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ORIGINAL ARTICLE

Silicon ameliorates wheat technological quality under biotic stress

Leandro José Dallagnol[1] · Paulo Cesar Pazdiora[1] · Martha Zavariz de Miranda[2] · Pihetra Oliveira Tatsch[2] · Andrea Elizabeth Román Ramos[1,3] · Jeronimo Viera de Araujo Filho[1,4]

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Abstract

Silicon applied in the soil is an alternative for wheat disease management, but there is no information about its effects on wheat technological quality. For this purpose, we collected wheat grains from plants of two cultivars differentially susceptible to diseases, grown in soil amended or not with silicon, and treated or not treated with fungicide. The results showed that greater severity of tan spot (*Pyrenophora tritici-repentis*) and Fusarium head blight (*Fusarium graminearum* species complex) compromised the grain quality and negatively altered wheat flour color, gluten levels, and the alveograph and farinograph parameters. Silicon fertilization had little effect on the wheat technological quality under lower disease intensity, but under higher disease intensity, it reduced the damage caused by pathogens, directly or indirectly influencing the flour yield, grain falling number, gluten strength, dough tenacity and tenacity/extensibility ratio, and elasticity index. The results of this study show for the first time the effect of silicon fertilization on wheat technological quality as a feasible alternative for inclusion in integrated disease management of wheat to maintain flour quality despite biotic stress.

Keywords Flour quality · Fusarium head blight · Physicochemical analyses · Rheological tests · Tan spot

Introduction

Wheat (*Triticum aestivum* L.) is cultivated widely and is the world's most consumed cereal (FAO 2020; Li et al. 2015). In Brazil, tan spot, caused by *Pyrenophora tritici-repentis* (Died.), and Fusarium head blight (FHB), caused by the *Fusarium graminearum* species complex, are among the main diseases affecting wheat (Joris et al. 2022).

✉ Leandro José Dallagnol
leandro.dallagnol@ufpel.edu.br

1 Laboratório de Interação Planta Patógeno, Departamento de Fitossanidade, Faculdade de Agronomia Eliseu Maciel, Universidade Federal de Pelotas, Capão do Leão, Rio Grande Do Sul 96160-000, Brazil

2 National Wheat Research Center (Embrapa Trigo), Brazilian Agricultural Research Corporation, P.O. Box 78, BR 285, km 294, Passo Fundo, Rio Grande Do Sul 99050-970, Brazil

3 Laboratory of Phytopathology, Agricultural Sciences Natural Resources and the Environment Faculty, Bolivar State University, EC020150, Guaranda, Ecuador

4 Laboratório de Nematologia, Departamento de Fitossanidade, Faculdade de Agronomia Eliseu Maciel, Universidade Federal de Pelotas, Capão do Leão, Rio Grande do Sul 96160-000, Brazil

Pyrenophora tritici-repentis affects leaves and spikes and, during the attack, produces toxins that compromise the photosynthetic machinery due to the disruption of photosystems and photooxidation of chlorophyll (Pandelova et al. 2012). As a result, the disease reduces the number of grains and their quality, due to shriveling and lower specific weight, causing yield losses of up to 48% (Rees and Platz 1983; Ronis et al. 2009). The *Fusarium graminearum* species complex causes premature senescence of the entire spike or a portion of it, which leads to the formation of shriveled grains, resulting in yield losses of up to 50%. It also causes a risk of contamination by a wide assortment of mycotoxins, the most common being deoxynivalenol (Haidukowski et al. 2005; McMullen et al. 2012).

Genetic factors, environment, and crop management affect the physical (size and shape) and compositional properties of wheat grains, influencing the milling yield and technological quality of flour. Depending on the flour-use requirements, the physical and compositional properties of the grains must satisfy various minimum requirements. In particular, shriveled grains are undesirable because they are associated with low flour yield (Gooding and Davies 1997; Nuttall et al. 2017). Wheat flour quality depends on the respective levels of several components, including starch, gluten and nongluten proteins, lipids, non-starch carbohydrates, and minerals (Graybosch et al. 1996), which interact during the mixing and baking processes. Furthermore, several flour parameters are also impaired by the pathosystems affecting wheat as well as the management strategies adopted (Matzen et al. 2019). The measures adopted to control wheat disease need to be effective in controlling the pathogens while also maintaining the grain technological quality.

For tan spot and FHB, despite the use of healthy seeds, crop rotation, and tillage (when applicable) to reduce pathogen inoculum, the main strategies used for the management of these diseases are the choice of resistant cultivars and application of fungicides. Since only cultivars with moderate resistance to FHB and tan spot are available to wheat growers, fungicidal treatments are employed to counteract the disease symptoms and improve the grain-filling process and thus to maintain the flour quality (Berdugo et al. 2012; Blandino and Reyneri 2009; Fleitas et al. 2018; Rodrigo et al. 2015). However, application of fungicides for disease management increases costs, and their efficacy can be extremely variable, often insufficient to control some pathogens, such as *F. graminearum* (D'Angelo et al. 2014). Furthermore, there is the risk of grain contamination by the fungicide (Da Luz et al. 2017).

An increasingly common strategy is to enhance the defense of plants against pathogens. In this sense, soil fertilization with calcium silicate, a source of soluble silicon (Si), is one of the most studied and has shown effectiveness in reducing several wheat diseases (review by Rodrigues et al. 2015; Debona et al. 2017; Coskun et al. 2019; Dallagnol et al. 2020). In wheat, a three-year field experiment showed that Si amendment reduced tan spot and FHB severity, increasing the grain yield by up to 1000 kg/ha (Pazdiora et al. 2021; 2023), but the authors only superficially mentioned the grain quality.

Many other studies have investigated the effects of fertilization, especially with nitrogen, and application of fungicides on the management of diseases and their relation to wheat flour quality (Castro et al. 2018; Dimmock and Gooding 2002; Fleitas et al. 2018; Matzen et al. 2019; Ruske et al. 2003). However, to the best of our knowledge, no previous study has investigated the effect of Si on different parameters of wheat technological quality. Since Si application is a new alternative for management of wheat diseases, it is necessary to learn the impact of this element on wheat quality. The hypothesis of this study was that increasing the supply of Si to wheat plants would reduce the disease intensities, increasing the technological quality of grains.

The objective of this study was thus to evaluate the effect of calcium silicate fertilization (Si source) on leaf and spike disease and on technological quality (physicochemical and rheological analyses) of wheat grains. For this, we compared calcium silicate fertilization to limestone fertilization for two wheat cultivars with different levels of resistance to leaf and spike diseases. All treatments were complemented with one or two applications of fungicide on the aerial part of the plants.

Material and methods

Study site, agronomy, and treatments

Two field experiments (2016 and 2017 crop seasons) were conducted at the Palma Agriculture Center (31° 48′ 06.4″ S, 52° 30′ 18.6″ W), belonging to Federal University of Pelotas. The wheat cultivars used were "TBIO Toruk" (Biotrigo®) and "TBIO Sossego" (Biotrigo®), with contrasting disease resistance, the former being more susceptible to tan spot and FHB than the latter (Joris et al. 2022).

The physicochemical characteristics of the soil were previously described by Pazdiora et al. (2021). The concentration of available Si (extracted with 0.01 M $CaCl_2$) was 8.0 $mg.dm^{-3}$. Calcium silicate (Agrosilício®, Agronelli Insumos Agrícolas, Uberaba, Brazil), composed of 10.5% silicon, 25.0% calcium, and 6.0% magnesium, was the source of Si and was applied at a rate of 4.0 t ha^{-1} $year^{-1}$. Extra-fine limestone (Dagoberto Barcellos, Caçapava do Sul, Brazil), composed of 26.5% calcium and 15.0% magnesium, was applied at a rate of 3.3 t ha^{-1} $year^{-1}$ in the control treatments to standardize the soil pH and the amount of calcium and magnesium supplied to the plants in the calcium silicate treatment. In both seasons, calcium silicate (+ Si) or limestone (− Si) was incorporated in the soil by harrowing 30 days before sowing. Soil and plant tissue concentration of Si were determined according to Korndorfer et al. (2004). In 2016, the soil concentrations of calcium (Ca^{2+}) were 4.6 and 4.4 $cmolc.dm^{-3}$ and of Si were 14 and 8 $mg.dm^{-3}$, respectively, for + Si and − Si treatments. The Si concentrations in leaves and spikes, respectively, were 14.2 and 6.7 g kg^{-1} for + Si and 11.8 and 5.8 g kg^{-1} for − Si. In 2017, the soil concentrations of Ca^{2+} were 6.6 and 5.6 $cmolc.dm^{-3}$, and the concentrations of Si were 18 and 8 $mg.dm^{-3}$, respectively, for + Si and − Si treatments. The Si concentrations in leaves and spikes, respectively, were 24.7 and 8.6 g kg^{-1} for + Si and 13.4 and 5.9 g kg^{-1} for -Si (Pazdiora et al. 2021).

Plots measuring 10.5 m^2 were sown with a seed drill (Semeato SHP model; 9 rows, 0.17 m row spacing) at a density of 300 $seeds.m^{-2}$. At the time of sowing, 300 kg ha^{-1} of chemical fertilizer (5–20-20: nitrogen, phosphorus, potassium) was applied. Total nitrogen (granular urea, N, 45%) input was 100 kg N ha^{-1} yr^{-1}, and 15% of the total N was applied as basal fertilizer and the remainder (85%) as top dressing at the phenological stages of tillering and stem elongation (Zadoks growth stages (GS) 25 and 37). Iodosulfuron-methyl-sodium (Hussar®; Bayer, 100 g c.p. ha^{-1}) and imidacloprid beta-cyfluthrin (Connect®; Bayer, 500 mL c.p. ha^{-1}) were used to control weeds and insects, respectively, as necessary to ensure that these factors would not influence the outcome of the experiment. The fungicide premix Fox® (Bayer, 0.5 c.p. ha^{-1}), consisting of prothioconazole (150 $g.L^{-1}$; triazolinthione) + trifloxystrobin (175 $g.L^{-1}$; strobilurin), was applied at the stem elongation stage (GS32/GS33) (one-spray treatment) or at both the stem elongation and flowering stages (GS60) (two-spray treatments). The fungicide was applied using CO_2 pressure, with a four-tip nozzle (TTJ60 11,002; Teejet®), delivering 200 L ha^{-1}.

Disease assessment occurred from seedling emergence to harvest. The main diseases during the crop cycle were tan spot and FHB. The assessment of tan spot severity was conducted from tillering (GS30) to early dough (GS83), and when applicable, the area under disease progress curve (AUDPC) was determined as described by Pazdiora et al. (2018). The severity of FHB was determined at the early dough stage according to the scale proposed by Stack and McMullen (2011).

Experimental design

The experimental design was a three-way (2 × 2 × 2) factorial scheme in a random block with four replicates. The factors were two silicon treatment (plants not supplied (− Si) or supplied (+ Si) with silicon source), two wheat cultivars (TBIO Toruk and TBIO Sossego), and two fungicide treatments (one or two fungicide applications). The experiment was conducted in the 2016 and 2017 crop seasons.

Grain harvesting and measurement of moisture

Wheat was hand harvested and threshed in a mechanical grain thresher (EDA, model TR. PARCELA) as described in Pazdiora et al (2021). The grain moisture content of a representative subsample was measured with a moisture tester (Gehaka Agri G600).

Wheat technological quality

The wheat quality was evaluated by physicochemical and rheological analyses. The tests performed according to AACC (2010) were hectoliter weight (*HW*) (Dalle Molle scale, Brazil—Method 55–10.01) with results expressed in kg hL^{-1}; grain falling number (*GFN*), which is an indirect measure of alpha-amylase activity (Falling Number System, Perten, Sweden—Method 56–81.03); flour yield (*FY*) after grain tempering to 14% moisture for 16–24 h followed by milling (Brabender Quadrumat Senior experimental mill, Germany—Method 26–10.02); gluten index (*GI*), wet gluten (*WG*), and dry gluten (*DG*) (Glutomatic System, Perten, Sweden—Method 38–12.02); alveography and its parameter tenacity (*P*) or maximum pressure, dough extensibility (*L*), tenacity/extensibility ratio (*P*/*L*), swelling index (*G*), dough strength (*W*) or dough deformation energy, and elasticity index (*Ie*) (Chopin Alveograph, France—Method 54–30.02); and farinography, using a 50 g bowl, considering the parameters: water absorption (*WA*), dough development time (*DDT*), dough mixing stability (*STB*), and mixture tolerance index (*MTI*) (Brabender Farinograph, Germany -Method 54–21.02). The other parameters tested were thousand kernel weight (*TKW*) (as described by Shuey and Gilles 1972) and wheat flour color, carried out with a colorimeter (using D_{65} illuminant, Ø 50 mm measurement area, and 10º viewing angle), with results expressed in the CIEL*a*b* system, considering the parameter lightness (L^*; 0: dark, 100: white), chromaticity coordinates: a^*(− 60: green, + 60: red) and b^* (− 60: blue, + 60: yellow), chroma (C^*) or color intensity, and hue (h^*) or color tonality (CR-410 Chroma Meter, Minolta, Japan).

Data analysis

The data from the two experiments (2016 and 2017 crop seasons) were analyzed separately because the year was a significant factor. All statistical analyses were conducted using R version 4.1.1 (R Development Core Team 2021) and various packages, such as FactoMineR and lavaan (Lê et al. 2008; Rosseel 2012). First, aiming to avoid redundancy, we subjected the data set to principal component analysis (PCA) to select dependent variables correlated (> 0.70) with the first two principal components (PC1 and PC2) (inertia > 70%). The selected variables were subjected to analysis of variance (ANOVA) of a three-way factorial design. Bartlett's test was applied and q-q plots were produced for checking data normality. When applicable, transformations were performed to meet the assumptions of the ANOVA using the Box-Cox function. Finally, when silicon effects were significant, we performed pathway analysis (mediation analysis to test the direct and indirect effects). To verify the effect of diseases on wheat technological quality, we calculated Pearson's linear correlation coefficients for all variables with each disease severity in each crop season.

Results

Intensity of diseases versus wheat technological quality

The main diseases occurring during both crop seasons were tan spot and FHB, and the highest severity was recorded in − Si plants of the cultivar TBIO Toruk treated with fungicide only at stem elongation (Fig. 1). In 2016, FHB severity reached 8.7% while the tan spot severity reached 7.5% at the end of the crop season. In 2017, the diseases occurred in much higher severity, reaching 16.6% for FHB, while the

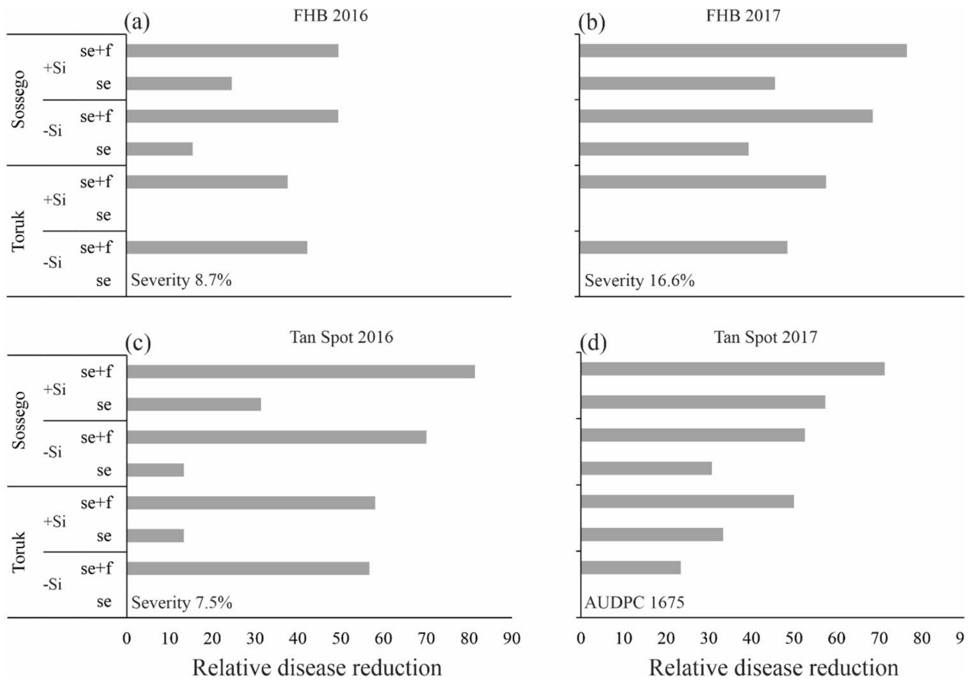

Fig. 1 **a–d** Relative disease severity reductions by silicon and fungicide application on wheat cultivars TBIO Toruk and TBIO Sossego grown in soil amended with extra-fine limestone (– Si) or calcium silicate (+ Si) and treated with fungicide at the stem elongation stage (se) or at stem elongation and flowering stages (se + f) in the 2016 and 2017 crop seasons. The relative disease reduction was calculated based on the higher disease severity or AUDPC, which occurred on the – Si plants of TBIO Toruk treated with fungicide at stem elongation

tan spot occurred since the stem elongation stage, resulting in an AUDPC of 1675 at the end of the crop cycle. FHB was reduced mainly by fungicide treatment at flowering and by genetic resistance (TBIO Sossego), but silicon amendment in the soil improved the fungicidal and genetic control (Fig. 1a, b). For tan spot, the effect of Si was more evident, reducing disease severity in both cultivars, regardless of crop season (Fig. 1c, d). The greatest tan spot reduction was obtained by fungicidal treatment in both cultivars on plants supplied with Si.

FHB and tan spot affected several wheat technological quality parameters. The Pearson correlation analysis indicated that in 2016, the main variables positively affected by both diseases were *GI*, *Ie*, and *DDT*, while negative correlation was observed with *HW* and *W* (Fig. 2). In 2017, almost all wheat technological quality parameters were affected, mainly by tan spot, but FHB also affected several quality parameters (Fig. 2). Tan spot and FHB had negative correlations with *HW*, *P*, *P*/*L*, *GFN*, *a**, *WA*, and *WG*, while positive correlations were observed with *G*, *b**, *C**, *h**, and *GI* (Fig. 2). For tan spot, negative correlations also occurred with *Ie*, *DG*, and *GFN* (Fig. 2).

Treatments and wheat technological quality

The PCA indicated that several variables were highly intercorrelated, showing redundancy, which allowed us to reduce the number of variables analyzed (supplementary information). The selected variables included the results of some of the grain quality tests (*TKW*, *FY*, *GFN*), wheat flour color (*L**), and alveograph parameters (*W*, *P*, *P*/*L*, *G*, and *Ie*). In the 2017 crop season, *TKW* and *G* were not selected by PCA, but we included these data in the graphs to allow comparison between years. Variables not selected are reported in the supplementary information.

The cultivar and the two fungicide applications had significant effects ($P < 0.05$) for *TKW*, *FY*, and *GFN* (Table S1; Fig. 3a–f). In both crop seasons, *TKW* and *FY* were higher on TBIO Toruk and for plants with two fungicide application, while *GFN* was higher on TBIO Sossego. However, in 2017, besides cultivar, the number of fungicide applications, the silicon supply (+ Si) in the soil, and some factor interaction were also significant ($P < 0.05$) (Table S1). Silicon application resulted in higher *TKW* and *FY*, especially in TBIO Toruk plants treated with fungicide at stem elongation (Fig. 3b, d). For *GFN*, in + Si plants, an increase in the value occurred for TBIO Toruk with two fungicide applications, but a reduction was recorded in TBIO Sossego plants, regardless of fungicide application.

The flour color parameter *L** was affected mainly by the cultivar in both crop seasons and to a lesser extent, by fungicide treatment and silicon application or their interactions (Table S1). In general, the flour of TBIO Toruk was lighter (higher *L** value) than that of TBIO Sossego (Fig. 3g, h). Silicon application only increased the *L** value of TBIO Sossego plants in 2016 (Fig. 3g), yielding whiter flour. In general, two fungicide sprays increased *L**, especially in – Si plants, regardless of cultivar.

With regards to the alveograph parameters, cultivar and fungicide treatments were the most influential in both crop seasons, but several factor interactions were also significant, especially in 2017 (Table S1). The values of *W*, *G*, and *Ie*

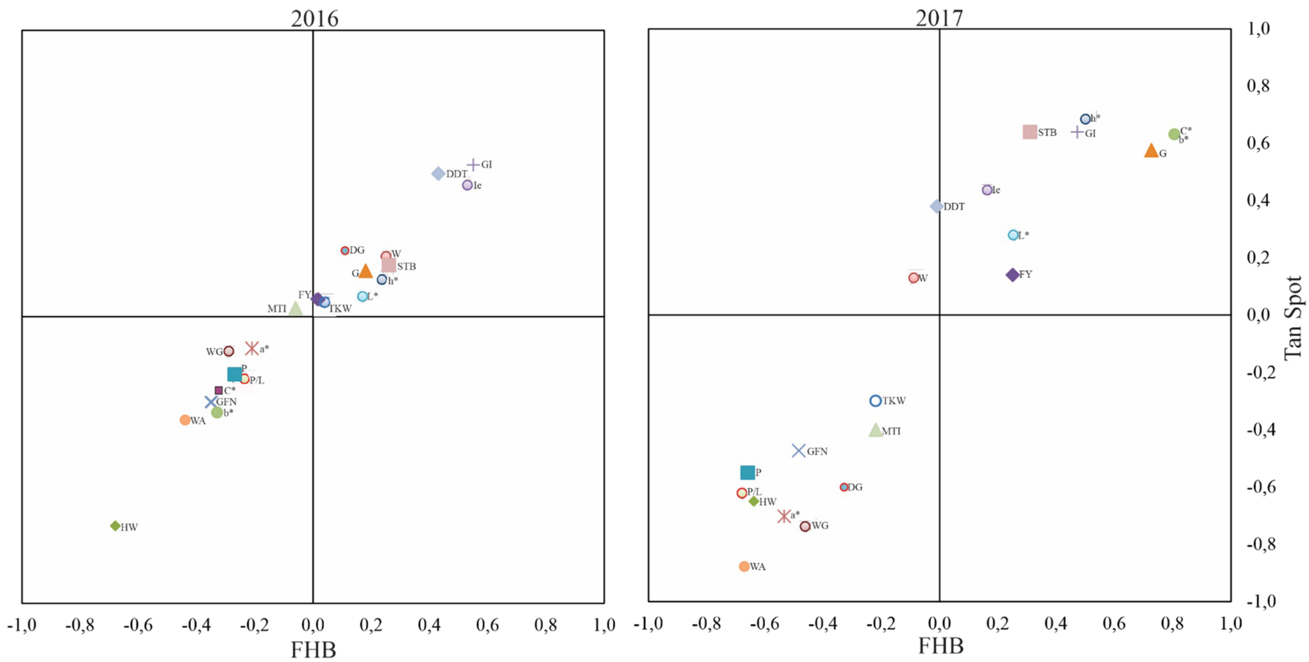

Fig. 2 Correlation analyses for Fusarium head blight (FHB) and tan spot with thousand kernel weight (*TKW*); hectoliter weight (*HW*); flour yield (*FY*); grain falling number (*GFN*); wheat flour color parameters: lightness (*L**), chromaticity coordinates (*a** and *b**), chroma (*C**), and hue (*h**); gluten parameters: gluten index (*GI*), wet gluten (*WG*), and dry gluten (*DG*); alveograph parameters: gluten strength (*W*), tenacity (*P*), tenacity/extensibility ratio (*P*/*L* ratio), swelling index (*G*), and elasticity index (*Ie*); and farinograph parameters: water absorption (*WA*), dough development time (*DDT*), dough stability (*STB*), mixing tolerance index (*MTI*) for two wheat cultivars (TBIO Toruk and TBIO Sossego) under two soil amendments (– Si: extra-fine limestone or + Si: calcium silicate), and two fungicide treatments (one or two sprays)

were higher for TBIO Toruk, while *P* and *P*/*L* were higher for TBIO Sossego (Fig. 4a–j).

Silicon supply affected *W* (reduced) (Fig. 4a), *P* (reduced) (Fig. 4c), *G* (reduced) (Fig. 4g), and *P*/*L* (increased) (Fig. 4e) in 2016 for the cultivar TBIO Sossego. In the 2017 crop season, silicon supply reduced *W* (Fig. 4b), *P* (Fig. 4d), and *Ie* (Fig. 4j) and increased *G* (Fig. 4h), especially in plants of TBIO Toruk treated with fungicide at stem elongation, in comparison to – Si plants. In this same crop season, an increase in *P* (Fig. 4d) due to silicon supply was recorded on TBIO Sossego plants treated with two fungicide sprays.

Two fungicide applications significantly altered some parameters (*W*, *P*, *P*/*L*, *G*, and *Ie*), but its effects were dependent on interaction with cultivar or silicon amendment in the soil (Fig. 4a–j). In 2016, + Si plants of TBIO Sossego with two fungicide applications had reductions of *P*/*L* (Fig. 4e) and *Ie* (Fig. 4i), compared to one fungicide application. For TBIO Toruk, two fungicide applications reduced the *Ie* value regardless of silicon supply. In the 2017 season, two fungicide applications on TBIO Sossego plants increased *W* (Fig. 4b), *P* (Fig. 4d), *P*/*L* (Fig. 4f), and *Ie* (Fig. 4j), regardless of Si supply, while *G* (Fig. 4h) was lower compared to one fungicide application. For + Si TBIO Toruk plants, two fungicide applications increased *P*, *P*/*L*, and *Ie* but reduced *G*, compared to one fungicide spray; while on – Si plants with two fungicide applications, reduction of *W*, *P*, and *Ie* occurred in comparison with one application.

In the 2016 crop season, through path analysis, we did not observe an indirect effect of tan spot reduction by silicon on the *P*/*L* ($P = 0.476$) and *G* ($P = 0.521$) values. On the other hand, in the 2017 crop season, there was an indirect effect of tan spot reduction by silicon on *FY* ($P = 0.008$), *GFN* ($P = 0.00$), and *P* ($P = 0.00$).

Discussion

The disease management measures employed during a crop cycle can alter some parameters of wheat technological quality. Indeed, the employment of different cultivars with varying susceptibility to diseases is a source of variation, but the effect on flour quality parameters is also dependent on the management used in the field, such as nutrient status of the plant and fungicide application (Hasniza et al. 2014). In this context, Si has emerged as a mineral element that reduces severity of several diseases in wheat, such as blast, FHB, powdery mildew, tan spot, and spot blotch (Dorneles

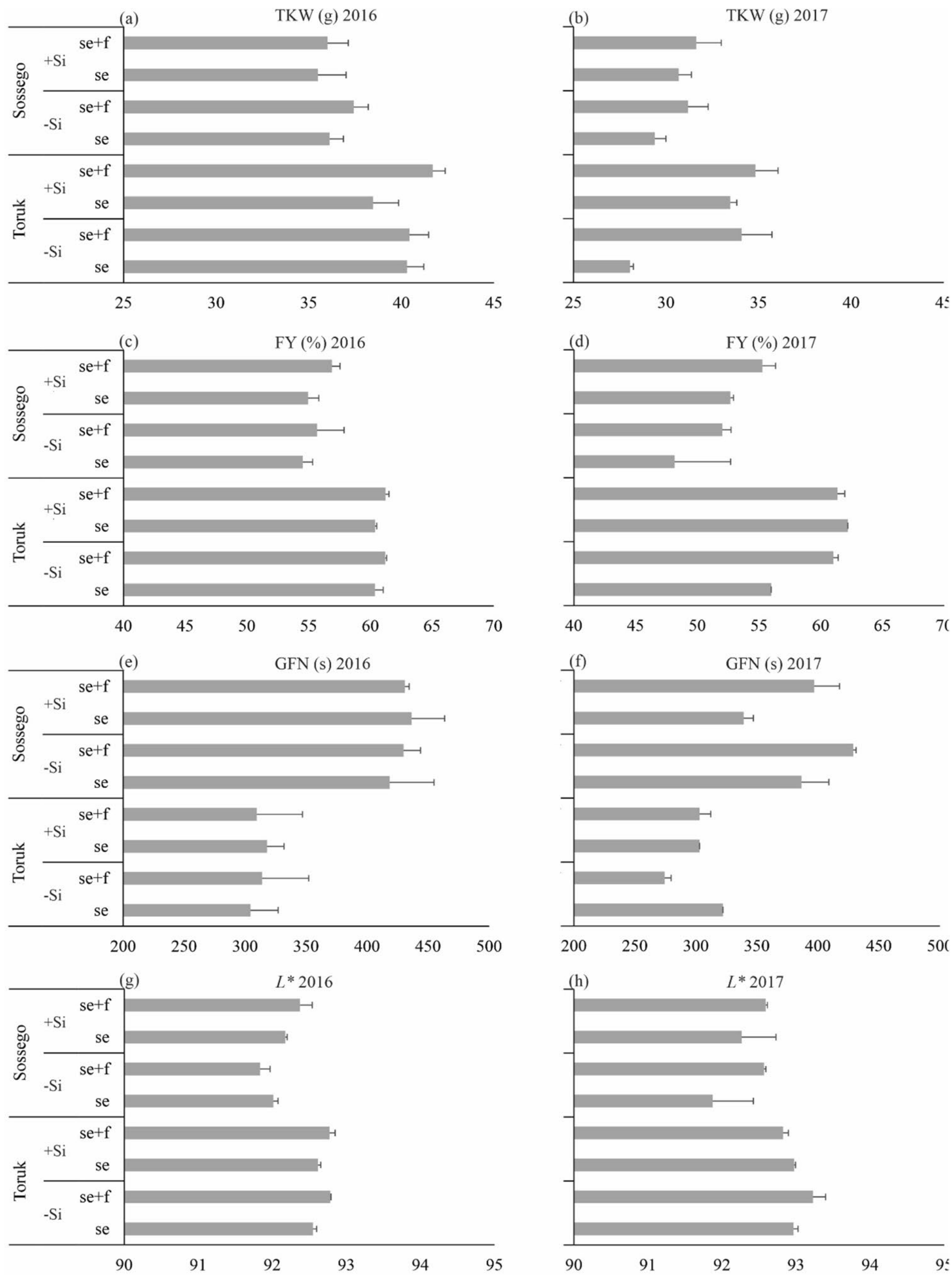

Fig. 3 Thousand kernel weight (*TKW*) (**a** and **b**), flour yield (*FY*) (**c** and **d**), grain falling number (*GFN*) (**e** and **f**), and lightness (*L**: 100 white; 0 black) (**g** and **h**) of grains of wheat cultivars TBIO Toruk and TBIO Sossego grown in soil amended with extra-fine limestone (− Si) or calcium silicate (+ Si) and treated with fungicide at the stem elongation stage (se) or at stem elongation and flowering stages (se + f) in the 2016 and 2017 crop seasons. The error bars represent the standard deviation of the means

et al. 2018; Dallagnol et al. 2020; Pazdiora et al. 2021; Rodrigues et al. 2015), indicating its effectiveness as a strategy to manage diseases in the field. However, for Si fertilization to be feasible, wheat technological quality also needs to be preserved alongside disease control. This study showed that silicon has little effect on wheat technological quality under low stress, but under high biotic stress, Si alleviated the damage caused by pathogens, keeping the flour quality parameters near the expected values for each cultivar. Differences in technological quality among wheat cultivars and fungicide treatments have been reported previously (Fleitas et al. 2018; Nuttall et al. 2017; Wang et al. 2004), but our study is the first to report the effects of silicon on flour quality parameters.

The weather conditions and the monocropping system in the field where the experiment was conducted were more favorable to disease development in 2017 compared to 2016 (Pazdiora et al. 2021), resulting in higher FHB and tan spot severities. Pearson's correlation analysis clearly showed that the increase in the severity of FHB and tan spot resulted in a high degree of damage to grain quality and flour parameters. In the 2016 crop season, the main disease affecting wheat technological quality was FHB, while in 2017, although FHB occurred in higher severity than in 2016, tan

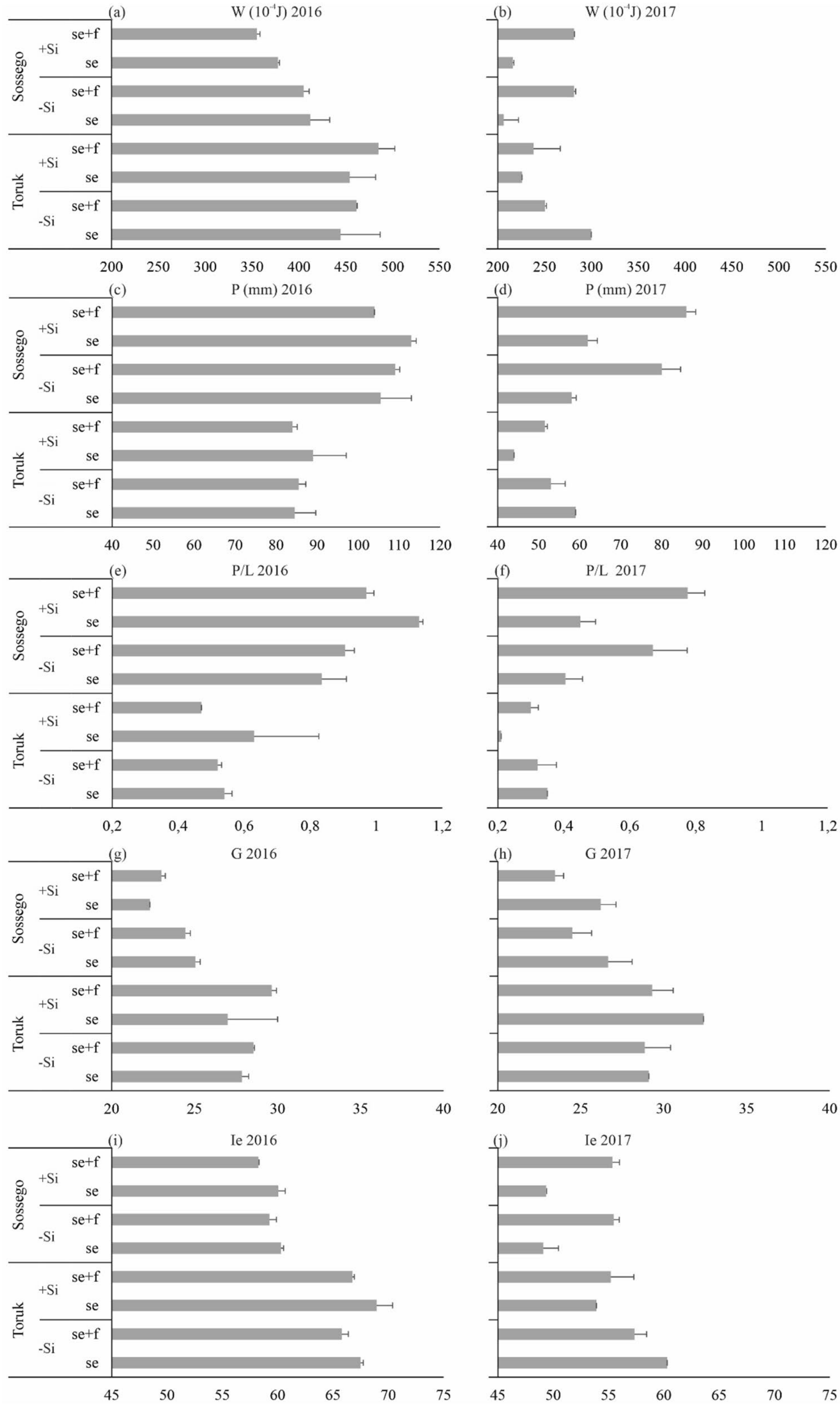

Fig. 4 Alveograph parameters: gluten strength (*W*) (**a** and **b**), tenacity (*P*) (**c** and **d**), tenacity/extensibility ratio (*P*/*L*) (**e** and **f**), swelling index (G) (**g** and **h**), and elasticity index (*Ie*) (**i** and **j**), from grains of wheat cultivars TBIO Toruk and TBIO Sossego grown in soil amended with extra-fine limestone (− Si) or calcium silicate (+ Si) and treated with fungicide at the stem elongation stage (se) or at stem elongation and flowering stages (se + f) in 2016 and 2017 crop seasons. The error bars represent the standard deviation of the means

spot generated a larger effect on some parameters of both grains and flour. In the case of FHB, disease reduction was achieved with fungicide spraying at flowering and by planting the cultivar TBIO Sossego, which was slightly more resistant than TBIO Toruk. With regards to tan spot, cultivar and fungicide application were important, but silicon had a greater impact in reducing the disease intensity.

The fungicide and silicon treatments had little influence on wheat technological quality under low disease pressure (2016 crop season), but under high disease pressure (2017 crop season), the effect was larger, due to a reduction in damage caused by the diseases. For instance, the effect of silicon was greater on tan spot than on FHB, which impacted grain quality during 2017. These results agree with the findings of other studies, in which Si's effect on tan spot control was demonstrated (Dorneles et al. 2017, 2018; Pazdiora et al. 2018, 2021; 2023).

Furthermore, spraying twice with fungicide during both crop seasons resulted in increased values of *TKW*, *FY*, and *GFN*. These results are comparable with the single-spray effect on the same parameters, due to the delay of senescence of the flag leaves (Dimmock and Gooding 2002; Ruske et al. 2003). *GFN* is a parameter associated with the level of alpha-amylase enzyme activity in a sample of grain or flour. It is affected by cultivar choice based on genetic background, fertilizers, and crop management (Kindred et al. 2005; Mares and Mrva 2008). In our study, *GFN* was mainly affected by the cultivar, where the TBIO Sossego plants had higher values than those of the TBIO Toruk cultivar. Moreover, a tendency towards lower values of *GFN* on + Si plants treated with fungicide at stem elongation was observed for the 2017 season but was still above the minimum values ($GFN > 200$ s).

Regarding flour color, light white flour is more desirable for many products. Typical white flour color values are + 92.5 of whiteness (L^*) (Wheat Marketing Center 2008). In our study, flour color was related to the cultivar. The flour of TBIO Sossego exhibited lower lightness and a tendency to be reddish and yellowish compared to TBIO Toruk. However, the high incidence of disease in 2017 changed the saturation and intensity of the flour color, increasing the lightness and the yellow tendency, mainly for TBIO Toruk. Also, some differences were found when silicon and fungicide were applied. For example, the tendency to increase L^* was recorded in both crop seasons due to silicon and fungicide application.

The alveograph simulates the dough behavior during fermentation, measuring mainly gluten strength (*W*) and dough viscoelastic properties (*P*, *L*). The parameters obtained by this method (*P*, *P*/*L* ratio, *G*, *W*, and *Ie*) were affected by the diseases, with tan spot having the greatest impact. Changes in the parameters affected negatively by the disease, such as *W*, *P*, and *P*/*L* ratio, allowed easy detection of the effects of fungicide and silicon application. Two fungicide sprays affected all the parameters under high disease pressure, but under low disease pressure, this mainly affected the *P*/*L* ratio, *G*, and *Ie*. In this context, Fleitas et al. (2018) also reported leaf disease reduction by fungicides and observed changes in some alveograph parameters as observed in the current study. In the case of silicon, the effect was mainly observed on plants of the cultivar TBIO Toruk (more susceptible) treated with only one fungicide spray, with a tendency for reduction on the alveograph parameters, except for *G*. In the case of low disease pressure (2016), some effects of silicon, generally with lower values, were also observed in the cultivar TBIO Sossego, such as the values of *W*, *P*/*L*, and *G*.

In conclusion, the two wheat diseases analyzed, FHB and tan spot, impaired the grain quality and negatively altered the wheat flour color, gluten level, and alveograph and farinograph parameters. Silicon fertilization had little effect on the wheat technological quality under low biotic stress, but under high biotic stress (tan spot and FHB), it ameliorated the damage caused by the diseases, maintaining the wheat technological quality near the expected levels for each cultivar, especially in conjugation with two fungicide applications. Thus, the results of previous studies showing the positive effect of silicon in reducing wheat diseases (Dallagnol et al. 2020; Pazdiora et al. 2021; 2023) along with our results demonstrate that silicon fertilization contributes to maintain wheat technological quality, suggesting that its application is a viable strategy for integrated disease management of wheat.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40858-023-00563-y.

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Author contribution Leandro José Dallagnol: conceptualization, methodology, funding acquisition, project administration, formal analysis, and writing—original draft, review, and editing. Paulo Cesar Pazdiora: conceptualization, methodology, investigation, and writing—review and editing. Martha Zavariz de Miranda: methodology and writing—original draft, review, and editing. Pihetra Oliveira Tatsch: investigation and writing—review and editing. Andrea Elizabeth Román Ramos: formal analyses and writing—original draft, review, and editing. Jeronimo Vieira de Araújo Filho: formal analyses and writing—review and editing. All authors approved the final version.

Data availability The data set generated during the current study will be available at the reasonable request to the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

References

AACC International (2010) Approved Methods of Analysis. 11th Ed. St. Paul: cereal & grains association. Method 26–10.02. Experimental milling: introduction, equipment, sample preparation, and tempering. Method 38–12.02. Wet gluten, dry gluten, water-binding capacity, and gluten index. Method 44–15.02. Moisture—air-oven method. Method 54–21.02 rheological behavior of flour by farinograph: constant flour weight procedure. Method 54–30.02 alveograph method for soft and hard wheat flour. Method 55–10.01. Test weight per bushel. Method 56–81.03. Determination of falling number. Available at: https://www.cerealsgrains.org/resources/methods/Pages/default.aspx. Accessed 28 June 2020

Berdugo CA, Mahlein AK, Steiner U, Dehne HW, Oerke EC (2012) Sensors and imaging techniques for the assessment of the delay of wheat senescence induced by fungicides. Functional Plant Biology 40:677–689

Blandino M, Reyneri A (2009) Effect of fungicide and foliar fertilizer application to winter wheat at anthesis on flag leaf senescence, grain yield, flour bread-making quality and DON contamination. European Journal of Agronomy 30:275–282

Castro AC, Fleitas MC, Schierenbeck M, Gerard GS, Simón MR (2018) Evaluation of different fungicides and nitrogen rates on grain yield and bread-making quality in wheat affected by Septoria tritici blotch and yellow spot. Journal of Cereal Science 83:49–57

Coskun D, Deshmukh R, Sonah H, Menzies JG, Reynolds O, Ma JF, Bélanger RR (2019) The controversies of silicon's role in plant biology. New Phytologist 221:67–85

D'Angelo DL, Bradley CA, Ames KA, Willyerd KT, Madden LV, Paul PA (2014) Efficacy of fungicide applications during and after anthesis against Fusarium head blight and deoxynivalenol in soft red winter wheat. Plant Disease 98:1387–1397

Da Luz SR, Pazdiora PC, Dallagnol LJ, Dors GC, Chaves FC (2017) Mycotoxin and fungicide residues in wheat grains from fungicide-treated plants measured by a validated LC-MS method. Food Chemistry 220:510–516

Dallagnol LL, Román AE, Dorneles KR (2020) Silicon use in the integrated disease management of wheat: current knowledge. In: Ansari MR (ed) Current trends in wheat research. IntechOpen, London, UK. Available at: https://www.intechopen.com/chapters/74509. Accessed 2021-07-05

Debona D, Rodrigues FA, Datnoff LE (2017) Silicon's role in abiotic and biotic plant stresses. Annual Review of Phytopathology 55:85–107

Dimmock J, Gooding MJ (2002) The influence of foliar diseases, and their control by fungicides, on the protein concentration in wheat grain: a review. Journal of Agricultural Science 138:349–366

Dorneles KR, Dallagnol LJ, Pazdiora PC, Rodrigues FA, Deuner S (2017) Silicon potentiates biochemical defense responses of wheat against tan spot. Physiological and Molecular Plant Pathology 97:69–78

Dorneles KR, Pazdiora PC, Hoffmann JF, Chaves FC, Monte LG, Rodrigues FA, Dallagnol LJ (2018) Wheat leaf resistance to *Pyrenophora tritici-repentis* induced by silicon activation of phenylpropanoid metabolism. Plant Pathology 67:1713–1724

FAO - Food and Agriculture Organization (2020). World food situation. https://www.fao.org/worldfoodsituation/csdb/en/. Accessed in march 2020

Fleitas MC, Schierenbeck M, Gerard GS, Dietz JI, Golik SI, Simón MR (2018) Breadmaking quality and yield response to the green leaf area duration caused by fluxapyroxad under three nitrogen rates in wheat affected with tan spot. Crop Protection 106:201–209

Gooding MJ, Davies WP (1997) Wheat production and utilization: systems, quality and the environment. CAB International. Wallingford, UK, p 335

Graybosch RA, Peterson CJ, Shelton DR, Baenziger PS (1996) Genotypic and environmental modification of wheat flour protein composition in relation to end-use quality. Crop Science 36:296–300

Haidukowski M, Pascale M, Perrone G, Pancaldi D, Campagna C, Visconti A (2005) Effect of fungicides on the development of Fusarium head blight, yield and deoxynivalenol accumulation in wheat inoculated under field conditions with *Fusarium graminearum* and *Fusarium culmorum*. Journal of the Science of Food and Agriculture 85:191–198

Hasniza MZN, Wilkes MA, Uthayakumaran S, Copeland L (2014) Growth environment influences grain protein composition and dough functional properties in three Australian wheat cultivars. Cereal Chemistry 91:169–175

Joris HAW, Penckowski LH, Kuhnem P, Rosa AC (2022) Informações técnicas para trigo e triticale: 14ª reunião da Comissão Brasileira de Pesquisa de trigo e triticale, 1st edn. Fundação ABC e Biotrigo Genética, Castro, PR

Kindred DR, Gooding MJ, Ellis RH (2005) Nitrogen fertilizer and seed rate effects on Hagberg falling number of hybrid wheats and their parents are associated with α-amylase activity, grain cavity size and dormancy. Journal of the Science of Food and Agriculture 85:727–742

Korndorfer GH, Pereira HS, Nolla OA (2004) Análise de silício: solo, planta e fertilizante. Instituto De Ciências Agrárias, Universidade Federal De Uberlândia, Boletim Técnico 2:34p

Lê S, Josse J, Husson F (2008) FactoMineR: a package for multivariate analysis. Journal of Statistical Software 25:1–18

Li AL, Geng SF, Zhang LQ, Liu DC, Mao L (2015) Making the bread: insights from newly synthesized allohexaploid wheat. Molecular Plant 8:847–859

Mares D, Mrva K (2008) Late-maturity α-amylase: low falling number in wheat in the absence of preharvest sprouting. Journal of Cereal Science 47:6–17

Matzen N, Jørgensen JR, Holst N, Jørgensen LN (2019) Grain quality in wheat—impact of disease management. European Journal of Agronomy 103:152–164

McMullen M, Bergstrom G, De Wolf E, Dill-Macky R, Hershman D, Shaner G, Van Sanford DA (2012) Unified effort to fight an enemy of wheat and farley: Fusarium head blight. Plant Disease 96:1712–1728

Nuttall JG, O'Leary GJ, Panozzo JF, Walker CK, Barlow KM, Fitzgerald GJ (2017) Models of grain quality in wheat - a review. Field Crops Research 202:136–145

Pandelova I, Figueroa M, Wilhelm LJ, Manning VA, Mankaney AN, Mockler TC, Ciuffetti LM (2012) Host-selective toxins of *Pyrenophora tritici-repentis* induce common responses associated with host susceptibility. PLoS One 7:e40240

Pazdiora PC, Dorneles KR, Forcelini CA, Del Ponte EM, Dallagnol LJ (2018) Silicon suppresses tan spot development on wheat infected by *Pyrenophora tritici-repentis*. European Journal of Plant Pathology 150:49–56

Pazdiora PC, Dorneles KR, Morello TN, Nicholson P, Dallagnol LJ (2021) Silicon soil amendment as a complement to manage tan spot and fusarium head blight in wheat. Agronomy for Sustainable Development 41:21

Pazdiora PC, Crizel RL, Dorneles KR, da Silva SM, Morello TN, Chaves FC, Dallagnol LJ (2023) Silicon amendment improves wheat defence against Fusarium graminearum and complements the control by fungicide of Fusarium head blight. Plant Pathology 72:53–66

R Core Team (2021) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

Rees R, Platz G (1983) Effects of yellow spot on wheat: comparison of epidemics at different stages of crop development. Australian Journal of Agricultural Research 34:39–46

Rodrigo S, Cuello-Hormigo B, Gomes C, Santamaria O, Costa R, Poblaciones MJ (2015) Influence of fungicide treatments on disease severity caused by *Zymoseptoria tritici*, and on grain yield and quality parameters of bread-making wheat under Mediterranean conditions. European Journal of Plant Pathology 141:99–109

Rodrigues FA, Dallagnol LJ, Duarte HSS, Datnoff LE (2015) Silicon control of foliar diseases in monocots and dicots. In: Rodrigues FA, Datnoff LE (eds) Silicon and plant diseases. Springer Cham, Springer International Publishing Switzerland, pp 67–108

Ronis A, Semaskiene R, Dabkevicius Z, Liatukas Z (2009) Influence of leaf diseases on grain yield and yield components in winter wheat. Journal of Plant Protection Research 49:151–157

Rosseel Y (2012) lavaan: an R package for structural equation modeling. Journal of Statistical Software 48:1–36

Ruske RE, Gooding MJ, Jones SA (2003) The effects of adding picoxystrobin, azoxystrobin and nitrogen to a triazole programme on disease control, flag leaf senescence, yield and grain quality of winter wheat. Crop Protection 22:975–987

Shuey WC, Gilles KA (1972) Milling evaluation of hard red spring wheats. III. Relation of some physical characteristics of wheats to milling results. The Northwestern Miller 279:14–17

Stack RW, Mcmullen MPA (2011) Visual scale to estimate severity of Fusarium head blight in wheat 2011. https://www.ag.ndsu.edu/ndipm/publications/wheat/documents/pp1095.pdf

Wang J, Welzik E, Weinert J, Hao QH, Wolf GA (2004) Effect of fungicide treatment on the quality of wheat flour and breadmaking. Journal of Agricultural and Food Chemistry 52:7593–7600

Wheat Marketing Center (2008) Wheat and flour testing methods: a guide to understanding wheat and flour quality: version 2Portland: Manhattan, Kansas State University. Available at: https://webdoc.agsci.colostate.edu/wheat/linksfiles/WheatFlour.pdf