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Effects of weak-light stress during grain filling on the physicochemical properties of normal maize starch

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ABSTRACT

The grain development of normal maize in Southern China is affected by decreases in sunlight intensity over the period of mid-June to mid-July. This study examined the starch structure and function of four normal maize varieties that had been exposed to weak-light stress (50% light deprivation; ambient light conditions served as the control) during grain filling. In all tested varieties, light deprivation decreased the contents of starch and amylose, and increased the size of starch granules and the proportion of long chains in amylopectin. Shading increased the relative crystallinity and ordered-to-amorphous ratio of starch. Shading decreased the gelatinization and retrogradation enthalpies and pasting and gelatinization temperatures of starches but increased retrogradation percentage and pasting viscosities. In conclusion, weak-light stress during grain filling increases starch viscosity and retrogradation tendency and decreases thermal stability by reducing amylose content, increasing the sizes of starch granules and the proportion of long chains in amylopectin, and improving the relative crystallinity.

1. Introduction

Maize is an important tropical C_4 crop that is extensively cultivated worldwide. Maize plants require high light intensity during growth to produce sufficient photoassimilates for plant growth and development. In Southern China, plants experience frequent rains over the period of mid-June to mid-July. This period coincides with the grain filling stage of spring maize. Rains during the grain filling stage result in grain yield loss by reducing light intensity and limiting photosynthesis through decreasing the leaf chlorophyll and soluble protein content and reducing ribulose-1,5-bisphosphate carboxylase and phosphoenolpyruvate carboxylase activities (Clay et al., 2009; Jia, Li, Dong, & Zhang, 2010). Weak light also reduces the activities of enzymes involved in protein (glutamine and glutamate synthase) and starch (adenosine diphosphate glucose pyrophosphorylase, soluble starch synthases, and granule-bounded starch synthases) syntheses. These effects, in turn, decrease endosperm cell number and volume and starch and amylose contents, increase protein and fat contents, and reduce normal maize flour viscosity (Jia, Dong, Wang, Zhang, & Li, 2007; Jia, Li, Dong, & Zhang, 2011). The change in grain quality after shading stress is caused by the increase in embryo/endosperm ratio and the variations in endosperm cell inclusion percentages (Jia et al., 2011). In rice, weak-light stress during grain filling decreases the starch and amylose content, increases protein content, and reduces the exterior and nutritional quality (Ren, Yang, Xu, Fan, & Ma, 2003; Yuan et al., 2005). The pasting properties of rice flour are affected by shading, and peak and breakdown viscosities decrease when shading stress occurs throughout all growth stages, whereas the shading responses of pasting are dependent on growth stages and stress durations (Wang, Deng, Ren, & Yang, 2013). In wheat, shading stress during grain filling increases protein content, dough development time, stability time, and sedimentation volume (Shi, Chen, Yu, & Xu, 2011). Shading stress decreases flour starch content and gelatinization temperatures by increasing large granule proportions and relative crystallinity; moreover, shading increases the peak, trough, final, and breakdown viscosities of normal wheat and decreases those of waxy wheat (Li, Yan, Yin, & Wang, 2010; Liu et al., 2017). We previously found that shading stress during grain filling restricts starch accumulation; micrifies the starch granules of waxy maize; decreases crystallinities; influences starch and flour functional properties, such as pasting and thermal properties; decreases flour and starch peak viscosity, decreases flour retrogradation percentages; and increases starch retrogradation percentages (Lu, Sun, Wang, Yan, & Lu, 2013; Lu, Cai, Xu, Zhao, & Lu, 2014; Yang, Shi, Xu, Lu, & Lu, 2016). However, information about the effects of shading on the structure and function of

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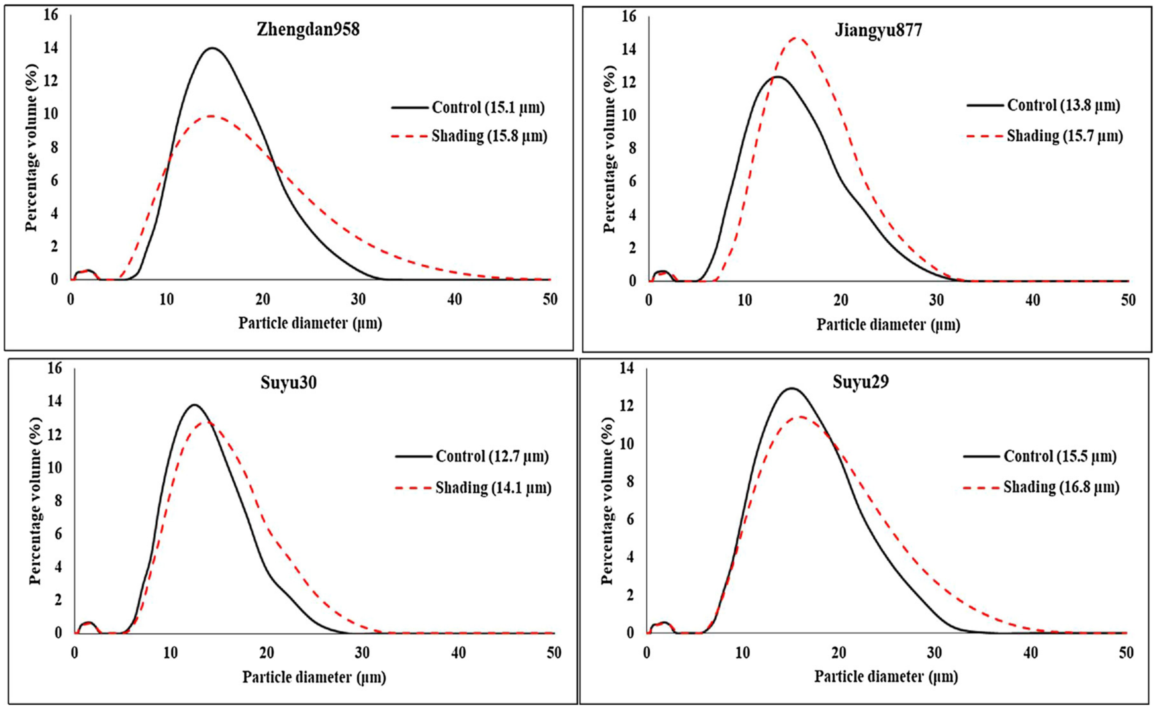

Fig. 1. Starch granule distribution and average granule size of normal maize under ambient and shading conditions. Data in bracket are the values of average granule size.

Table 1
Effect of shading during grain filling on starch, amylose, protein, and ash content, average DP, amylopectin S/L, crystallinity, and 1,045/1022 cm^{-1} ratio of normal maize starch.

Variety	Treatment	Starch (%)	Amylose (%)	Protein (%)	Ash (%)	Average DP	S/L	1,045/1022 cm^{-1}
Zhengdan958	Control	63.18c	26.30ab	0.45	0.12	23.13b	0.262b	0.751de
	Shading	51.40f	22.03c	0.32	0.21	22.89c	0.259c	0.763c
Jiangyu877	Control	65.28bc	27.67a	0.32	0.28	22.82d	0.297a	0.739f
	Shading	57.45d	22.17c	0.41	0.22	23.18ab	0.250d	0.778b
Suyu30	Control	68.28a	28.40a	0.38	0.17	23.23a	0.259c	0.756cd
	Shading	54.27e	24.27bc	0.35	0.09	23.10b	0.251d	0.804a
Suyu29	Control	66.78ab	26.47ab	0.27	0.25	22.90c	0.261b	0.745ef
	Shading	59.37d	24.97b	0.31	0.16	22.87c	0.258c	0.795a

DP, Degree of polymerization; S/L, ratio of short chains (DP ≤ 12) to long chains (DP > 12). Mean values in the same column followed by different letters are significantly different ($P < 0.05$).

normal maize starch remains limited. Understanding the thermal and pasting property changes exhibited by normal starch derived from the grains of plants that have been exposed to shading stress is necessary for the efficient utilization of normal maize starch for different purposes. We hypothesis that weak-light stress during grain filling changes physicochemical properties by changing the size and structure of starch granules. Plants of four normal maize varieties that had been grown under ambient and 50% light deprivation conditions were harvested. We analyzed the physicochemical properties of the starches to determine the influence of weak-light stress on development. Our results may provide a reference for efficient maize starch utilization in zones that frequently experience low sunlight during the grain filling.

2. Materials and methods

2.1. Maize samples

Four normal maize varieties, i.e., Zhengdan958, Jiangyu877, Suyu30, and Suyu29, were planted at Yangzhou University, Yangzhou, China, in 2016. Seeds were sown on March 15 and transplanted to the field on March 28 at a density of 75,000 plants per ha. The plot size was $24\,m^2$ ($4\,m \times 6\,m$) with three replicates prepared in a randomized complete block design. Plants were treated with 600 kg/ha compound fertilizer ($N/P_2O_5/K_2O$ = 15%/15%/15%) at transplantation, and then with 500 kg/ha urea (N = 46%) at the eight-leaf stage.

After pollination, the plants were covered with a layer of black polyethylene nets, which blocked approximately 50% of solar radiation. Plants without shading treatment were set as the controls. Nets were placed 450 cm above the ground to provide good ventilation conditions. The control plants and shaded plants were grown under similar microclimates (CO_2 and temperature) but different light intensities. The average values of light intensity at 10, 20, 30, and 40 days after pollination for control and shading treatments were 1085 and 559 μmol/m^2/s, respectively.

2.2. Starch isolation

Plants were harvested upon maturity (50 days after pollination). Grains (100 g) were steeped for 48 h in 500 mL of distilled water containing 1 g/L sodium hydrogen sulfite (SO_2) at room temperature. Starch was isolated following a previously described method (Lu & Lu, 2012).