Seeding density and lodging control using a calcium and potassium-based organomineral fertilizer in oat crops

Densidade de semente e controle de alojamento com adubo organomineral à base de cálcio e potássio em culturas de aveia

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ABSTRACT
Technologies ensuring high crop yield and plant competitiveness without lodging can contribute to an efficient and sustainable management of oat crops. The objectives of this study were to evaluate the use of high seeding density in current oat cultivars grown in the northwestern Rio Grande do Sul (RS), Brazil; assess the effects of plant growth regulators on grain yield indicators, industrial grain quality, and stem structure; and evaluate a calcium and potassium-based organomineral product as a sustainable technology for controlling lodging. Two experiments were conducted in Augusto Pestana, RS, in a randomized block design. Experiment I (2021) was set up in a 4×3 factorial arrangement consisted of 4 oat seeding densities (100, 300, 600, and 900 seeds m⁻²) and 3 treatments with plant growth regulator (PGR) application (control; application of trinexapac-ethyl and organomineral product at the stage between the 1st and 2nd visible stem nodes). Experiment II (2022) was set up in a 4×4 factorial arrangement consisted of 4 seeding densities (100, 300, 600, and 900 seeds m⁻²) and 4 PGR application treatments (control; application of trinexapac-ethyl and organomineral product at the stage between the 1st and 2nd visible stem nodes; and sequential application of organomineral product at V4 and at the stage between the 1st and 2nd visible stem nodes). The results of both experiments showed the need for a higher seeding density (between 400 and 520 seeds m⁻²) than that recommended. High air temperatures and limiting soil water conditions increased the phytotoxic potential of trinexapac-ethyl in oat crops. Evaluations of the Ca and K-based organomineral product, as a sustainable technology for controlling plant lodging, requires further analysis in years with more favorable environmental conditions for oat crops.
Keywords: avena sativa, yield, uniformity, stem resistance, sustainable agriculture, 2030 agenda.

1 INTRODUCTION

Oats are a widely grown winter crop in the South region of Brazil for grain production and soil cover (Mantai et al., 2020; Kraisig et al., 2020; Kraisig, et al., 2023). They are essential for animal feed, provided as fresh mass, dry mass, hay, or silage (Silva et al., 2020; Basso et al., 2022; Schmidt, et al. 2023). Furthermore, oats are increasingly included in human diet due to their properties related to reductions in LDL cholesterol and, consequently, risk of cardiovascular diseases (Malanchen et al., 2019; Reginatto et al., 2021; Treter et al., 2023). The increased consumption of cereals reflects the increasing demand for healthier and nutritious foods (Scremin et al., 2017; Babeski et al., 2023; Henrichsen et al., 2023).
The growing demand for cereals has significantly increased the importance of using management practices that ensure satisfactory crop yields (Scremin et al., 2020; Dornelles et al., 2023; Pereira et al., 2023). Determining factors of oat production potential include plant population and arrangement (Storck et al., 2014; Arenhardt et al., 2015; Loro et al., 2022). Adjusting seeding density is essential for achieving satisfactory crop yields and soil coverage. Rapid soil coverage favors the control of invasive species (Romitti, et al., 2016; Rosa, et al., 2022; Sangiovo et al., 2022).

Technical recommendations from the Brazilian Oat Research Commission show seeding densities ranging from 200 to 300 seeds m$^{-2}$, which has been followed, as oat crops became commercially important in the 1990s (Indicação Técnica Aveia, 2021). However, continuous genetic improvement of oat plants has modified plant architecture and other characteristics, decreasing plant height, cycle, and straw to grain ratio, generating varieties with plant height less than one-meter, shorter cycle, and high caryopsis weight compared to husk weight (Hawerroth et al., 2015; Silva et al., 2015; Pereira et al., 2023). These changes may alter responses of cultivars to plant population, denoting the need for adjusting recommendations for current white oat cultivars commonly grown in southern Brazil (Romitti, et al., 2016; Silva et al., 2020; Bazzo et al., 2021).

Advancements in sustainable management practices for improving grain quality in the largest oat producing region in Brazil have pointed out the need for adjustment seeding density based on the currently most grown cultivars, which are characterized by short cycles and short plants (Silva et al., 2012; Romitti et al., 2017; Loro et al., 2021). A higher number of plants per area can improve plant competitiveness and suppress weeds, increase straw volume to prevent erosion, control soil moisture, and result in better maturation uniformity, reducing the use of pre-harvest agrochemicals. Pre-harvest burndown is carried out based on herbicides that dry or defoliate plants, facilitating harvesting (Daltro et al., 2010; Silva et al., 2012; Rosa et al., 2023). Air and water contamination by these herbicides exposes insects and other living beings, including humans, to the risk of harmful effects. For example, suspended particles of herbicides have easy contact with bees, which carry the molecule to the hive, contaminating others bees (Peruzzolo, Grange and Ronqui, 2021; Basso et al., 2022; Jung et al., 2023).

The use of high seeding density in favorable years, combined with application of nitrogen fertilizers to increase grain yield, increases lodging in oat plants. Lodging is a complex
phenomenon; the plant loses its vertical position, leaning and falling towards the ground, which affects grain yield and quality and makes harvesting difficult (Hawerroth et al., 2015; Krysczun et al., 2017). Lodging can be caused by genetic factors combined with external factors, such as wind, rain, hail, soil, plant density, and other management techniques (Silva et al., 2015; Marolli et al., 2017). This phenomenon is one of the main factors causing losses in grain quality and yield due to the difficulty of translocating photoassimilates to the grains (Kashiwagi et al., 2005). Despite advances in genetic improvement for reducing crop cycle and plant height, oats are among the most affected agronomic species by lodging, which hinders harvest and reduces grain quality (Silva et al., 2012; Arenhardt et al., 2017).

Favorable growth conditions increase grain yield, but also increase vegetative vigor, contributing to the occurrence of lodging (Berry et al., 2003; Silva et al., 2012). An alternative for cereals, such as rice (Arf et al., 2012), wheat (Schwerz et al., 2015), and oat (Marolli et al., 2018) is the use of plant growth regulators, which are chemical compounds that make the stem more resistant to breakage and lodging (Kaspary et al., 2015). Currently, the recommended plant growth regulator for oat and other cereal crops in Brazil is a synthetic product containing trinexapac-ethyl as the active ingredient (Moddus®), which should be applied by spraying at the stage between the 1st and 2nd visible stem nodes (Marolli et al., 2021). However, the application of this product is challenging, as it can cause harmful effects to plants when applied under limiting water conditions, high temperatures, and in the days preceding frosts, causing high phytotoxicity and significant decreases in grain yield; in addition, it is toxic to humans and dangerous to the environment (Mapa, 2019; Souza et al., 2021).

Several studies have reported the potential of foliar fertilizer applications for improving crop agronomic performance and yield (Castro and Vieira, 2001). Foliar fertilizers are nutritional products usually composed of micro and macro nutrients, amino acids, and hormones, which are applied to the aerial part of plants. They are an alternative for fertilizer application and stimulation of crop development, often more efficient for specific problems due to their rapid assimilation (Haim et al., 2012; Silva et al., 2020). Field results reported by a fertilizer industry on the use of an organomineral foliar fertilizer based on calcium and potassium with the characteristic of reducing lodging in soybean and wheat crops have raised the interest in studying this technology, focusing on mitigating limiting factors of production and establishing a
sustainable management in the northwest region of Rio Grande do Sul, the largest oat producing state in Brazil.

The objectives of this study were to evaluate the use of high seeding density in current oat cultivars grown in the northwestern Rio Grande do Sul (RS), Brazil; assess the effects of plant growth regulators on grain yield indicators, industrial grain quality, and stem structure; and evaluate a calcium and potassium-based organomineral product as a sustainable technology for controlling lodging.

2 MATERIAL AND METHODS

Two field experiments were conducted, one in 2021 and other in 2022, in Augusto Pestana, RS, Brazil (28°26’30″S and 54°00’58″W). The soil of the experimental area was classified as Typic Hapludox (Latossolo Vermelho Distroférrico típico; Santos et al., 2018). The region has a humid subtropical climate, according to the Köppen classification. Soil samples from the experimental area were analyzed before sowing, and showed the following chemical characteristics: pH = 6.3; P = 34.1 mg dm\(^{-3}\); K = 198 mg dm\(^{-3}\); organic matter = 3.2%; Al = 0 cmolc dm\(^{-3}\); Ca = 6.5 cmolc dm\(^{-3}\), and Mg = 2.5 cmolc dm\(^{-3}\). Oat seeds were sown in the second half of May using a seeder-fertilizer. The plots consisted of five 5-meter rows spaced 0.20 m apart, forming an experimental unit of 5 m\(^2\). Soil nitrogen fertilizer was applied for an expected grain yield of 3 Mg ha\(^{-1}\), using 10 kg ha\(^{-1}\) at sowing and as topdressing, when the plants had four expanded leaves. \(P_2O_5\) and \(K_2O\) were applied at sowing, using 45 and 30 kg ha\(^{-1}\), respectively, based on the soil P and K contents.

The experiment in 2021 (Experiment I) was conducted in a randomized block design with 4 replications, using a 4×3 factorial arrangement consisted of 4 seeding densities (100, 300, 600, and 900 viable seeds m\(^{-2}\)) and 3 treatments with plant growth regulator (PGR) (without PGR; synthetic PGR trinexapac-ethyl - Moddus®; and a Ca and K-based organomineral fertilizer - Maxx Grow®). The two PGRs were applied at the oat stage between the 1st and 2nd visible nodes on the aboveground stem, following the manufacture's recommendations for white oat crops. The organomineral product was applied at the rate of 100 mL ha\(^{-1}\), and trinexapac-ethyl was applied at the rate of 250 mL ha\(^{-1}\).

The experiment in 2022 (Experiment II) was conducted in a randomized block design with 4 replications, using a 4×4 factorial arrangement consisted of 4 seeding densities (100, 300,
600, and 900 viable seeds m⁻²) and 4 treatments with PGR (without PGR; synthetic PGR - Moddus®, applied at the stage between the 1st and 2nd visible stem nodes; organomineral fertilizer - Maxx Grow®, applied at the stage between the 1st and 2nd visible stem nodes; and organomineral fertilizer applied sequentially at the V4 stage (fourth expanded leaf) and at the stage between the 1st and 2nd visible stem nodes). The organomineral fertilizer was applied at the recommended rate (100 mL ha⁻¹) in both treatments (single application and sequential application at two stages). Trinexapac-ethyl was applied at the rate of 200 mL ha⁻¹.

Yield and industrial quality of oat grains were assessed in both experiments (2021 and 2022). The evaluated grain yield indicators were i) grain yield (kg ha⁻¹): evaluated by mechanically harvesting the central three rows of each plot when grain moisture content was approximately 18%; the material was then sent to a laboratory for correcting grain moisture content to 13%, threshed, and weighed to measure grain yield (g), which was converted into kg ha⁻¹; ii) thousand grain weight (g), obtained by weighing 250 grains on a precision scale and multiplying the result by four; and iii) hectoliter weight (kg hl⁻¹), obtained by converting the weight of grains in a 250 cm³ cube into kg hl⁻¹. The evaluated industrial grain quality indicators were: i) number of grains larger than 2 mm, determined by placing 100 grains on a 2-mm mesh sieve and counting those larger in size; ii) weight of grains larger than 2 mm (g), determined by weighing 50 grains larger than 2 mm on a precision scale; iii) caryopsis weight of grains larger than 2 mm, obtained by weighing 50 grains larger than 2 mm without husk on a precision scale; iv) husking index (g g⁻¹), determined by calculating the ratio between the caryopsis weight of 50 grains larger than 2 mm and their total grain weight; v) industrial yield (kg ha⁻¹), obtained by multiplying grain yield (TGY), the number of grains larger than 2 mm (NG>2 mm), and the husking index (HI), according to the following equation: IGY = GY × NG>2 mm × HI.

Meteorological data regarding mean, minimum, and maximum air temperatures (°C) and rainfall depths (mm) were from a weather station installed at approximately 200 meters from the experimental field.

Physical-mechanical properties of stems were analyzed in Experiment II (2022) on three plants collected from each plot before harvest. The plants were cut at the stem node position using scissors. Stem-related variables were measured at the midpoint position of the stems. This procedure was carried out from the first to the last internode near the panicle. Each internode was measured to determine internode length (cm); internode weight (g), using a precision scale;
external and internal internode diameters (mm), using a digital caliper; internode thickness (mm), obtained by calculating the ratio between the external and internal diameters; and internode resistance (N), determined using a digital dynamometer by measuring the force applied at the central position of each internode that caused it to bend, simulating lodging.

The obtained data were subjected to analysis of variance to assess the main and interaction effects, and the Scott-Knott mean test was applied at 5% probability level. Subsequently, quadratic regression analysis \( y = b_0 \pm b_1 x \pm b_2 x^2 \) was performed to estimate the maximum technical and economic efficiency of seeding density as a function of grain yield and industrial grain quality. All statistical analyses were performed using the software GENES (Cruz, 2013).

3 RESULTS AND DISCUSSION

Experiment I (2021) was characterized by high maximum air temperatures and low water availability at essential stages for the oat crop development (Figure 1). Water demand during the cycle of white oat crops is approximately 350 mm, with an adequate distribution (Frizzone et al., 1995; Mantai et al., 2021). The rainfall depth exceeded 600 mm, but was unevenly distributed, with significant low volumes during nitrogen and plant growth regulator (PGR) application periods. The combination of high temperatures and low water availability may have been decisive for reducing nitrogen use by plants and the significant stress caused by the application of the synthetic PGR (trinexapac-ethyl; Moddus®), as shown by the low grain yield found. No lodging was found, which may be connected to the meteorological conditions, which did not favor satisfactory plant growth and development. Results from the National Household Sample Survey (NHSS) showed that 97.2% of the Brazilian population used safely managed drinking water services in 2017 (Brasil, 2017).
Figure 1 - Meteorological data of air temperatures and rainfall depths during the oat crop cycles in Experiment I (2021) and Experiment II (2022).

Experiment II (2022) was characterized by high maximum air temperatures (approximately 30 °C) during nitrogen and PGR applications at the V4 stage (fourth expanded leaf) and during PGR application at the stage between the 1st and 2nd visible stem nodes, resulting in significant stress of oat plants subjected to application of trinexapac-ethyl. The optimal air temperature for oat crops ranges from 20 to 25 °C (Penning de Vries et al., 1989; Marolli et al., 2018). Rainfall depths were better distributed throughout the crop cycle, providing...
adequate soil moisture conditions during nitrogen and PGR applications. These conditions may have favored nutrient absorption, as PGR application had higher effects on oat grain yield and industrial grain quality. However, high air temperatures throughout the crop cycle were decisive for grain production, which did not achieve the expected yield based on the soil fertilizer applications at sowing and as topdressing.

The analysis of variance showed that treatments with and without application of PGR (trinexapac-ethyl and an Ca and K-based organomineral product) had no effects on the grain yield and industrial grain quality (Table 1). However, the tested seeding densities affected grain yield, husking index, and industrial yield. In Experiment II, the application of organomineral PGR, trinexapac-ethyl, the sequential application of organomineral PGR, and the control treatment affected all grain yield indicators and industrial yield (Table 1). Seeding density affected grain yield, hectoliter weight, husking index, and industrial yield.

Table 1. Analysis of variance for effects of application of plant growth regulators (PGR) and seeding densities (SD) on oat grain yield and industrial grain quality.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>DF</th>
<th>GY (kg ha⁻¹)</th>
<th>TGW (g)</th>
<th>HW (kg ha⁻¹)</th>
<th>NG&gt;2mm (n)</th>
<th>HI (g g⁻¹)</th>
<th>IGY (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment I (2021)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block</td>
<td>3</td>
<td>24579</td>
<td>1.6</td>
<td>5.6</td>
<td>23.9</td>
<td>0.001</td>
<td>4867</td>
</tr>
<tr>
<td>PGR</td>
<td>2</td>
<td>294853</td>
<td>73.3</td>
<td>0.0</td>
<td>240</td>
<td>0.000</td>
<td>13317</td>
</tr>
<tr>
<td>SD</td>
<td>3</td>
<td>258242*</td>
<td>13.7</td>
<td>3.1</td>
<td>51.5</td>
<td>0.010*</td>
<td>86163*</td>
</tr>
<tr>
<td>PGR × SD</td>
<td>6</td>
<td>7314</td>
<td>8.4</td>
<td>0.6</td>
<td>7.7</td>
<td>0.020</td>
<td>3793</td>
</tr>
<tr>
<td>Error</td>
<td>33</td>
<td>12783</td>
<td>5.7</td>
<td>2.1</td>
<td>20.9</td>
<td>0.001</td>
<td>4572</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>47</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Overall mean</strong></td>
<td>-</td>
<td>1088</td>
<td>27.4</td>
<td>40.8</td>
<td>61</td>
<td>0.63</td>
<td>426</td>
</tr>
<tr>
<td><strong>CV (%)</strong></td>
<td>-</td>
<td>10.3</td>
<td>8.7</td>
<td>3.5</td>
<td>7.4</td>
<td>5.8</td>
<td>15.8</td>
</tr>
<tr>
<td><strong>Experiment II (2022)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block</td>
<td>3</td>
<td>1738</td>
<td>1.6</td>
<td>7.7</td>
<td>3.8</td>
<td>0.009</td>
<td>8863</td>
</tr>
<tr>
<td>PGR</td>
<td>3</td>
<td>2529504*</td>
<td>39.2*</td>
<td>46.6*</td>
<td>21.1</td>
<td>0.002</td>
<td>577009*</td>
</tr>
<tr>
<td>SD</td>
<td>3</td>
<td>124139*</td>
<td>6.2</td>
<td>23.6*</td>
<td>0.2</td>
<td>0.03*</td>
<td>67926*</td>
</tr>
<tr>
<td>PGR × SD</td>
<td>9</td>
<td>20478</td>
<td>5.4</td>
<td>2.2</td>
<td>7.4</td>
<td>0.03</td>
<td>8026</td>
</tr>
<tr>
<td>Error</td>
<td>45</td>
<td>10555</td>
<td>4.1</td>
<td>2.3</td>
<td>27.0</td>
<td>0.001</td>
<td>3998</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>63</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Overall mean</strong></td>
<td>-</td>
<td>847</td>
<td>28.9</td>
<td>45.2</td>
<td>69</td>
<td>0.70</td>
<td>411</td>
</tr>
<tr>
<td><strong>CV (%)</strong></td>
<td>-</td>
<td>12.1</td>
<td>6.9</td>
<td>3.6</td>
<td>7.5</td>
<td>5.3</td>
<td>15.3</td>
</tr>
</tbody>
</table>

*= significant at a 5% probability level by the F test; CV = coefficient of variation; DF = degrees of freedom; GY = grain yield; TGW = thousand grain weight; HW = hectoliter weight; NG>2 mm = number of grains larger than 2 mm, HI = husking index; IGY = industrial yield. Experiment I** = field experiment consisted of applications of plant growth regulators (PGR) (trinexapac-ethyl; and an organomineral product) at the stage between the 1st and 2nd visible stem nodes and different seeding densities (100, 300, 600, and 900 seeds m⁻²); Experiment II** = field experiment consisted of applications of trinexapac-ethyl PGR and organomineral PGR at the stage between the 1st and 2nd visible stem nodes, organomineral PGR application at V4 and at the stage between the 1st and 2nd visible stem nodes, and different seeding densities (100, 300, 600, and 900 seeds m⁻²).

Source: Prepared by the authors
Grain yield, husking index, and industrial yield were affected in Experiments I and II, indicating the need for adjustments to identify the optimal seeding density. Additionally, no significant interaction between PGR application and seeding density was found in the experiments, denoting similar responses to PGR application managements, regardless of seeding density. The effects of PGR applications in Experiments I and II differed, indicating that environmental conditions in the agricultural year can affect these variables. No plant lodging was observed in the experiments, even under high plant density conditions in different treatments. However, the comparison between the PGR application and seeding density effects in Experiment II showed significant effects of PGR application on grain yield and industrial yield, different from Experiment I.

The treatments with and without PGR application in Experiment I had no effect on grain yield and industrial grain quality (Table 2). However, the application of trinexapac-ethyl at the stage between the 1st and 2nd stem nodes in Experiment II had significant negative effect on grain yield and industrial yield. This was due to the low soil moisture conditions and high air temperature during PGR applications, reinforcing the need for application managements based on phenological characteristics and favorable soil moisture and air temperature conditions. The other evaluated variables related to grain filling and size were not affected, thus, the number of grains per panicle was affected by the significant decreases in yield.

Table 2. Means of indicators of oat grain yield and industrial grain quality under the effect of plant growth regulator (PGR) application.

<table>
<thead>
<tr>
<th>PGR</th>
<th>GY (kg ha⁻¹)</th>
<th>TGW (g)</th>
<th>HW (kg ha⁻¹)</th>
<th>NG&gt;2mm (n)</th>
<th>HI (g g⁻¹)</th>
<th>IGY (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment I (2021)**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No application</td>
<td>1128 a</td>
<td>26.7 a</td>
<td>40.9 a</td>
<td>59 a</td>
<td>0.63 a</td>
<td>427 a</td>
</tr>
<tr>
<td>Trinexapac-ethyl 1N</td>
<td>936 a</td>
<td>29.8 a</td>
<td>40.8 a</td>
<td>66 a</td>
<td>0.63 a</td>
<td>397 a</td>
</tr>
<tr>
<td>Organomineral product 1N</td>
<td>1199 a</td>
<td>25.6 a</td>
<td>40.8 a</td>
<td>59 a</td>
<td>0.63 a</td>
<td>455 a</td>
</tr>
<tr>
<td>Experiment II (2022)**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No PGR application</td>
<td>986 a</td>
<td>29.6 a</td>
<td>41 a</td>
<td>68 a</td>
<td>0.71 a</td>
<td>483 a</td>
</tr>
<tr>
<td>Trinexapac-ethyl 1N</td>
<td>255 b</td>
<td>26.6 a</td>
<td>40 a</td>
<td>70 a</td>
<td>0.70 a</td>
<td>128 b</td>
</tr>
<tr>
<td>Organomineral product 1N</td>
<td>1109 a</td>
<td>30.2 a</td>
<td>42 a</td>
<td>69 a</td>
<td>0.69 a</td>
<td>536 a</td>
</tr>
<tr>
<td>Organomineral product V41N</td>
<td>1037 a</td>
<td>29.2 a</td>
<td>44 a</td>
<td>69 a</td>
<td>0.69 a</td>
<td>496 a</td>
</tr>
</tbody>
</table>

GY = grain yield; TGW = thousand grain weight; HW = hectoliter weight; NG>2 mm = number of grains larger than 2 mm, HI = husking index; IGY = industrial yield; Trinexapac-ethyl 1N and Organomineral product 1N = application at the stage between the 1st and 2nd visible stem nodes; Organomineral product V41N = sequential applications at V4 and at the stage between the 1st and 2nd visible stem nodes.

Source: Prepared by the authors
The effects of trinexapac-ethyl on grain yield may vary according to the plant species, genotype, and product rate used (Arf et al., 2012; Silva et al., 2015). Penckowski et al. (2010) and Schwerz et al. (2015) found that trinexapac-ethyl rates between 400 and 500 mm ha\(^{-1}\) reduced height and lodging in wheat plants, with no effects on grain yield, similar to results found in the present study for oats. Significant decreases in lodging were found for wheat (Pagliosa et al., 2013; Trevizan et al., 2015) and rice (Arf et al., 2012; Alvarez et al., 2014) plants, when using the trinexapac-ethyl rate of 400 mL ha\(^{-1}\), and for sunn hemp (Kappes et al., 2011) and soybean (SOUZA et al., 2013) plants, when using a trinexapac-ethyl rate of 500 mL ha\(^{-1}\). Kaspary et al. (2015) and Guerreiro and Oliveira (2012) evaluated the effects of trinexapac-ethyl on oat grain yield and quality and found that the rate of 500 mL ha\(^{-1}\) reduced plant height by up to 60%.

Despite the reported efficiency of using trinexapac-ethyl for controlling lodging in oat plants, this chemical compound causes high stress in plants when applied under low water availability or high air temperature conditions (Souza et al., 2021).

Grain yield and industrial yield were affected by the highest seeding densities tested in Experiment I, showing lower means (Table 3). The lowest and highest seeding densities reduced grain yield and industrial yield in Experiment II. Under these conditions, a quadratic response seems to be more suitable for biological explanation. The husking index increased linearly, with the highest indices were found for the densities of 600 and 900 seeds m\(^{-2}\). Grain yield and industrial yield data in Experiment I fitted a quadratic function, which was also found in Experiment II (Table 3).
The quadratic polynomial function indicated an optimal seeding density of 400 seeds m\(^{-2}\) for maximum grain yield in Experiment I (Table 4); the optimal seeding density estimated for maximum industrial yield was 450 seeds m\(^{-2}\). The adjusted estimated seeding density based on the oat seed (input) and oat grains (output) prices that provide economic efficiency was 300 seeds m\(^{-2}\). Regarding industrial yield, the economic efficiency in seeding density is based on the technical efficiency.
Table 4. Regression function of indicators of oat grain yield and industrial grain quality as a function of seeding density, with analysis of technical and economic efficiency.

<table>
<thead>
<tr>
<th>Function</th>
<th>R²</th>
<th>MET (Seeds m⁻²)</th>
<th>MEE (Seeds m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment I (2021)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GY y= 1010+1.05x-0.0013x²</td>
<td>99</td>
<td>± 400</td>
<td>± 300</td>
</tr>
<tr>
<td>IGY y= 330+0.82x-0.0009x²</td>
<td>99</td>
<td>± 450</td>
<td>± 450</td>
</tr>
<tr>
<td><strong>Experiment II (2022)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GY y= 647+1.14x-0.0011x²</td>
<td>98</td>
<td>± 520</td>
<td>± 340</td>
</tr>
<tr>
<td>IGY y= 252+0.79x-0.00065x²</td>
<td>99</td>
<td>± 600</td>
<td>± 600</td>
</tr>
</tbody>
</table>

GY = grain yield; IGY = industrial yield; R² = coefficient of determination; MET = maximum technical efficiency; MEE = maximum economic efficiency; Experiment I = field experiment consisted of different seeding densities (100, 300, 600, and 900 seeds m⁻²), with applications of plant growth regulators (PGR) at the stage between the 1st and 2nd visible stem nodes; Experiment II = field experiment consisted of different seeding densities (100, 300, 600, and 900 seeds m⁻²), with applications of PGR at the stage between the 1st and 2nd visible stem nodes, and sequential PGR application at V4 and at the stage between the 1st and 2nd visible stem nodes; input price (oat seeds) = BRL (R$) 1.70 kg⁻¹; output price (oat grains) = BRL (R$) 0.90 kg⁻¹.

Source: Prepared by the authors

In Experiment II, the maximum estimated grain yield and industrial yield were found for densities of 520 and 600 seeds m⁻² (Table 4). Therefore, economic calculations involving input and output prices estimated 340 and 600 seeds m⁻² for maximum economic efficiency in grain yield and industrial yield, respectively. However, higher seeding densities can increase grain yields, favor soil coverage and maintenance of soil moisture, control invasive species, and improve nutrient cycling. These conditions were also assessed through visual analysis in the field.

Rapid soil coverage at the initial growing stage of oat plants is essential for improving the crop's competitiveness with weed species. Weeds negatively impact crops by competing for water, light, and nutrients, and hosting insects and diseases that affect agricultural species (Romitti et al., 2017; Rosa et al., 2022). Silveira et al. (2010) studied several wheat varieties and found that seeding densities higher than those recommended resulted in better crop yield performances, which may explain improvements in agronomic indicators of cultivars by adjusting seeding density based on specific adaptations; they emphasized that high grain yields can be obtained by adjusting the equidistant distribution of seeds in the area based on the tillering potential of each genotype, indicating seeding densities between 350 and 500 seeds m⁻², higher than those recommended.

Valério et al. (2008) evaluated oat genotypes with high tillering potential and found small variation in tiller production with increasing seeding density. Genotypes with lower tillering potential are more dependent on seeding density and impacts on crop yield, confirming the need for a high seed quantity. Increases in seeding density contribute to increases in yield and in
competitive potential of oat plants (Silva et al., 2012; Romitti et al, 2017). Furthermore, a rapid soil coverage can improve light and nutrient use by plants (Fleck et al., 2009; Krüger et al., 2011). Crop competition with weeds for environmental resources increases under limited environmental conditions, reinforcing the need for using higher seeding densities (Valério et al, 2008).

The possibility of no occurrence of lodging in oat plants in the experimental years evaluated in the present study was expected and confirmed; therefore, greater efforts were made to obtain data by using different PGR applications and seeding densities for analyzing morphological characteristics related to stem structure of oat plants. Results of internode length, weight, diameter (external and internal), thickness, and resistance in the different treatments are shown in Tables 5 and 6.

The analysis of variance showed no effects of the interaction between PGR application and seeding density on variables related to stem internodes of oat plants. However, differences were found along the stem internodes (data not shown), denoting isolated effects of seeding density and PGR application. The means found for effects of PGR application and seeding density on internode-related characteristics are shown in Tables 5 and 6, respectively. PGR application treatments affected internode length, weight, and external diameter from the third internode on the stem of oat plants (Table 5), presenting significant decreases when trinexapac-ethyl was applied. The internal diameter of the fourth and fifth internodes was affected, reinforcing the decrease in this variable when applying trinexapac-ethyl.

Table 5. Means of stem internode characteristics in oat plants under the effect of plant growth regulator (PGR) application.

<table>
<thead>
<tr>
<th>PGR application</th>
<th>Internode length (cm)</th>
<th>Internode weight (g)</th>
<th>Internode external diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I1</td>
<td>I2</td>
<td>I3</td>
</tr>
<tr>
<td>No application</td>
<td>3.4a</td>
<td>7.7a</td>
<td>11.5a</td>
</tr>
<tr>
<td>Trinexapac-ethyl (1st node stage)</td>
<td>3.5a</td>
<td>7.2a</td>
<td>9.0b</td>
</tr>
<tr>
<td>Organomineral (1st node stage)</td>
<td>3.5a</td>
<td>8.0a</td>
<td>12.3a</td>
</tr>
<tr>
<td>Organomineral (V4 and 1st node stages)</td>
<td>3.4a</td>
<td>7.6a</td>
<td>11.2a</td>
</tr>
</tbody>
</table>
Table 6. Means of stem internode characteristics in oat plants under the effect of seeding density.

<table>
<thead>
<tr>
<th>Seeding density (seeds m$^{-2}$)</th>
<th>Internode length (cm)</th>
<th>I1</th>
<th>I2</th>
<th>I3</th>
<th>I4</th>
<th>I5</th>
<th>I6</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>I1</td>
<td>3.3a</td>
<td>7.9a</td>
<td>11.7a</td>
<td>17.0a</td>
<td>23.3a</td>
<td>5.3a</td>
</tr>
<tr>
<td>300</td>
<td>I2</td>
<td>3.3a</td>
<td>7.3a</td>
<td>10.8a</td>
<td>14.5b</td>
<td>22.7a</td>
<td>5.1a</td>
</tr>
<tr>
<td>600</td>
<td>I3</td>
<td>3.7a</td>
<td>7.9a</td>
<td>10.7a</td>
<td>12.9c</td>
<td>20.4b</td>
<td>7.0a</td>
</tr>
<tr>
<td>900</td>
<td>I4</td>
<td>3.7a</td>
<td>7.7a</td>
<td>10.9a</td>
<td>12.3c</td>
<td>17.8c</td>
<td>4.5a</td>
</tr>
</tbody>
</table>

Means followed by the same letter in the column are not significantly different from each other at a 5% probability level by the Scott & Knott test; I1 = internode 1; I2 = internode 2; I3 = internode 3; I4 = internode 4; I5 = internode 5; I6 = internode 6.

Source: Prepared by the authors
<table>
<thead>
<tr>
<th>Seeding density (seeds m$^{-2}$)</th>
<th>Internode external diameter (mm)</th>
<th>Internode internal diameter (mm)</th>
<th>Internode thickness (mm)</th>
<th>Internode resistance (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I1</td>
<td>I2</td>
<td>I3</td>
<td>I4</td>
</tr>
<tr>
<td>100</td>
<td>3.0a</td>
<td>3.4a</td>
<td>3.3a</td>
<td>3.3a</td>
</tr>
<tr>
<td>300</td>
<td>2.6b</td>
<td>2.8b</td>
<td>2.9b</td>
<td>2.6b</td>
</tr>
<tr>
<td>600</td>
<td>2.5b</td>
<td>2.6b</td>
<td>2.6b</td>
<td>2.5b</td>
</tr>
<tr>
<td>900</td>
<td>2.2c</td>
<td>2.2c</td>
<td>2.2c</td>
<td>2.0c</td>
</tr>
</tbody>
</table>

Means followed by the same letter in the column are not significantly different from each other at a 5% probability level by the Scott & Knott test; I1 = internode 1; I2 = internode 2; I3 = internode 3; I4 = internode 4; I5 = internode 5; I6 = internode 6.

Source: Prepared by the authors

Internode external and internal diameters were significantly affected by seeding density (Table 6). The results showed that these characteristics tend to decrease from the first to the fifth internode as seeding density is increased. Despite the differences found for internode diameters, internode thickness did not differ. However, differences in stem resistance were found when using a PGR. Although internode thickness did not differ due to the use of PGR, it is expected that the resistance would not change either (Table 5). Despite seeding density did not affect internode thickness, the differences found in the external and internal diameters of the first internodes may contribute to understanding internode resistance and that may be connected to effects on lodging of oat plants.

Estimating lodging percentage has been the most used method to assess lodging resistance in cereal plant breeding. Loading percentage is estimated based on visual analysis and grades of crops or experimental plots evaluating crop yields. Sousa (1998) developed an elaborate system based on lodged area percentage and stem inclination angle; however, it cannot reliably
determine the resistance to lodging. Lodging can directly impact grain yield by affecting dry matter accumulation, indirectly decrease grain yield by causing difficulties during harvesting, and affect grain quality, significantly impacting the economic value of the product (Hawerroth et al., 2015; Marolli et al., 2018). The effects of lodging on grain yield depend on the genotype and its severity and time; it results in higher losses for tall-plant varieties and when lodging occurs during anthesis (Weibel and Pendleton, 1964; Wiersma et al., 1986; Federizzi et al., 1994). The introduction of shorter genotypes has significantly increased the grain yield potential of cereal plant species, especially wheat and rice (Cruz et al., 2005). Reductions in plant size have enabled the growing of these cereals in favorable environments for their development, mainly with improvement of the growing environment through irrigation and application of higher fertilizer rates (Stoddart and Lloyd, 1986). Kheiralla (1994) evaluated wheat plants and found that characteristics related to the stem resistance to lodging, such as plant height, length of the 2nd internode, stem diameter, and stem wall thickness are promising for identifying lodging-resistant plants. Plant height, length of the 2nd internode, and peduncle length are connected to resistance to lodging in wheat plants; high values of these characteristics make plants significantly susceptible to lodging (Cruz et al., 2001; Cruz et al., 2004).

The present work is significantly connected with some Sustainable Development Goals (SDGs) presented in the 2030 agenda established in 2015 during the United Nations (UN) General Assembly. These SDGs cover social and economic development issues, including poverty, hunger, health, education, global warming, gender equality, water, sanitation, energy, urbanization, environment, and social justice. Specifically, this study is connected to SDG 2, which address zero hunger and sustainable agriculture. This goal involves the achieving of 5 targets by 2030; the present study focused on target 4, ensuring sustainable food production systems and implementing resilient agricultural practices that contributed to increases in agricultural production and yield while conserving ecosystems, strengthening the capacity to adapt to climate change and extreme weather conditions, such as droughts, floods, and other disasters, and progressively improving land and soil quality (Maluf, 2000, Fome Zero, 2019).

4 FINAL CONSIDERATIONS

The meteorological conditions during the experiments limited the development of oat plants, requiring a higher seeding density (between 400 and 520 seeds m⁻²) than that
recommended. Although it was not scaled, greater plant uniformity was observed at the highest evaluated seeding densities, denoting a potential strategy to avoid the use of pre-harvest herbicides.

High air temperature and limiting soil water conditions denoted the phytotoxic potential of using a growth regulator containing trinexapac-ethyl as active ingredient, with a significant reduction in stem structure and grain yield. The calcium and potassium-based organomineral product, used as a sustainable technology for controlling oat plant lodging, requires further studies in years with more favorable environmental conditions for oat crops.
REFERENCES


