SEEDING DENSITY AND FOLIAR APPLICATION OF A CALCIUM AND POTASSIUM-BASED ORGANOINERAL FERTILIZER IN OAT CROPS

Karin Coppetti 1
José Antonio Gonzalez da Silva2
Ivan Ricardo Carvalho3
Deivid Araújo Magano4
Luís Eduardo Panozzo5
Juliana Aozane da Rosa6
Cibele Luisa Peter7
Pedro Diel8
Lara Laís Schünemann9

ABSTRACT

Purpose: To present the benefits of increasing oat sowing density on productivity, uniformity, soil quality and reduction of pesticides and the use of an organomineral product based on calcium and potassium as an alternative to lodging control, promoting more sustainable cultivation systems.

Theoretical framework: Increasing plant density can promote productivity, rapid soil coverage, reduction of weeds and greater harvest uniformity, reducing the use of pesticides. However, increasing seeding density can promote lodging. Lodging is the phenomenon in which plants leave the vertical position and fall to the ground, affecting the quality of the grains. The commercial product registered to control lodging is highly toxic to the environment. Organomineral sources with potassium and calcium represent an alternative for controlling lodging with reduced environmental impacts.

Results: Benefits of increased seeding density to promote grain yield have been found for several crop species, reinforcing the need for adapting seeding density for oat crops. The use trinexapac-ethyl as a growth regulator, it poses risks of phytotoxicity and environmental contamination. In this context, several studies have indicated that potassium and calcium favor cell wall rigidity, potentially contributing to oat stem strength.

Originality/value: This study provides significant contribution to the advancement of research on oat in Brazil, bringing new information benefiting farmers, technical assistance agents, and the food industry and improving the production system to ensure food security and care for the environment.

1 Universidade Regional do Noroeste do Estado do Rio Grande do Sul, Ijuí, Rio Grande do Sul, Brasil. E-mail: karin1609@hotmail.com Orcid: https://orcid.org/0009-0007-6579-6002
2 Universidade Regional do Noroeste do Estado do Rio Grande do Sul, Ijuí, Rio Grande do Sul, Brasil. E-mail: jagesaem@yahoo.com.br Orcid: https://orcid.org/0000-0002-9335-2421
3 Universidade Regional do Noroeste do Estado do Rio Grande do Sul, Ijuí, Rio Grande do Sul, Brasil. E-mail: carvalho.irc@gmail.com Orcid: https://orcid.org/0000-0001-7947-4900
4 Universidade Regional do Noroeste do Estado do Rio Grande do Sul, Ijuí, Rio Grande do Sul, Brasil. E-mail: deivid.magan0@unijui.edu.br Orcid: https://orcid.org/0000-0002-7942-3123
5 Universidade Federal de Pelotas, Pelotas, Rio Grande do Sul, Brasil. E-mail: lepanozzo@gmail.com Orcid: https://orcid.org/0000-0001-6216-3663
6 Universidade Regional do Noroeste do Estado do Rio Grande do Sul, Ijuí, Rio Grande do Sul, Brasil. E-mail: juaozane@gmail.com Orcid: https://orcid.org/0000-0002-0430-1615
7 Universidade Regional do Noroeste do Estado do Rio Grande do Sul, Ijuí, Rio Grande do Sul, Brasil. E-mail: cibele.peter2017@gmail.com Orcid: https://orcid.org/0000-0003-3376-8211
8 Universidade Regional do Noroeste do Estado do Rio Grande do Sul, Ijuí, Rio Grande do Sul, Brasil. E-mail: diel.pedro@gmail.com Orcid: https://orcid.org/0009-0009-7062-3434
9 Universidade Regional do Noroeste do Estado do Rio Grande do Sul, Ijuí, Rio Grande do Sul, Brasil. E-mail: laralaisschunemann@gmail.com Orcid: https://orcid.org/0000-0002-2229-5108
1 INTRODUCTION

White oat (Avena sativa L.) is a versatile species with multiple purposes. Approximately 90% of oat production in Brazil is concentrated in the southern states (CONAB, 2023; Treter et al., 2023). This crop produces grain and straw for soil coverage (Silva et al., 2020; Schmidt et al., 2023). Oat green and dry matter production can be an excellent option for animal feed (Reginatto et al., 2021; Dornelles et al., 2023a), as pre-dried hay or silage can be made and provided to animals in non-grazing periods, in addition to direct grazing (Zamarchi, et al., 2014; Marolli et al., 2018; Pansera et al., 2022). In terms of human nutrition, oats have become prominent due to their nutraceutical characteristics, which are responsible for reducing bad cholesterol (LDL) and the risk of cardiovascular diseases (Maximino et al., 2021; Kraisig et al., 2023). Oat consumption has increased due to the pursuit of a higher quality of life with a preference for more nutritious and healthy foods (Cruz et al., 2018; Babeski et al., 2023).

Thus, searching for managements that ensure a satisfactory oat production is essential due to the growing demand for this cereal. Storck et al. (2014) and Arenhardt et al. (2015), reported that the yield potential of cereals, including wheat and oats, is directly related to population and arrangement of plants, among other factors. Plant densities that promote rapid canopy closure and, consequently, soil coverage and protection result in better utilization of water, light, and nutrients, longer maintenance of soil moisture, effective weed control, and
improved plant uniformity at harvest, contributing to reduce or eliminate the use of agrochemicals (Fleck et al., 2009; Lamego et al., 2013).

Technical guidelines from the Brazilian Oat Research Commission have recommended a seeding density of 200 to 300 seeds m$^{-2}$, which is a recommendation adopted since the cultivation of this species became commercially important in the 1990s. However, the continuous genetic improvement of oats has altered plant architecture, among other traits, changing their biotype (tall plants, late cycle, and high straw-to-grain ratio) to create genotypes with plants smaller than one meter in height, shorter cycles, and larger caryopsis volumes in relation to the husk (Hawerroth et al., 2015; Silva et al., 2015). These changes may modify the response of cultivars to plant population, denoting the need for adjusting recommendations for the current oat biotypes grown in southern Brazil.

Advances in sustainable management practices for improving grain quality in the largest oat producing region in Brazil have highlighted the need for adjusting seeding density based on current biotypes with short cycles and small plant heights (Silva et al., 2012; Romitti et al., 2016). Increasing the number of plants per area improves crop yield and plant competitive ability, increases straw volume on the soil, and promotes better plant uniformity due to intraspecific pressure to suppress late tillers (Silveira et al., 2010; Romitti et al., 2017), reducing or eliminating the use of pre-harvest agrochemicals. Pre-harvest desiccation involves the use of herbicides that dry and defoliate plants, ensuring plant and grain moisture levels suitable for harvest (Daltro, et al., 2010; Silva, et al., 2011; Albrecht, et al., 2022). Soil, water, and air contamination by these herbicides exposes insects and other living beings 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 (Pereira et al., 2020; Peruzzolo, Grange, Ronqui, 2021).

Using higher seeding densities, combined with favorable years for growing oat crops and application of nitrogen fertilizers, to increase grain yield may result in lodging of oat plants. Lodging is a complex phenomenon in which the plant loses its upright position, leans, and falls to the ground, affecting grain yield and quality and making harvesting difficult (Hawerroth et al., 2015; Krysczun, et al., 2017). This phenomenon leads to losses in grain quality and yield due to the difficulty of translocating photoassimilates to the grains. It is induced by genetic factors genetic factors combined with external factors, such as wind, rain, hail, soil, plant density, and other management techniques (Kashiwagi et al., 2005; Marolli et al., 2017a). Despite advances in genetic improvement for reducing crop cycle and plant height, been achieved, oats are among the crop species most affected by lodging, making harvesting difficult and devaluing the grains for commercialization (Hawerroth et al., 2015; Marolli et al., 2017b).

The use of growth regulators is an alternative for cereal crops such as rice (Arf et al., 2012), wheat (Schwerz et al., 2015), and oats (Marolli et al., 2017c); these chemical compounds make the stem more resistant to breakage and lodging to ensure grain yield and quality (Kaspary et al., 2015). Synthetic commercial products with trinexapac-ethyl as the active ingredient are currently the recommended growth regulators for oats and other cereals; they should be applied by spraying at the stage between the 1st and 2nd visible stem nodes (Marolli et al., 2017a). 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; additionally, it is toxic to humans and dangerous to the environment (Mapa, 2009; Souza et al, 2021).

Unfavorable environmental conditions during application often create difficulties, reducing the efficiency of technologies, nutrient absorption, pest and disease control, and may even cause phytotoxicity (Kraisig et al., 2021; Henrichsen et al., 2022). Applications of pesticides and fertilizers under these conditions result in low efficiency, leading to yield losses, increased production costs, and human and environmental contamination (Mantai et al., 2021;
Seeding Density and Foliar Application of a Calcium and Potassium-Based Organomineral Fertilizer in Oat Crops

Bubans et al., 2021; Montagner et al., 2021). These use restrictions typically occur under high air temperatures and low soil moisture contents due to longer periods without rainfall (Pereira et al., 2023a; Meotti et al., 2023).

The efficiency of nutrient utilization in agricultural crops can be improved by foliar application of biostimulants (Domingos et al., 2015; Bester et al., 2021). Several studies have reported the potential of foliar application of fertilizers for improving crop agronomic performance and yield (Castro and Vieira, 2001; Henrichsen et al., 2023a). Foliar fertilizers are usually composed of micro and macro nutrients, amino acids, and hormones, and are applied to the aerial part of plants. They are an alternative for fertilizer application and stimulation of crop development, often more efficient in solving specific problems due to their rapid assimilation (Haim et al., 2012; Silva et al., 2020). Some studies have reported promising results with the use of calcium and potassium-based foliar fertilizers to generate stem strength and, consequently, reduce lodging. Some of these products are classified as organomineral, presenting low environmental impact (Karin, 2023), therefore raising the interest in further discussions about these technologies to ensure yield and sustainability for oat crops.

The objectives of this literature review are to bring into discussion the seeding density used for crops with current oat biotypes, including the need for improvements in technical guidelines and increasing seed density; and address the effects of lodging on oat grain yield and the use of the growth regulator trinexapac ethyl, as well as the potential use of a calcium and potassium-based organomineral foliar fertilizer as a more sustainable technology for lodging control.

2 OAT: A MULTIFUNCTIONAL SPECIES

According to the Brazilian National Food Supply Company (CONAB), oats were grown in approximately 503,400 hectares in Brazil in the 2022 crop season, with a production of 1.14 million Mg and an average yield of 2,271 kg ha⁻¹ (CONAB, 2023; Henrichsen et al., 2023b). White oat production has been intensified in the state of Rio Grande do Sul, with the highest productions concentrated in the northern half of the state, which had approximately 361,600 hectares cultivated with oat crops in 2022, with a production of 878,000 Mg and an average yield of 2,428 kg ha⁻¹ (CONAB, 2023; Berlezi et al., 2023). Oats have been an alternative to wheat crops in the winter season for producing large amounts of dry matter and grains, contributing to no-tillage systems, and serving as a key crop element in crop rotation.

White oat crops are also grown in the Southwest and Central-West regions of Brazil to produce grains and straw for soil coverage, favoring the implementation of summer crops under no-tillage system (Mantai, et al., 2015; Pereira et al., 2023b).

White oats are an excellent option for biomass production, reaching 59 Mg ha⁻¹ of green matter and more than 19 Mg ha⁻¹ of dry matter in southern Brazil (Pansera et al., 2021a; Marolli et al., 2021). These crops can fit into the forage planning, with sowing from March onwards, meeting the feed demand for animals during the transition period between summer and winter, known as the forage gap. Although often used for animal grazing, white oats are widely utilized as silage and pre-dried hay, taking advantage of idle lands during winter to store preserved forage (De Mori, et al., 2012; Paris et al., 2015). Silage is the process of forage preservation through anaerobic fermentation, which converts soluble carbohydrates into organic acids through the action of proliferating microorganisms, providing suitable conditions for conservation, preserving the plant's nutritional value (Zamarchi, et al., 2014; Marolli et al., 2018).

Considering human consumption, oats can be used in the production of baby food, hot or cold breakfast cereals, granola, cereal bars, and baked goods such as breads, cookies, and cakes. They are also used as an additional component in thicken soups and sauces and to
increase the volume of meat products. The use of oat flour and bran has grown and contributed to disease control, mainly due to its high content of polysaccharides, soluble and insoluble fibers, proteins, minerals, and health-beneficial lipids (Reginatto et al., 2021; Howarth et al., 2021). Oats stands out among other cereals for their protein content and quality—varying from 12.40% to 24.50% in hulled grains—and higher percentage of lipids, ranging from 3.10% to 10.90%, with a predominance of unsaturated fatty acids (Hawerroth et al., 2013; Bouchard et al., 2022).

Oats have received attention for being recommended by doctors and nutritionists due to their nutritional characteristics, mainly regarding the content and quality of their proteins and fibers, including beta-glucans, which are responsible for reducing bad cholesterol (LDL), contributing to the reduction of cardiovascular disease risks (Pereira et al., 2020; Maximino et al., 2021). Beta-glucans are structural components of cereal cell walls. Consuming oats also assists in maintaining satiety for longer, reducing frequent food intake, thus contributing to a healthier diet. Consequently, the demand for foods with high nutritional quality and bioactive properties has been increasing, as people have focused on changing habits to improve their quality of life and reduce the occurrence of diseases. In this sense, the consumption of functional foods such as oats has become prominent in human nutrition due to their several benefits (Crestani et al., 2012; Toni et al., 2020; Pansera et al., 2021b).

3 INDICATION OF OAT SEEDING DENSITY

Increasing oat crop yields is essential, considering the market demand; however, this expansion depends on numerous factors, including the genetic performance of cultivars, management technologies, and favorable climate and soil conditions (Hawerroth et al., 2015; Schmidt et al., 2023).

The expected oat production depends on cultivation zoning, seeding density and spacing, plant nutrition, application of soil fertilizers and growth regulators, disease control, and meteorological factors during the crop cycle, such as air temperature and humidity, rainfall, radiation, photoperiod, and wind intensity (Scremin et al., 2023; Dornelles et al., 2023b).

Regarding seeding density, the Technical Guidelines of the Brazilian Oat Research Commission (2001; 2006; 2014; 2021) have recommended 200 to 300 viable seeds per square meter, with spacing between rows varying from 17 to 20 cm. This recommendation has been practiced since the 1990s, when oat crops became commercially significant for grain production (Silva et al., 2012; Dornelles et al., 2018). In this context, continuous genetic improvement in oats has altered the plant architecture, among other traits, shifting their biotype from tall plants with a late cycle and high straw-to-grain ratio into genotypes with plants smaller than one meter in height, shorter cycles, and larger caryopsis volumes in relation to the husk (Silva et al., 2015; Alessi et al., 2021). These changes can modify the response of cultivars to plant population, resulting in a shorter time for tiller production for rapid canopy closure and soil coverage, reducing the competitive ability of oats (Silva et al., 2012; Romitti et al., 2016).

Plant population is associated with the plant’s ability to produce fertile tillers, affecting the number of panicles produced per area (Valério et al., 2009; Castro et al., 2012). Additionally, rapid soil coverage through canopy closure can favor the use of light and nutrients, providing more effective control of weed species (Fleck et al., 2009; Lamego et al., 2013; Rosa et al., 2022). The plant population per area can affect the performance of oat crops intended for grain production and depends on several factors, such as genetic potential, solar radiation, water and nutrient availability, and the incidence of pests, diseases, and weeds (Abreu et al., 2006; Romitti et al., 2016).
4 INCREASING SEEDING DENSITY

Plant population is an essential factor for the expression of biomass and grain yield potentials (Ceccon, Grassi Filho, Bicudo, 2004; Dornelles et al., 2018). Several crops have already defined or are undergoing research studies to qualify the optimal seeding densities based on changes involving genetic and environmental factors. Moreover, increasing plant population by shortening spacing between rows or between plants in the rows can be an alternative for improving plant uniformity and grain yield (Momoh & Zhou, 2001; Romitti et al., 2016; Sangiovo et al., 2022; Rosa et al., 2023a; Rosa et al., 2023b).

High plant populations have favored soil coverage and reduced weed infestation in early maturation cultivars, as shown in research studies on wheat crops grown in different environments. Increasing seeding density from 100 to 200 plants m$^{-2}$ reduced weed dry matter by half and reduced the wheat grain yield loss from 23% to 17%, improving crop uniformity at harvest time (Lemerle et al., 2004; Silveira et al., 2010). Valério et al. (2008) found significant responses of wheat genotypes to increases in seeding density: those with high tillering subjected to high densities undergo greater competition for water, light, and nutrients, resulting in reduced grain yield and increased lodging (Ozturk et al., 2006). Equidistant distribution of wheat seeds at densities of 350 to 500 seeds m$^{-2}$ increased grain yield for different cultivars, and the yield increases with stability were obtained at higher seeding densities (Silveira et al., 2010; Valério et al., 2013).

Abreu et al. (2006) evaluated late-cycle oat genotypes and found a linear increase in biomass production and grain yield with increasing the population from 100 to 400 plants m$^{-2}$. Silva et al. (2015) highlighted that a seeding density exceeding those recommended by technical guidelines for oat crops can increase grain yield, provided lodging does not occur. Additionally, it benefits crop management regarding the control of weed species and maintenance of soil moisture due an increased vegetation cover.

Romitti et al. (2016) evaluated the white oat cultivars URS Taura and Brisasul and emphasized the need for investigations to determine seeding density recommendations, considering their evolution towards increasingly earlier cycles and changes in the species' morphological characteristics. The optimal seeding density for these cultivars to express their potentials for biomass production and grain yield was 500 seeds m$^{-2}$, regardless of the agricultural year. Furthermore, they highlighted that using the optimal seeding density can favor plant lodging in a soybean-oat rotation system; however, it was efficient in improving grain yield in a corn-oat system, with a significant reduction in lodging, despite a lower release of residual N.

Light interception by the canopy, as well as plant population and arrangement, in white oat crops depend on tillering capacity, plant height, number and distribution of leaves, degree of decumbency, shoot dry matter, and leaf area and angle (Fleck et al., 2009; Loro et al., 2022).

Corn is a crop species that does not produce tillers; thus, high corn yields are connected to genotype interaction and plant density. Almeida et al. (2000) reported that narrower planting spacing and higher seeding densities resulted in yield increases of over 20%. Resende (2003) reported that densities of 70,000 and 90,000 plants per hectare were effective in increasing grain yield compared to the plant density recommended by the corn technical committee (55,000 plants per hectare), regardless of the planting spacing. Von Pinho et al. (2008) found that increases in plant density result in increases in plant height and grain yield for corn crops.
5 TILLER UNIFORMITY AND SEEDING DENSITY

The asynchronous development of tillers is one of the issues connected to uniformity in oat and wheat crops; this condition can suppress or cause the emergence of late fertile tillers, resulting in uneven crop stands (Valério, et al., 2009; Bender et al., 2021). Pre-harvest desiccation using burndown herbicides is an alternative that has been used by farmers to quickly reduce grain moisture and minimize their deterioration in the field, ensuring a uniform harvest. This practice also promotes uniform maturation and faster harvesting, serving as a strategy to control challenging weeds in summer crops (Griffin; Boudreax; Miller, 2010; Pereira et al., 2015).

Pre-harvest desiccation should be carried out cautiously, as it can have negative effects on the physical and physiological quality of winter cereal seeds, reducing their germination potential (Bellé et al., 2014; Krenchinski et al., 2017). Furthermore, it involves herbicide applications when the plant is typically metabolically active, which can result in transport of chemicals to the grains, resulting in contamination of the harvested product; the worrying increase in the incidence of pesticide-related diseases in humans is attributed to the amounts of herbicides applied, especially glyphosate (Silva et al., 2011; Vargas et al., 2016). Seidler et al. (2019) emphasized the lack of research experiments evaluating the grain quality for human consumption based on the application of burndown herbicides, reinforcing the need for research on this topic in Brazil.

Adjusting seeding density to prevent the formation of late tillers or minimize the presence of tillers is a cost-effective, safe, and more sustainable alternative for achieving greater crop uniformity (Silva et al., 2012). In this context, studies on canola, a species with an indeterminate growth habit, have shown its plasticity and adjustable structures (Krüger et al., 2011a; Krüger et al., 2011b). Managing plant arrangement by reducing spacing between rows and increasing population density has been an alternative for increasing plant uniformity and yield for this species (Momoh & Zhou, 2001; Krüger et al., 2016). Some studies have shown that increasing plant density for canola crops tends to affect grain yield components, change oil content, decrease harvest index, and generate grain yield stability and uniformity, especially when the plants are evenly distributed (Leach et al., 1999; Angadi et al., 2003; Shahin & Valiollah, 2009).

Tourino et al. (2002) found changes in plant architecture and grain yield of soybean crops by changing the arrangement of plants, with a significant connection between genotype and changes in plant architecture.

The number of grains per area in corn crops was improved by reducing spacing between rows and increasing plant population, contributing to the formation of single, well-formed ears (Strieder et al., 2008; Carvalho et al., 2021). Coimbra et al. (2004) found that increasing the number of plants per unit area and grains per plant in canola crops is connected to grain yield and the generation of more uniform plants. Biomass production rate is decisive in defining seeding density, enabling the establishment of a canopy that favors light and nutrient utilization, associated with a greater uniformity of plants and grains (Fleck et al., 2009; Silva et al., 2012).

6 LODGING OF OAT PLANTS

Lodging is a phenomenon in which the plant loses its upright position, leans, and falls to the ground, resulting in bent plants and even stem breakage (Pinthus, 1973; Cruz et al., 2004; Cruz et al., 2005). Lodging affects grain yield and quality by bringing the panicle structure and grains into contact with the soil, increasing moisture and the occurrence of fungi, decreasing the product quality, and making commercialization unfeasible. Additionally, it poses challenges during harvest (Silva et al., 2012; Hawerroth et al., 2015; Krysczun et al., 2017). The occurrence...
of lodging depends on genetic factors and is influenced by external factors, such as wind, rain, soil, plant density, and cultural practices; oats are highly sensitive to this phenomenon. Lodging affects the plant's morphological structure, and the earlier it occurs, the greater its effect on reducing grain yield and quality. It can disrupt the movement of photoassimilates within the plant, resulting in losses, especially in grain size, and can affect the industrial quality of grains, mainly towards the end of the crop cycle (Silva et al., 2015; Trevizan et al., 2015; Romitti et al., 2017). The microclimate created by lodged plants can trigger grain germination when it occurs after the grain-filling stage, affecting grain and hectoliter weights, reducing yield and industrial quality, and generating risks of contamination by mycotoxin-producing fungi (Luche et al., 2012; Benin et al., 2012; Romitti et al., 2017).

Despite continuous genetic improvement in oats has significantly changing the plant architecture by reducing plant height and leaf area, issues related to lodging have not been fully addressed. Oats are the most lodging-sensitive cereal species, denoting a high priority for scientific and technological advancements to solve this issue (Hawerroth et al., 2015; Mantai, et al, 2015; Marolli et al., 2018). Cracking and lodging are complex phenomena, and their expression depends on genetic factors correlated with climate, soil, and cultural practices (Repke et al., 2012). Cultural practices include nitrogen fertilizer applications, which stimulate vegetative growth, and determination of plant density, as high densities tend to reduce stem diameter, resulting in less resistance and facilitating lodging (Kaspar et al., 2015, Scremin et al., 2017). Several studies have investigated the dynamics of cell wall composition in nodes and internodes, mainly cellulose, hemicellulose, and lignin contents, which are structural components associated with the mechanical strength of oat stems (Peng, et al., 2014).

7 TRINEXAPAC ETHYL AS GROWTH REGULATOR

The ineffectiveness in developing oat cultivars resistant to lodging in high-fertility soils, the use of high plant densities, and favorable conditions to oat development (Kong et al., 2013; Sinniah et al., 2012) has led to the development of technologies based on the application of growth regulators to minimize lodging occurrences (Hawerroth et al., 2015; Krysczun et al., 2017; Marolli et al., 2018).

The use of growth regulators, such as trinexapac-ethyl, to minimize lodging occurrences has been evaluated in rice (Arf et al., 2012), wheat (Schwerz et al., 2015), and oat (Marolli et al., 2018) crops. Growth regulators are chemical compounds that reduce stem length by obstructing the gibberellic acid biosynthesis, making the plant more adapted and efficient (Kaspar et al., 2015; Hawerroth et al., 2015). The application of growth regulators is restricted to white oat cultivars with a tendency to lodging that are grown in high-fertility soils (natural or fertilized), as well as to crops with a history of high yield and lodging occurrences (Souza et al, 2021).

Kaspar et al. (2015) found that the application of increasing rates of trinexapac-ethyl to white oat plants resulted in decreased plant height and progressive control of lodging. The product showed improvements in crop yield at a rate of 100 g per hectare. However, studies have shown negative impacts of the product on white oat seeds, affecting germination, vigor, establishment, and early maturation. Guerreiro and Oliveira (2012) found that increasing the application rate of this growth regulator to oat crops decreased plant height and shortened peduncle length; however, higher trinexapac ethyl rates had unfavorable impacts on plant yield components.

The use of growth regulators to prevent lodging in wheat (Triticum aestivum) crops is well-established, without resulting in decreased yields (Espindula et al., 2010; Pagliosa et al., 2013). Trinexapac-ethyl has shown efficacy in reducing plant height, improving leaf structure, and increasing stem diameter, resulting in reduced lodging, optimizing solar radiation capture
and, consequently, increasing the crop yield (Zagonel & Fernandes, 2007). Pricinotto et al. (2015) evaluated the agronomic efficiency of this growth regulator in corn cultivars; the product was effective in reducing plant height, allowing the use of higher plant densities. Carvalho et al. (2013) evaluated the agronomic efficiency of a growth regulator in soybean crops and found significant results, with increases in production parameters compared to the control. Souza et al. (2013) evaluated a growth regulator in soybean crops and found that it can make plant architecture more erect and more tolerant to lodging, providing greater grain yield potential.

Although the efficiency of trinexapac-ethyl in controlling lodging in oat plants has been proven, this chemical compound causes high stress to plants when applied under low water or high temperature conditions; therefore, its use is not recommended under conditions of water deficit, frost occurrence, or high temperatures (Souza et al., 2021; Marolli et al., 2018; Marolli et al., 2021). Furthermore, it is a synthetic chemical compound with high toxicity to the environment. According to the Brazilian Ministry of Agriculture, Livestock, and Supply, trinexapac ethyl is classified as a synthetic growth regulator with Toxicological Class IV (slightly toxic to humans) and Environmental Hazard Class II (dangerous to the environment). It is a relatively expensive product, with a market value of approximately 100 Reais (BRL) per liter; the recommended rate for cereals ranges from 250 to 400 mL ha⁻¹ (Indicações Técnicas Para a Cultura Da Aveia, 2021).

8 CALCIUM AND POTASSIUM-BASED ORGANOINERAL FERTILIZER

Field studies with soybean and wheat crops have shown that an organomineral product containing calcium and potassium, used as a foliar fertilizer, presented promising results as growth regulator and lodging controller. Considering the interests of oat growers and the company that supplies this product in the region, it may be validated as a cheaper and more sustainable alternative compared to trinexapac-ethyl. This possibility can validate this technology for oat crops to avoid lodging issues, ensuring grain yield and quality with lower environmental impacts. According to the regulation (IN) DAS No. 23 of 2005, Article 1, an organomineral fertilizer is "the product resulting from the physical mixture or combination of mineral and organic fertilizers" (MAPA, 2009; Basso et al., 2022). Combining organic residues with mineral fertilizers is an option that has been used to generate organomineral fertilizers with characteristics of both organic and mineral fertilizers. These formulations vary and are affected by the amounts of organic and mineral fertilizers used in their composition. Nevertheless, organomineral fertilizers have some similar characteristics, such as gradual nutrient release and promotion of increases in agronomic efficiency, correction of soil acidity, and improvement of soil physical characteristics (Kiehl, 2008; Anup et al., 2017).

This product contains potassium, the second most required mineral nutrient in quantity by plant species, following nitrogen. Potassium is absorbed by plant roots in ionic form (K⁺). It is the most abundant macronutrient in plants and moves mainly through diffusion. The amount of potassium (K⁺) absorbed by plants from the soil solution depends on the species and developmental stage (Meurer, 2006; Prado, 2008; Fagan et al., 2016). Although most soils contain significant potassium contents, only a small percentage (approximately 2%) is available to plants during their development stage (Lopes; 1998). Potassium contributes to the reduction of disease and pest incidences, increasing photosynthetic activity and, consequently, leaf size, and allowing greater movement of assimilates to the grains (Prabhu et al., 2007).

Potassium is an essential macronutrient that assist in plant growth and development, performing several physiological functions, including the maintenance of cellular osmotic pressure, improvement of photosynthetic assimilation and nutrient absorption, and assistance in transporting water by controlling stomatal opening and closing (Prajapati & Modi, 2012; Etesami, Emami & Alíkhani, 2017; Hu et al., 2016; Sardans & Peñuelas, 2021). It also
contributed to the activation of several enzymes in plants and animals that are responsible for energy metabolism, starch synthesis, nitrate reduction, photosynthesis, and sugar degradation (Almeida et al., 2015; Mikkelsen, 2017; Souto et al., 2018; Kumar et al., 2020). Potassium deficiency can reduce photosynthetic CO2 fixation and the transport and use of assimilates, cause membrane and chlorophyll degradation, and hinder cell wall synthesis and cell turgor, making plants susceptible to lodging when subjected to strong winds, rain, or excessive nitrogen fertilization. Therefore, applying adequate amounts of potassium for plant development can promote cell rigidity (Façanha, Canellas & Dobbs, 2008; Zaheri et al., 2015; Dahiya et al., 2018; Hasanuzzaman et al., 2018). Plants with potassium deficiency are light-sensitive and exhibit chlorotic and necrotic symptoms, reducing the photosynthetically active area and, consequently, the yield of crop species (Hu et al., 2016; Hasanuzzaman et al., 2018; Qi et al., 2019).

Calcium is also a component of this organomineral product. It is generally found in low concentrations in acidic soils, which are common in Brazil, and in soils with primary materials composed of dolomite, calcite, apatite, and calcium feldspars. Clayey soils with high CEC (cation exchange capacity) have higher calcium content. The two plant's mechanisms for calcium absorption are mass flow and root interception; calcium is absorbed in the form of Ca+2. Approximately 60% of the total cellular Ca is found in the cell wall as Ca pectate, also found in the middle lamella (Paiva et al., 2009). This nutrient participates in structural and osmotic functions and as a cytoplasmic messenger (White & Doebley, 1998). In plants, Ca is involved in cell division and elongation and is an important structural component of the middle lamella in the form of Ca pectates, which have a cementing action, adhering firmly to cell walls (Epstein & Bloom, 2004). Therefore, Ca affects the integrity and stability of membranes and strengthens the cell wall structure (Dordas 2008; Caffall & Mohnen, 2009; Carpita et al., 2015).

Calcium protects membranes and cell walls and signals responses to biotic or abiotic stress conditions (Yamamoto et al, 2011). Plant cells develop primary and secondary cell walls and a middle lamella that connects the cell walls of adjacent cells in a tissue (Paiva et al., 2009); these components are responsible for promoting the structural strength of tissues and high turgor pressures in cell growth processes (Alberts et al., 2017). The matrix of structural constituents of cell walls and the middle lamella consists of pectic polysaccharides, cellulose, hemicellulose, and proteins, which vary in content and chemical structure depending on the species, tissue, and developmental stage (Paiva et al., 2009; Alberts et al., 2017). Lignin is the last constituent forming cell walls, interspersing the matrix of pectic polysaccharides and providing greater rigidity, impermeability, and resistance (Cesarino et al., 2012). Contrastingly, secondary cell walls formed after lignin formation are a resistant and enduring structural barrier (Nafisi et al., 2015). Thus, the application of Ca fertilizers can promote the development of plant tissues with well-structured cell walls and middle lamellae, increasing plant strength. Indirect functions of Ca include improvements in nodulation for biological N fixation, assistance in protein synthesis and carbohydrate transfer, stimulation of microbial activity, increases in molybdenum availability, and absorption of other nutrients.

9 FINAL CONSIDERATIONS

Lodging, caused by the difficulty or interruption in sap flow to the reproductive structures, leads to losses in grain yield and quality, directly impacting the product's market value. Although oat breeding programs have developed cultivars with reduced plant height, challenges in preventing lodging persist, indicating issues in understanding the phenomenon and in genetic progress towards mitigating this problem.

Despite the apparent potential of using trinexapac-ethyl as a growth regulator, it poses risks of phytotoxicity and restrictions due to weather conditions, air temperature, and soil
moisture. In this context, several studies have indicated that potassium and calcium favor cell wall rigidity, potentially contributing to oat stem strength. However, research results on the use of calcium and potassium-based organomineral foliar fertilizers to control oat lodging are still inconclusive.

Benefits of increased seeding density for increasing grain yield and quality have been found for several crop species, reinforcing the need for adapting seeding density for oat crops grown in the largest oat producing regions in Brazil based on current short-cycle and low-height cultivars. Increasing seeding density can also result in greater competitive ability, straw volume on the soil, and plant uniformity by reducing the application of burndown herbicides, provided it does not cause lodging and reduce grain yield.

Considering the current scenario, efforts to increase crop yields and food security while caring for natural resources and biodiversity are essential. However, it requires a broader and systematic approach, encompassing the environment, technologies, and society, highlighting the importance of this research, which is consistent with UN SDG 2 of the 2030 Agenda, Zero Hunger and Sustainable Agriculture.

REFERENCES


Seeding Density and Foliar Application of a Calcium and Potassium-Based Organomineral Fertilizer in Oat Crops


Seeding Density and Foliar Application of a Calcium and Potassium-Based Organomineral Fertilizer in Oat Crops


Seeding Density and Foliar Application of a Calcium and Potassium-Based Organomineral Fertilizer in Oat Crops


Seeding Density and Foliar Application of a Calcium and Potassium-Based Organomineral Fertilizer in Oat Crops


