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Mepiquat chloride application increases lodging resistance of maize by enhancing stem physical strength and lignin biosynthesis

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ABSTRACT

Lodging is a major adversity which limits maize grain yields and quality, especially under dense population. The present study was conducted to determine the efficacy of mepiquat chloride, a potential anti-gibberellic plant growth retardant on plant height, the physical strength of stem, lignin content and its relationship with lodging resistant in maize crop. Maize seeds were dressed with mepiquat chloride at the rate of 0 (MC0), 2.0 (MC1), 2.5 (MC2), and 3.0 (MC3) g kg^{-1} during 2015–2016. Our results showed that mepiquat chloride treatments enhanced the culm physical strength, as revealed by enhanced rind puncture strength and stalk bending strength, increased dry weight per cm, stem diameter, and lignin accumulation resulting in strong lodging resistance. A significant and negative correlation was detected between stalk bending and rind puncture strength with lodging rate. Moreover, the lodging rate, plant height, internodes length and gravity center height were significantly reduced following a dose-response trend, and MC2 and MC3 treatments resulted in relatively shorter plants, compared to control treatment. In addition, the grain yield, lignin contents and activities of lignin-related enzymes were enhanced by mepiquat chloride, and the MC2 (2.5 g kg^{-1}) treatment showed the best effect of all treatments. The correlation analysis revealed that lignin accumulation was negatively and significantly correlated with lodging rate of the maize crop. Our results imply that plant height obviously, as well as the culm physical strength and lignin are closely associated with the lodging resistance in maize, and the decreased plant height, enhanced culm morphological characteristics and lignin content could strengthen the resistance of crops to lodging.

1. Introduction

Maize (*Zea mays* L.) is an important cereal crop, used not only for human food but also for livestock feed and bio-fuel at a global scale (Zhang et al., 2014). The global food security is being threatened by the rapidly increasing world population and drastic changes in the climate, which have endangered the sustainability and productivity of the agricultural production systems (Cassman and Liska, 2007). High plant densities is the most efficient agronomic approach for obtaining higher maize grain yield (Grassini et al., 2011; Tollenaar et al., 2006; Valadabadi and Farahani, 2010; Van Ittersum and Cassman, 2013; Xue et al., 2016b), which improves resource utilization including solar radiation, water and nutrients more efficiently (Novacek et al., 2013; Ren et al., 2017; Wang et al., 2016). Nevertheless, high plant densities increase plant heights with comparatively thinner maize stems, thereby increasing the lodging risk (Ling et al., 2007; Novacek et al., 2013; Xue et al., 2016b), which had a detrimental effect on yield (Zhang et al., 2014). Moreover, high plant densities do not only result in lower number of kernels per ear, reduced kernel weight, and declination of growth per unit area (Tokatlidis et al., 2011; Vega et al., 2001), but also accelerate leaf senescence rate (Ren et al., 2017), and exacerbate early abortion of ear and kernel by reducing the ratio between growth rate of ear to plant growth rate (Vega et al., 2001).

Lodging is one of the most important constraint limiting quality and yield of grains in crop production globally (Islam et al., 2007; Ling et al., 2007; Sposaro et al., 2008). Lodging destroys the plant canopy structure, reducing the efficiency of nutrients assimilation, remobilization, and utilization, combined with poor light penetration

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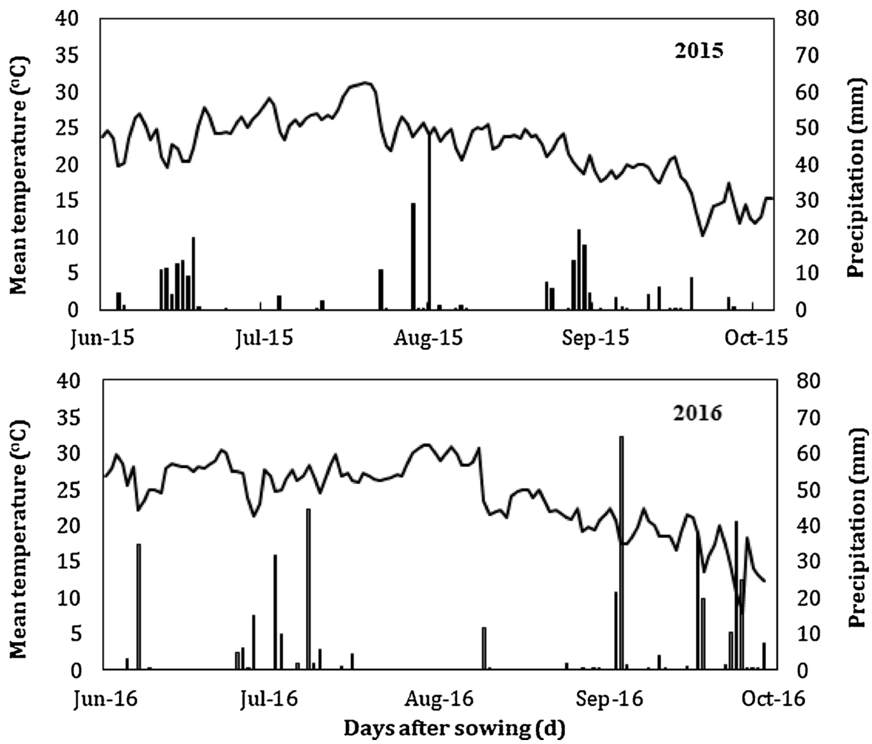

Fig. 1. Daily mean temperature (lines) and precipitation (bars) at the experimental site during the maize growing seasons from 2015 to 2016.

results in poor quality and yield of grains (Berry and Spink, 2012; Wang et al., 2015a). Previously, it was reported that lodging reduces yields of spring wheat by 8.3% (Tripathi et al., 2004), and maize yields by approximately 30% (Xue et al., 2016a). In addition, to yield losses, lodging also reduces mechanical harvesting efficiency, thereby increasing the cost of time and labor at harvest (Kuai et al., 2015; Weng et al., 2017). Many researchers have reported that plant height, the gravity center height, ear height, and ear ratio (the ratio of ear height to plant height) are the major morphological traits affecting crop resistance to lodging (Gou et al., 2010; Islam et al., 2007; Zheng et al., 2017), and each of these traits are positively correlated with lodging percentage in crops (Islam et al., 2007; Ma et al., 2014; Zheng et al., 2017). Accordingly, lodging risk can be minimized by shortening of the plant height (Kuai et al., 2016; Lu et al., 2014). However, the plant and ear heights were reportedly not the only primary lodging-related factors for completely preventing lodging under high planting densities, where a reduction in culm width and wall thickness are other major constraints (Islam et al., 2007; Ma et al., 2014; Xu et al., 2017). Nevertheless, several studies shown too much reduction in plant height to improve lodging resistance could result in a reduction of grain yield (Guoping et al., 2001; Wang et al., 2015a; Weng et al., 2017), due to limitation of photosynthetic efficiency of shorter plant canopies (Peng et al., 2014). Previous literature demonstrated that under densely planted maize, about 60% of stalk lodging primarily occurred at the basal 3rd or 4th internode above the ground surface during grain-filling stage (Gou et al., 2010; Wu et al., 2017; Xue et al., 2016a). At grain-filling, the stem carbohydrates are transported to the ear, which reduces the basal internode quality and gradually increase the ear weight, thus raising the gravity center height, and thereby increasing the risk of lodging in maize crop (Xue et al., 2016a). Therefore, a new strategy for increasing the lodging resistance of crops is to improve the physical strength of basal internodes (Kashiwagi and Ishimaru, 2004; Weng et al., 2017).

The physical strength of the stems primarily depends on the cell wall, which affords mechanical support to the cells tissues and the entire plant body (Kenneth, 2010). Lignin is an integral structural component of the cell wall in vascular plants, which lend strength and rigidity to the cell wall (Nguyen et al., 2016; Vanholme et al., 2010). Lignin plugs in the space between cellulose structures to improve the cell wall stiffness and the mechanical strength of the plant bodies (Chabannes et al., 2001). Lignin content has been shown to be closely associated with lodging resistance of wheat (Peng et al., 2014), rice (Weng et al., 2017; Wu et al., 2017) and buckwheat (Wang et al., 2015a, 2015b). The enzymes phenylalanine ammonia-lyase (PAL), cinnamyl alcohol dehydrogenase (CAD), 4-coumarate: CoA ligase (4CL), and peroxidase (POD) are involved in catalyzing many of the steps in lignin biosynthesis pathway (Boudet et al., 2003; Peng et al., 2014; Yang et al., 2015). Previously it was proposed that lignin metabolism had a strong relationship with lodging resistant of the stem, and are significantly and positively correlated with the stalk mechanical strength (Kamran et al., 2018; Valadabadi and Farahani, 2010; Zhang et al., 2014; Zheng et al., 2017). Wheat varieties susceptible to lodging and culm snapping had a lower accumulation of lignin and its related enzyme activities than lodging-resistant wheat varieties (Chen et al., 2011; Zheng et al., 2017).

Previous literature has shown the efficacy of plant growth regulators (PGRs), such as paclobutrazol and mepiquat chloride which induce more compact plants through shortening the internode length (Guoping et al., 2001; Kuai et al., 2015; Ren et al., 2013; Wang et al., 2015a), and could be used as a chemical approach to curtailed lodging. PGRs are not only used for manipulating plant canopies, but they also increase grain yield by up-regulating chlorophyll contents and photosynthetic capacity (Han et al., 2011; Kuai et al., 2015; Wang et al., 2016). However, limited literature is yet available on the effectiveness of mepiquat chloride on the culm physical strength, lignin accumulation, and possible effects on minimizing the lodging risk in maize crop. Therefore, the objective of the present study was to quantify the efficacy of mepiquat chloride on plant height, culm morphological characteristics, lignin accumulation, related enzyme activities and its relationship with lodging resistance of maize. A greater understanding of the present information could be used as a basis to improve the culm physical strength, minimize the risk of lodging and improve grain yield of the maize crop, especially under dense plant cultivation.