Variables Evaluated in all Experiments

In all experiments, several plant distribution parameters were assessed: distance between plants (DP), acceptable spacing (AC), flawed spacing (FA), double spacing (DU), and plant population (PO). The distance between plants was measured with a graduated tape across all five rows in each plot. The classifications of spacing were as follows: distances less than 0.5 times the expected average spacing of 4.15 cm (Xref.) were classified as "double" (DU); distances between 0.5 to 1.5 times the expected average spacing of 8.3 cm (Xref.) were considered "acceptable" (AC); and distances greater than 1.5 times the expected average spacing of 12.45 cm (Xref.) were deemed "flawed" (FA), following the model proposed by Kachman and Smith (1995).

At harvest, evaluations included the mass of one thousand grains (MMG) and grain yield (PG). Grain yield was determined by weighing the grains collected from the effective area of each plot. Both MMG and PG values were adjusted for 13% moisture content as per standards set in Brazil (Brasil, 2009).

Statistical analysis

Data were subjected to analysis of variance (ANOVA) at a significance of 5% for determining error probability. When significant differences were found, the means were differentiated using the Scott-Knott test or regression analysis based on the significance determined by ANOVA. These analyses were conducted using the Sisvar software (Ferreira, 2011).

Results

First planting season, Santa Maria, Rio Grande do Sul State, Brazil 2018/2019 and 2019/2020

In the 2018/19 crop year, a significant interaction was observed between planting speed and coinoculation for acceptable and double spacing. For flawed spacing, the distance between plants, and plant population, a notable effect occurred due to coinoculation. During the 2019/2020 crop year, significant effects were noted from planting speed on acceptable, double, and flawed spacings, and from coinoculation on the distance between plants and plant population (Online Resource 1).

In the 2018/19 crop year, the incidence of acceptable spacings decreased as planting speed increased (Figure 2a). At lower speeds, coinoculation resulted in a higher percentage of acceptable spacings compared to plots without coinoculation. The fastest speed tested (10.2 km h^{-1}) resulted in a 34.9% reduction in acceptable spacing compared to the slowest speed (2.2 km h^{-1}). The lowest percentages of double spacings were observed between speeds of 2.2 and 4.8 km h^{-1}, irrespective of coinoculation status. Conversely, the highest percentages of double spacings were recorded at speeds between 8.1 and 10.2 km h^{-1}, with coinoculation achieving the highest averages (Figure 2b).

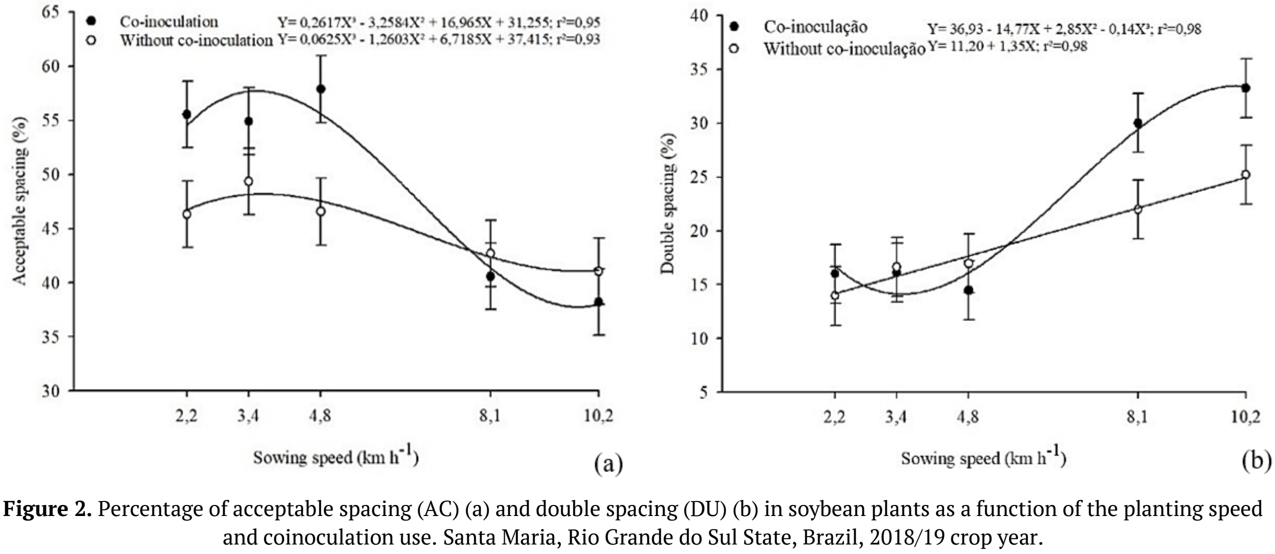

Figure 2. Percentage of acceptable spacing (AC) (a) and double spacing (DU) (b) in soybean plants as a function of the planting speed and coinoculation use. Santa Maria, Rio Grande do Sul State, Brazil, 2018/19 crop year.

In the 2019/20 experiment, a decrease in acceptable spacings was noted as planting speeds increased. The highest planting speed, 10.2 km h^{-1}, led to a 36.6% reduction in acceptable spacings when compared to the lowest speed of 2.2 km h^{-1} (Figure 3a). The lowest incidence of double spacing was observed at a speed of 2.2 km h^{-1} (27%), while the highest was at 6.7 km h^{-1} (32.7%) (Figure 3b). Similarly, the percentage of flawed spacings increased with greater speeds. At the speeds of 2.2 and 10.2 km h^{-1}, the occurrences of flawed spacings were 10 and 30%, respectively (Figure 3c).

In the 2018/19 crop year, coinoculation led to lower values for flawed spacing (FA) and distance between plants (DP), while the plant population (PO) was higher. During the 2019/20 crop year, there was a reduction in DP and an increase in PO with coinoculation (Table 1). Plant population is a critical component of soybean productivity, and its increase typically correlates with higher productivity levels. Additionally, coverage (CS) and soil moisture decreased because of increased planting speeds, while soil temperature rose (Online Resource 2).

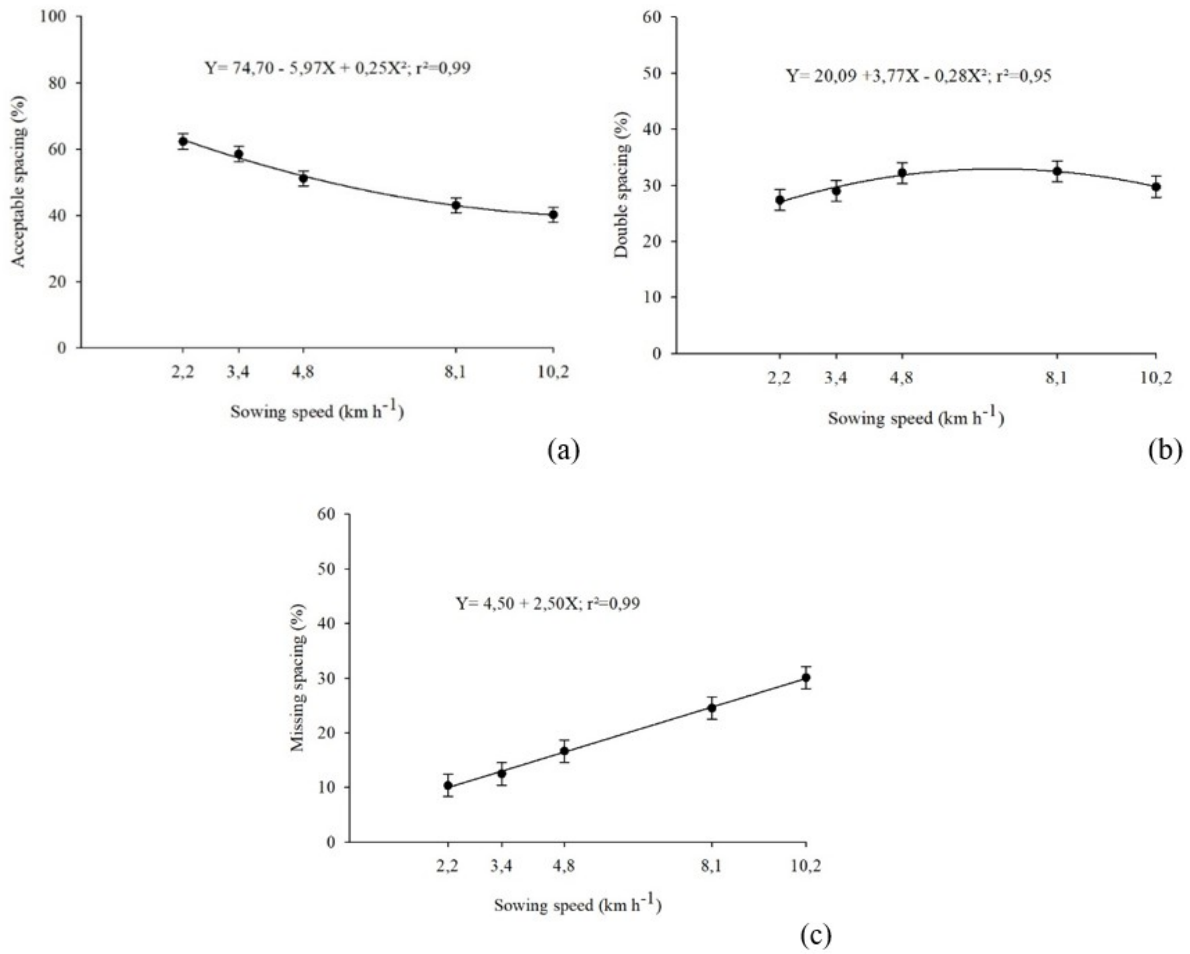

Figure 3. Percentage of acceptable spacing (AC) (a), double spacing (DU) (b), and flawed spacing (c) in soybean plants as a function of the planting speed and coinoculation use. Santa Maria, Rio Grande do Sul State, Brazil 2019/20 crop year.

Table 1. Averages of the number of flawed spacing (FA, %), the distance between plants (DP, cm), and observed plant population (PO, m²). Santa Maria, Rio Grande do Sul State, Brazil.

Crop year 2018/19			
Treatment	FA (%)	DP (cm)	PO (m²)
Coinoculation	28.59 b*	10.51 b	21.60 a
Non-inoculated	35.85 a	11.89 a	19.46 b
Crop year 2019/20			
Coinoculation	-	8.38 b	17.59 a
Non-inoculated	-	8.56 a	16.99 b

*Different letters within columns differ statistically from each other by the F-test at 5% probability.

At a planting speed of 2.2 km h^{-1}, the ground cover was 97%, while at the speed of 10.2 km h^{-1}, it reduced to 72%. Consequently, for each increase of 1 km h^{-1} in planting speed, there was a reduction of 3.12% in ground cover (Figure 4a). Soil temperature also showed variation with changes in planting speed, increasing from 30.6°C at 2.2 km h^{-1} to 33.3°C at 10.2 km h^{-1} (Figure 4b).

Soil moisture was 6.5% at a planting speed of 4.0 km h^{-1}, which decreased to 3.5% at 10.2 km h^{-1}. This approximate 3% reduction in moisture is critical for bacterial survival under elevated temperatures. Optimal infection temperatures are known to significantly enhance soybean nodulation (Deak et al., 2019).

The 2018/19 crop year analysis of variance showed a significant interaction between planting speed and coinoculation concerning the number of nodules and their dry mass. Grain yield was influenced by planting speed, while one-thousand-grain mass remained unaffected by the treatments. In the 2019/20 experiment, an interaction between velocity and coinoculation (VxI) affected both grain yield and one-thousand-grain mass (Online Resource 3).

Coinoculation resulted in a higher number and dry mass of nodules during the 2018/19 crop year (Figure 5a). However, the dry mass of nodules decreased with increased planting speeds.

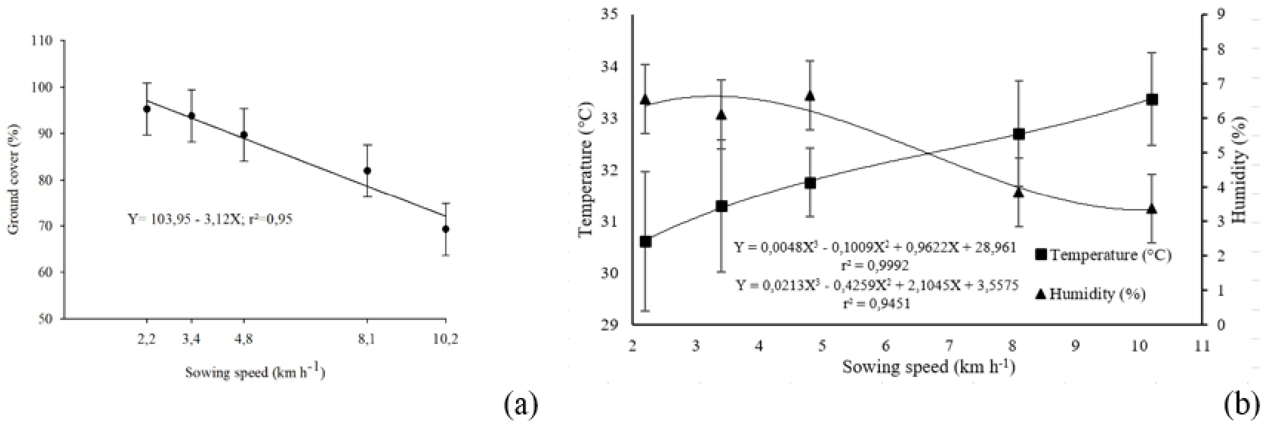

Figure 4. Percent variation of soil cover (CS) (a), temperature (°C), and soil moisture (%) at four days after planting (DAS) (b) as a function of the planting speed (2.2, 3.4, 4.8, 8.1, and 10.2 km h^{-1}). Santa Maria, Rio Grande do Sul State, Brazil 2018/19 crop year.

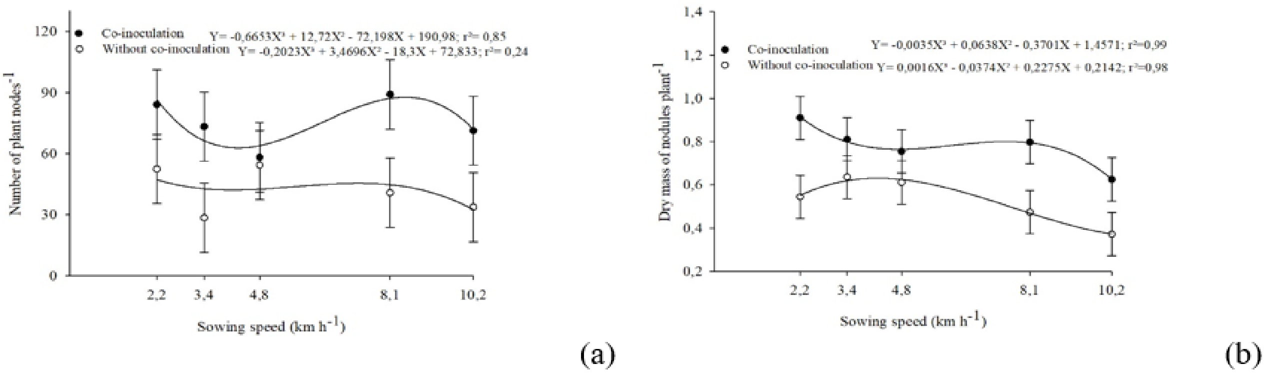

Figure 5. Number (a) and dry mass (b) of nodules per plant as a function of the coinoculation use and planting speed (2.2, 3.4, 4.8, 8.1, and 10.2 km h^{-1}). Santa Maria, Rio Grande do Sul State, Brazil 2018/19 crop year.

The highest soybean productivity was recorded at a planting speed of 4.0 km h^{-1}, yielding 4,029.4 kg ha^{-1}, while the lowest productivity occurred at a speed of 8.7 km h^{-1}, with 3,766.9 kg ha^{-1} (Figure 6). An increase in planting speed from 4.0 to 8.7 km h^{-1} resulted in a productivity reduction of 262.2 kg ha^{-1}.

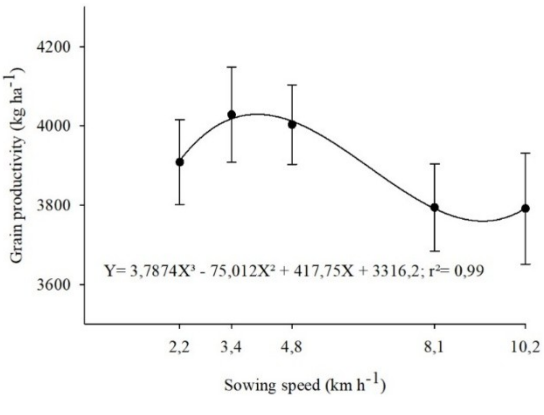

Figure 6. Grain yield (GY; kg ha^{-1}) as a function of the planting speed (2.2, 3.4, 4.8, 8.1, and 10.2 km h^{-1}). Santa Maria, Rio Grande do Sul State, Brazil 2018/19 crop year.

In the 2019/20 crop year experiment, one-thousand-grain mass (MMG) was highest with coinoculation at a planting speed of 4.0 km h^{-1} (167.38 g) and lowest at a speed of 10.2 km h^{-1} (153.73 g) (Figure 7a). Without coinoculation, the lowest grain mass was observed at a speed of 2.2 km h^{-1} (155.63 g), with the highest recorded at a speed of 10.2 km h^{-1} (159.32 g). MMG is influenced by genetic factors, as well as plant nutritional status, health, and population density. However, coinoculation has shown to be effective in enhancing this yield component. Indeed, coinoculation combined with a lower planting speed, which achieved high MMG, also led to higher grain yields (Figure 7b).

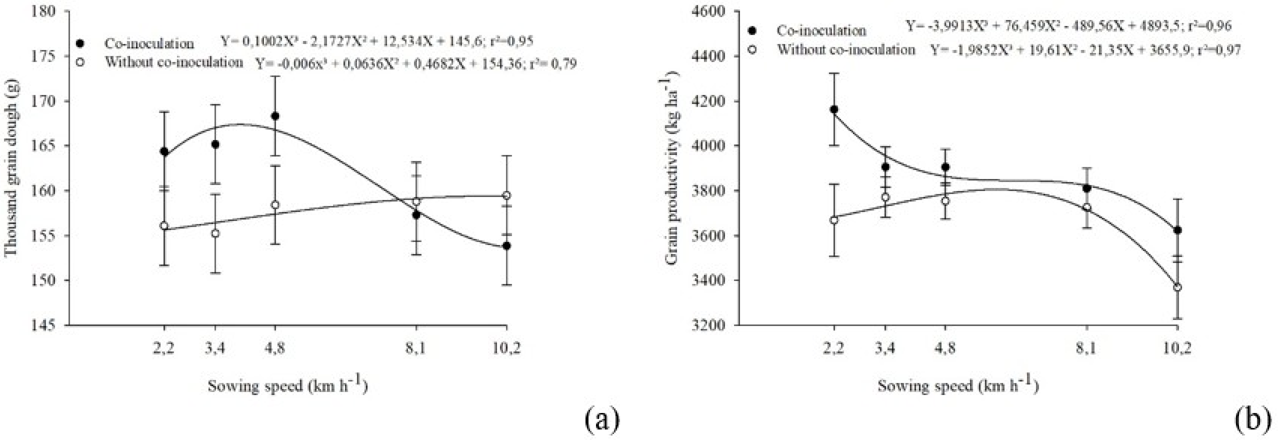

Figure 7. One-thousand-grain mass (a) and grain yield (b) of soybeans as a function of the coinoculation use and planting speed (2.2, 3.4, 4.8, 8.1, and 10.2 km h^{-1}). Santa Maria, Rio Grande do Sul State, Brazil 2019/20 crop year.

Increasing planting speeds tend to disrupt plant distribution uniformity within rows, as evidenced by an increase in flawed and double spacings and a decrease in acceptable spacings. This non-uniformity negatively impacts several critical parameters, including nodule number, nodule mass, one-thousand-grain mass, and overall grain yield. However, maintaining planting speeds between 2.2 and 4.8 km h^{-1} and employing coinoculation could significantly enhance these parameters in both crop years.

Second planting season, Santa Maria, Rio Grande do Sul State, Brazil 2018/2019 and 2019/2020

Planting speed significantly influenced the number of nodules observed in both crop years (Online Resource 4). In the 2018/19 crop year, the highest number of nodules was recorded at a planting speed of 8.1 km h^{-1}, a result attributed to altered plant spacing within rows as planting speed increased. This speed resulted in a greater number of flawed spacings.

In contrast, during the 2019/20 crop year, the greatest number of nodules per plant (Figure 8b) was observed at the lowest speed of 2.2 km h^{-1}, totalling 51.52 nodules, while the lowest count was at 10.2 km h^{-1}, with 39.3 nodules. This variation across the two crop years might be linked to irregular rainfall patterns. With coinoculation in the 2019/20 crop year, nodule counts ranged from 55 to 47.2, with and without coinoculation, respectively. Coinoculation led to an increase of 7.8 nodules per plant, enhancing biological nitrogen fixation (FBN) and potentially boosting productivity. Hungria et al. (2013) noted that coinoculation can increase the number of nodules and raise soybean grain yields by up to 8.4%.

Nodule dry mass demonstrated increases with coinoculation up to a planting speed of 5 km h^{-1}, decreasing at higher speeds (Figure 9a). For plots without coinoculation, the dry mass of nodules was more stable, beginning to decline at a speed of 7.5 km h^{-1}. The control treatment showed that the dry mass of nodules was less affected by increases in planting speed.

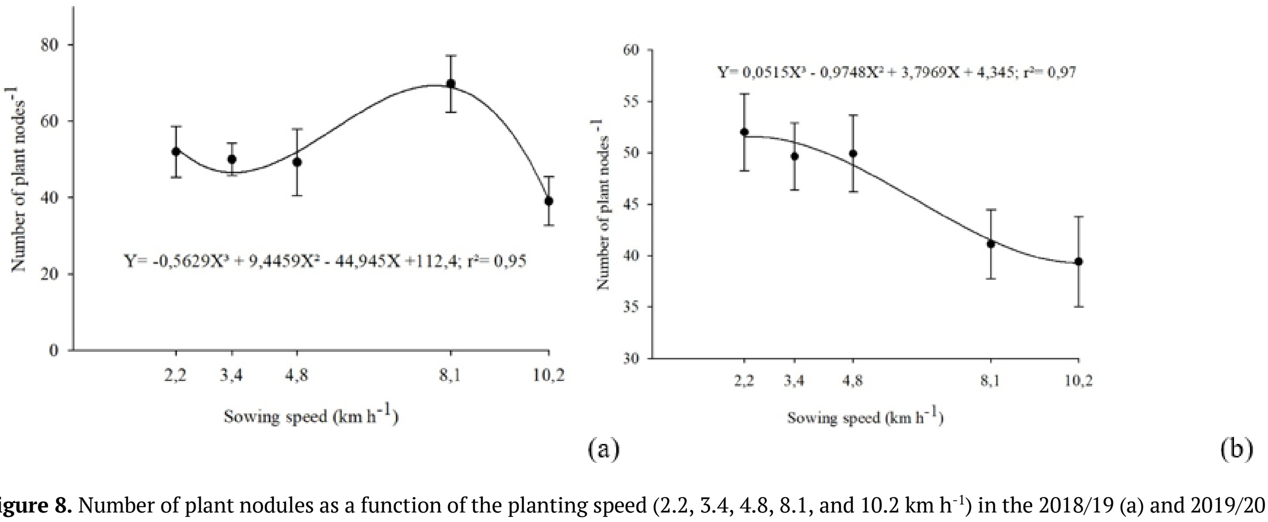

Figure 8. Number of plant nodules as a function of the planting speed (2.2, 3.4, 4.8, 8.1, and 10.2 km h^{-1}) in the 2018/19 (a) and 2019/20 (b) crop years.

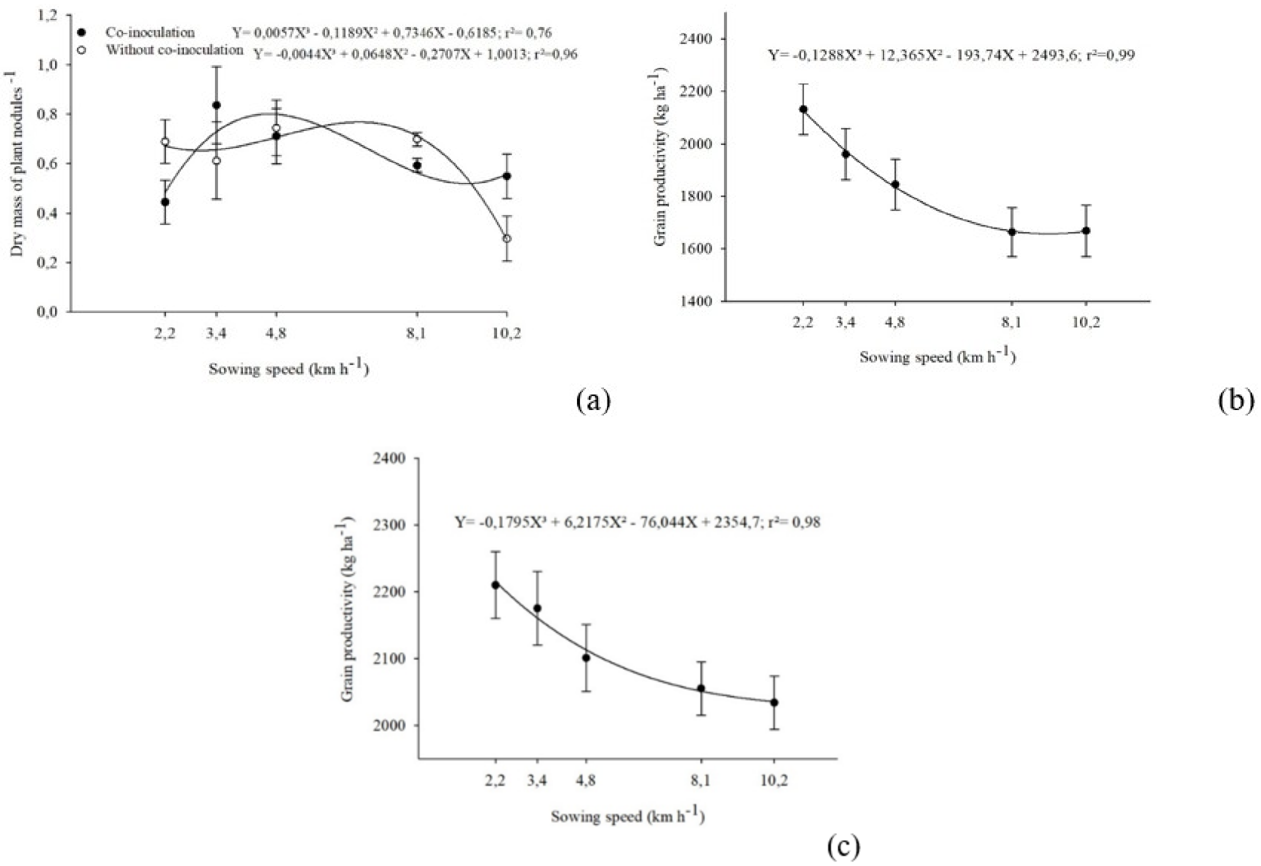

Figure 9. Nodule dry mass per plant (a) and grain yield in the 2018/19 crop year (b) and 2019/20 (c) as a function of the coinoculation use and seeding speed (2.2, 3.4, 4.8, 8.1, and 10.2 km h^{-1}). Santa Maria, Rio Grande do Sul State, Brazil.

Grain yield declined with increasing planting speeds during both the 2018/19 and 2019/20 crop years, with the lowest yields recorded at speeds of 9.1 and 10.2 km h^{-1}, respectively (Figure 9b and c). In the 2018/19 crop year, there was an average reduction of 468.38 kg ha^{-1} in grain yield when comparing the highest to the lowest planting speeds. This decrease in yield at higher speeds can be attributed to the reduced nodulation observed in the study.

Restinga Sêca, Rio Grande do Sul State, Brazil (2018/19 and 2019/20 Crop years)

Planting speed significantly impacted the occurrence of double and flawed spacings (Online Resource 5). Coinoculation notably influenced the number of acceptable spacings, the distance between plants, and overall plant population. In the 2019/20 crop year experiment, there was a notable interaction between coinoculation and planting speed affecting double spacing, flawed spacing, the distance between plants, and plant population. Coinoculation also altered the percentage of acceptable spacings. Specifically, with increasing planting speeds, the number of double spacings rose by 8.7%, while flawed spacings decreased by 5.7% (Figure 10a and b).

In the 2019/20 crop year experiment, coinoculation at the lowest planting speed of 1.06 km h^{-1} resulted in 14.2% flawed spacings, which increased to 23.36% at the highest speed of 7.2 km h^{-1} (Figure 11a). Soybeans can compensate for gaps by expanding the coverage area of the remaining plants, but this compensation is dependent on environmental conditions that support plant development.

For double spacings, there was a noticeable effect due to coinoculation. The optimal percentage of spacing occurred at a speed of 4.5 km h^{-1}, recording 35.93% (Figure 11b). Regarding the distance between plants, the speed of 1.06 km h^{-1} recorded the shortest average distance at 6.94 cm, in contrast to the speed of 7.2 km h^{-1}, which increased the distance to 8.4 cm (Figure 11c). Consequently, as the distance between plants increased, there was a corresponding rise in flawed and double spacings, leading to a reduced plant population at higher speeds (Figure 11d).

In the 2018/19 crop year, coinoculation resulted in a higher number of acceptable spacings (AC), a lower distance between plants (DP), and an increased plant population (PO). Conversely, in the 2019/20 crop year, the number of acceptable spacings was lower when coinoculation was used (Table 2). Nonetheless, coinoculation favourably influenced the plant population, leading to an increase of 0.84 plants m^{-2} (Table 2). These changes in plant spacing and population can significantly impact grain yield.

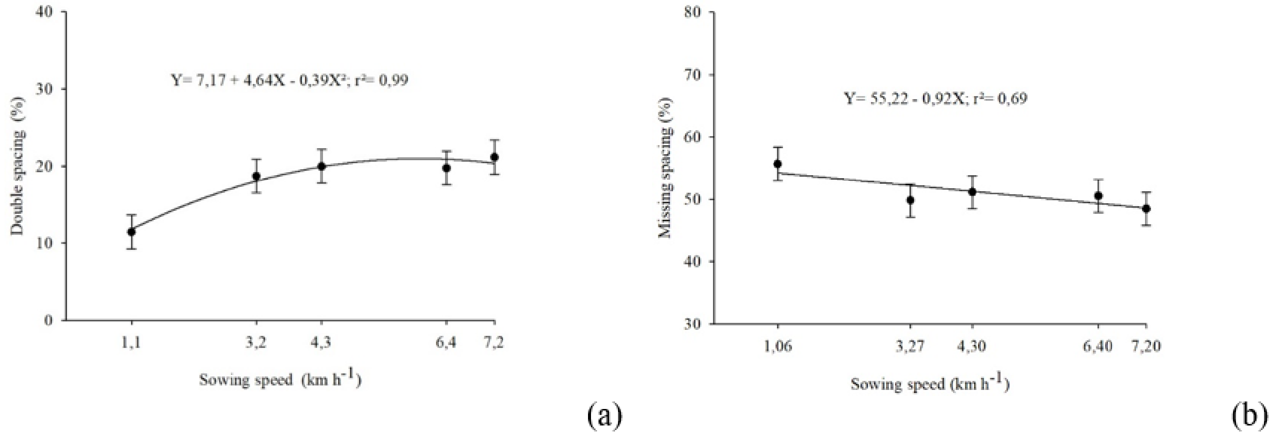

Figure 10. Percentage variation of double spacing (DU) (a) and flawed spacing (FA) (b) as a function of the seeding speed (1.0, 3.2, 4.3, 6.4, and 7.2 km h^{-1}). Restinga Sêca, Rio Grande do Sul State, Brazil 2018/19 crop year.

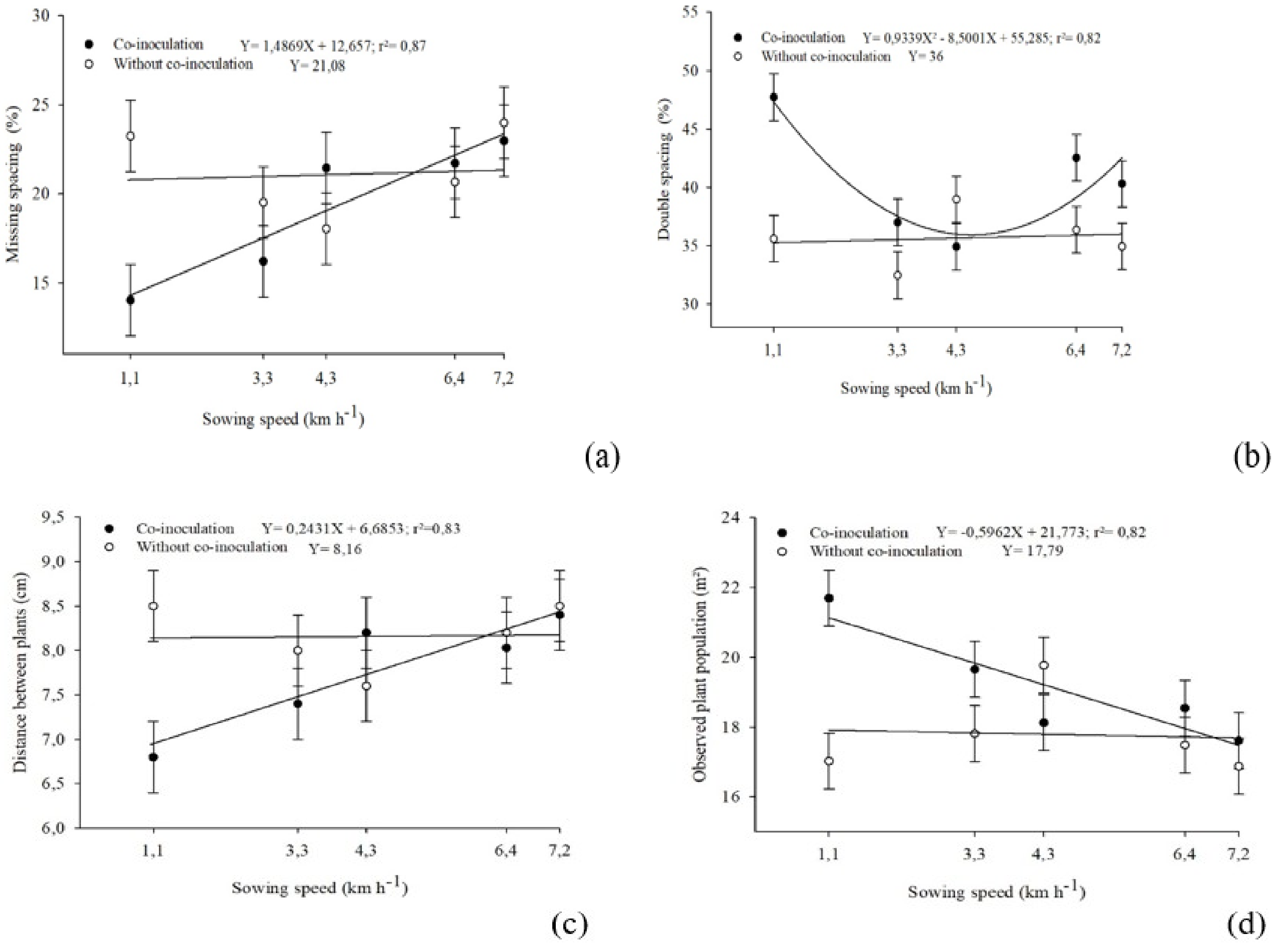

Figure 11. Flawed spacing (a), double spacing (b), the distance between plants (c), and plant population (d) as a function of the coinoculation use and seeding speed (1.0, 3.2, 4.3, 6.4, and 7.2 km h^{-1}). Restinga Sêca, Rio Grande do Sul State, Brazil 2019/20 crop year.

Table 2. Averages of acceptable spacing (AC), the distance between plants (DP), and observed plant population (PO) as a function of the coinoculation use. Restinga Sêca, Rio Grande do Sul State, Brazil.

Crop year 2018/19			
Treatment	AC (%)	DP (cm)	PO (m^2)
Coinoculation	31.85 a*	17.21 b	12.96 a
Non-inoculated	29.49 b	18.64 a	12.12 b
Crop year 2019/20			
Coinoculation	43.24 b	-	-
Non-inoculated	40.23 a	-	-

*Different letters within columns differ statistically from each other by the F-test at 5% probability.

Planting speed has a significant impact on soil cover percentage, with the percentage of soil cover decreasing as planting speed increases (Figure 12a). Specifically, at a planting speed of 1.06 km h^{-1}, the straw coverage on the ground was 91%, whereas at a speed of 7.2 km h^{-1}, it dropped to 68.3%. This equates to a total reduction of 22.7% in soil cover or a reduction of 3.69% for each 1 km h^{-1} increase in planting speed.

It is important to highlight that maintaining straw cover is a key aspect of the no-tillage system. Straw cover helps create a conducive environment for germination and emergence of plants by maintaining moisture content in the soil.

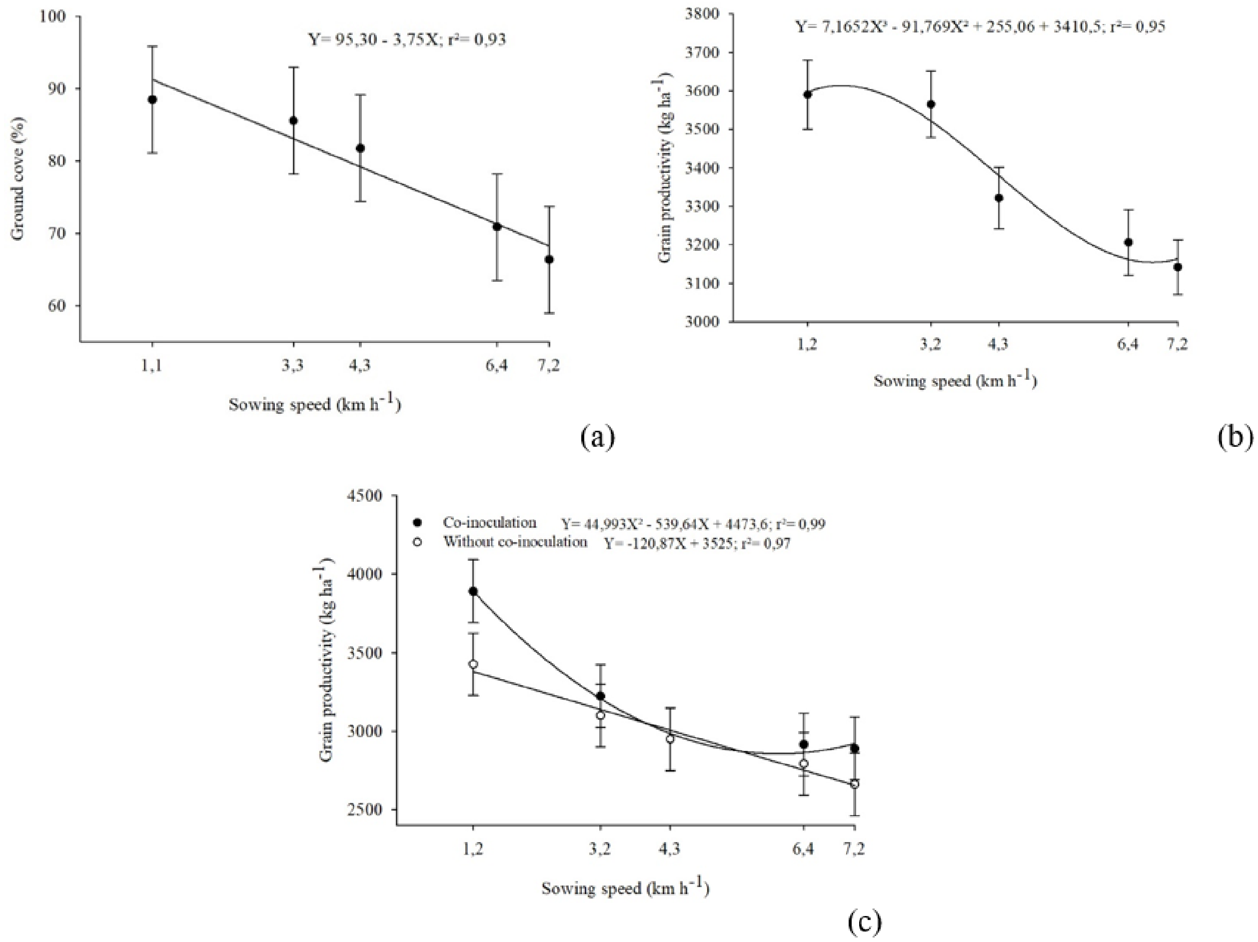

Figure 12. Soil cover percentage as a function of the planting speed (1.0, 3.2, 4.3, 6.4, and 7.2 km h^{-1}) (a), grain yield as a function of the planting speed (1.0, 3.2, 4.3, 6.4, and 7.2 km h^{-1}) during the 2018/19 crop year (b), grain yield as a function of the planting speed (1.0, 3.2, 4.3, 6.4, and 7.2 km h^{-1}) during the 2019/20 crop year (c), and grain yield as a function of the coinoculation use and planting speed (1.0, 3.2, 4.3, 6.4, and 7.2 km h^{-1}). Restinga Sêca, Rio Grande do Sul State, Brazil.

Soybean grain yield decreased with increasing planting speeds in both the 2018/19 and 2019/20 crop years (Figure 12b and c). However, in the 2019/20 crop year, coinoculation at a lower planting speed of 1.06 km h^{-1} resulted in higher average yields. In the 2018/19 crop year, yields were consistently higher with coinoculation compared to without, across all planting speeds (Table 3).

The non-equidistant distribution of plants within rows, a direct consequence of faster planting speeds, has been shown to adversely affect soybean yield (Brandelero et al., 2015). This uneven distribution, exacerbated by increased planting speeds, can significantly reduce productivity (Reynaldo et al., 2016). Consequently, employing coinoculation in conjunction with slower planting speeds can enhance the productivity of soybean grains.

Table 3. Soybean yield as a function of the coinoculation use. Restinga Sêca, Rio Grande do Sul State, Brazil.

Crop year 2018/19	
Treatment	Yield (kg ha^{-1})
Coinoculation	3437.64 a
Non-inoculated	3292.33 b

*Different letters within columns differ statistically from each other by the Scott-Knott test at 5% probability.

Discussion

First planting season, Santa Maria, Rio Grande do Sul State, Brazil, 2018/2019 and 2019/2020

As planting speed increases, the uniformity of plant spacing within rows decreases, resulting in a higher number of flawed and double spacings, and a reduction in acceptable spacings (Reynaldo et al., 2016). However, the use of coinoculation at lower speeds has been found to significantly improve the percentage of acceptable spacings, whereas, at higher speeds, it leads to an increase in double spacings. Lower planting speeds combined with coinoculation can achieve better uniformity of plant distribution in rows. Coinoculation not only enhances germination, emergence, and plant growth but also promotes more extensive root branching and nodulation (Juge et al., 2012), which are particularly beneficial under adverse weather conditions for rapid and uniform soybean establishment (Jisha et al., 2013).

At high planting speeds, the mechanical disturbance caused by the seeder's furrower rod is increased, potentially disrupting the protective layer of straw, and leaving seeds less covered with soil. This greater exposure can lead to increased erosion risk, seed displacement, reduced soil-seed contact, and ultimately lower germination and seedling establishment rates (Odhiambo & Irmak, 2012).

The optimal temperature range for nodulation and biological nitrogen fixation in soybeans is 20 to 30°C (Siczek & Lipiec, 2011). Temperatures outside this range can adversely affect the survival and efficacy of nitrogen-fixing bacteria (Santos et al., 2012), leading to fewer nodules and reduced activity of the nitrogenase enzyme (Becana et al., 2018). Elevated temperatures may also induce genetic changes in the bacteria, rendering them less effective than naturalized soil bacteria (Fukami et al., 2018).

Bortoli et al. (2021) associated increased planting speeds with a reduced dry mass of nodules due to the greater non-uniformity in plant distribution, especially an increase in double spacings. This proximity can hinder photosynthetic rates and decrease the carbon supply to the nodules (Luca & Hungria, 2014).

Therefore, while planting speed is a critical factor influencing the efficiency of the planting process and impacting the longitudinal distribution of seeds in the furrow (Bertelli et al., 2016), there is no one-size-fits-all speed. Instead, an optimal range should be determined based on specific cultivars, environmental conditions, and the planting system used (Jasper et al., 2011).

Second planting season, Santa Maria, Rio Grande do Sul State, Brazil, 2018/2019 and 2019/2020

This observed variation in plant growth and nodulation can be attributed to soil disturbance during the furrow opening and the differential straw coverage, which alters the edaphic conditions in terms of moisture and temperature (Zhao et al., 2021). Both soil moisture and temperature are crucial for successful soybean nodulation (Deak et al., 2019). Furthermore, the second planting season, occurring on 07/12/2018, faced suboptimal air temperature conditions and, notably, photoperiods that are not ideal (Ferrari et al., 2015), which can inhibit a plant's ability to fully express its developmental potential, negatively affecting nodulation.

Luca and Hungria (2014) explain that greater spacing between plants can lead to enhanced branching and leaf area, as well as increased production of photoassimilates. This facilitates a greater translocation of carbohydrates to nitrogen-fixing bacteria, supporting their growth, development, and multiplication. However, a water deficit can significantly reduce the number of nodules, primarily due to fewer roots per plant and less soil exploration (Márquez-García et al., 2015).

Moreover, native microorganisms are typically better adapted to local environmental conditions compared to bacteria that are selected for inoculation and applied via seeds. This means that inoculated bacteria might be less effective under certain conditions (Wakelin et al., 2010).

Restinga Sêca, Rio Grande do Sul State, Brazil (2018/19 and 2019/20 crop years)

An increase in seeding speed leads to more flawed and double spacings (Bertelli et al., 2016), particularly in seeders equipped with a horizontal disk-type dosing mechanism. To minimize the unevenness of plant distribution within rows, it is recommended that these seeders operate at a maximum speed close to 5 km h^{-1} (Garcia et al., 2011).

Conclusion

Higher planting speeds reduced plant distribution uniformity within rows, which generally decreased nodulation and soybean yield. Planting speeds near 4 km h^{-1} are deemed more suitable as they ensure better distribution uniformity, improved nodulation, and enhanced soybean yield. Furthermore, coinoculation proved to increase the number and dry mass of nodules per plant, enhancing grain yields from 140 and 220 kg ha^{-1} when compared to non-coinoculation.

Data availability

Not applicable.

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