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吐丝后不同阶段干旱胁迫对糯玉米子粒产量和淀粉品质的影响

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摘 要：以苏玉糯5号和渝糯7号为材料，试验对照和干旱处理下土壤相对含水量分别为75%和55%，干旱胁迫时间分别为子粒建成期和灌浆充实期，研究结实期不同阶段(子粒建成期和灌浆充实期)干旱胁迫对糯玉米子粒产量和淀粉品质的影响。结果表明，结实期干旱胁迫显著降低子粒产量，且降幅子粒建成期大于灌浆充实期。干旱胁迫下淀粉含量显著降低，总蛋白、球蛋白、谷蛋白含量显著增加，淀粉平均粒径增大、支链淀粉平均链长增加，相对结晶度升高，且影响子粒建成期大于灌浆充实期。糯玉米粉峰值黏度受灌浆充实期干旱胁迫影响较小，在子粒建成期干旱胁迫下显著降低。糯玉米粉热焓值在子粒建成期干旱胁迫下降低，灌浆充实期干旱胁迫下增加。苏玉糯5号回生值干旱胁迫下显著降低，且降幅灌浆充实期较大；渝糯7号回生值受子粒建成期干旱胁迫影响较小，灌浆充实期干旱胁迫下显著增加。

关键词：糯玉米；干旱胁迫；淀粉粒；糊化特性；回生值

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Effect of Drought Stress at Different Post-silking Stages on Grain Yield and Starch Quality of Waxy Maize

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Abstract: The effects of drought stress at different post-silking stages(grain formation stage and grain filling stage) on grain yield and starch quality of waxy maize were studied using Suyunuo 5 (SYN5) and Yunuo 7(YN7) as materials. The soil relative moisture contents were 75% and 55% under control and drought conditions, respectively. The grain yield was significantly reduced by drought at different stages, and the reduction was severe when water deficit occurred at grain formation stage. Drought stress significantly decrease the starch content, increase the contents of total protein, globulin and glutelin, enlarge the average starch granule size, rise the proportion of long amylopectin chains, and improve the relative crystallinity, and the effect of grain formation stage was greater than that of grain filling stage. Flour peak viscosity was unaffected by grain filling stage drought stress but significantly decreased when plants suffered water deficit at grain formation stage. The flour gelatinization enthalpy was decreased and increased when drought occurred at grain formation and filling stages, respectively. Drought stress decreased the retrogradation percentage of SYN5 and the decrease was larger when plants suffered drought at grain filling stage. The retrogradation percentage of YN7 was not affected by drought at grain formation stage but was increased by drought at grain filling stage, respectively.

Key words: Waxy maize; Drought stress; Starch granule; Pasting property; Retrogradation percentage

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玉米生长季水分需求主要依赖自然降雨，由于年度间季节间降雨不均衡，易发生干旱或涝渍，最终影响产量和品质。干旱是限制玉米生长最严重的自然灾害[1]，我国玉米旱灾面积约占总受灾面积的40%以上，且受灾程度随全球气候变化和剧烈人类活动干扰逐渐加剧[2]。未来全球将出现更多容易发生干旱区域，我国东北玉米带玉米生长季的干旱频率及强度均高于美国玉米带，粮食产量不稳定性增强，甚至有可能危及地区及全球粮食安全[3~6]。我国南方地区夏季降雨量集中、蒸发量大，易发生季节性干旱，且干旱季节与玉米生长中后期重叠，是影响江苏乃至南方地区玉米生长发育的重要环境因子[7]。

研究表明，干旱胁迫使玉米株高降低、干物质积累量下降、叶片数和叶面积指数减少、穗长缩短、粒数减少、粒重降低、生长速率减缓、光合速率和蒸腾速率发生不利变化，最终导致子粒产量损失[8~12]。干旱胁迫通过改变激素含量、限制胚乳细胞分化发育、抑制淀粉合成、缩短灌浆期，导致子粒变小[13~16]。结实期干旱胁迫使子粒淀粉含量降低，蛋白质含量升高[17~19]，淀粉含量降低主要是由于淀粉粒数量变少、粒径降低所致[20,21]。干旱胁迫下淀粉含量、淀粉大小和淀粉结构变化显著改变淀粉品质。结实期短暂干旱胁迫有利于增加小麦子粒中大淀粉粒比例，引起糊化温度下降，峰值黏度、终值黏度和回复值增加[22]。Xia[23]发现，干旱胁迫使小麦淀粉粒数量减少、体积变小，进而降低淀粉峰值黏度和谷值黏度。亦有研究发现，干旱胁迫使小麦淀粉粒变小，进而增加淀粉的峰值黏度、谷值黏度、崩解值和回复值[24]。Zhang[25]发现，适度干旱胁迫下小麦淀粉中大淀粉粒比例增加，支链淀粉中长链比例及平均链长增大，热焓值降低，胶凝温度、回生热焓值和回生值升高，重度干旱胁迫下影响相反。大麦上研究发现，干旱胁迫下淀粉中支链淀粉中短链比例和直链淀粉中长链比例增加，进而影响淀粉发酵能力和营养品质[26]。蔡一霞等[27,28]发现，结实期干旱胁迫使米粉崩解值降低，终值黏度和回复值升高，米饭硬度增加，蒸煮食味品质变劣。Liu [29]研究发现，限制灌溉条件下，玉米蛋白质含量升高，淀粉含量降低，淀粉粒变小，进而导致黏度降低、胶凝温度和热焓值增加。

糯玉米由于 *wx* 基因突变，子粒胚乳淀粉由近100%支链淀粉组成。鲜食糯玉米是我国种植面积最大的非设施蔬菜作物，是最好的食用玉米。成熟糯玉米淀粉与普通玉米淀粉相比具有高黏度、低回生、易消化等特点，在食品或非食品工业上具有特殊用途，如用作增稠剂、稳定剂[30,31]。课题组针对南方地区易发生季节性干旱气候特征与糯玉米利用首要关注品质特点，持续开展了干旱胁迫对糯玉米子粒产量和淀粉品质的影响研究，发现结实期(吐丝-成熟)干旱胁迫下糯玉米子粒淀粉合成酶活性降低、淀粉积累受限、淀粉粒变小、淀粉结晶度和支链淀粉长链比例降低是糯玉米(鲜食期、成熟期)子粒产量降低和淀粉品质劣化的主要原因[31~35]。淀粉发育可以发育两个阶段，前期(子粒建成期)以淀粉粒数量增多，后期(灌浆充实期)以淀粉粒径变大为主[36]。因此结实期不同阶段干旱胁迫对糯玉米子粒淀粉品质影响与全结实期胁迫可能不同。课题组在前期研究基础上，设置子粒建成期(授粉后1~15 d)和灌浆充实期(授粉后16~30 d)两个阶段干旱胁迫，研究结实期不同阶段水分胁迫对糯玉米子粒产量和淀粉品质的影响，为糯玉米抗旱栽培和品质调优提供理论基础。

1 材料与方法

1.1 供试材料

试验品种为国家南方糯玉米区域实验对照品种苏玉糯5号(SYN5)和渝糯7号(YN7)。

1.2 试验设计

试验于2018年在扬州大学实验盆钵场进行，3月15日盘育乳苗，1叶1心时移栽盆钵中(高 38 cm、直径 43 cm)，每盆移栽2株，6叶期定苗至1株，每盆基施复合肥($N-P_2O_5-K_2O$=15-15-15)10 g，拔节期追施6.6 g含N 46%的尿素。

开花前将盆钵移至高5 m的透明雨棚下防止降雨影响，利用负水头供水控水盆栽装置(专利编号：200510123976)来控制土壤水分含量，盆栽土壤相对含水量控制在75%左右。人工辅助授粉后设置对照和干旱处理，每个处理20盆，对照和干旱胁迫相对含水量分别为75%和55%，干旱处理时期分别为子粒建成期(授粉后1~15 d)和灌浆充实期(授粉后16~30 d)，干旱处理结束后所有盆栽相对含水量恢复至正常水平(75%)。

1.3 测定项目与方法

1.3.1 糯玉米子粒产量

成熟期收获各处理果穗，晒干后进行考种，计算每穗粒数和千粒重，然后剥下子粒计算产量(g/株)。

1.3.2 子粒可溶性糖、淀粉、蛋白质含量

子粒60℃烘干至恒重，粉碎过100目筛，采用蒽酮-硫酸法测定可溶性糖和淀粉含量[37]。蛋白组分提取参照张智猛等[38]的方法，使用凯氏定氮法测定含氮量[39]，总蛋白及蛋白组分含量为N×6.25。

1.3.3　淀粉粒度、碘结合力和晶体结构

糯玉米淀粉提取参照本课题组前期报道的方法进行。淀粉粒度、碘结合力和晶体结构参照本课题组前期报道的方法进行,激光衍射粒度分析仪为Mastersizer 2000(Malvern,England),紫外分光光度计为Lambda650(PE,USA),X射线衍射分析仪为D8 Super Speed(BA,Germany)。

1.3.4　糯玉米粉热力学特性和糊化特性

参照本课题组前期报道的方法测定糯玉米粉的热力学特性和糊化特性。差示扫描量热仪为200*F3* Maia(NETZSCH,Germany),快速黏度分析仪为Model 3D RVA(Newport Scientific,Australia)。

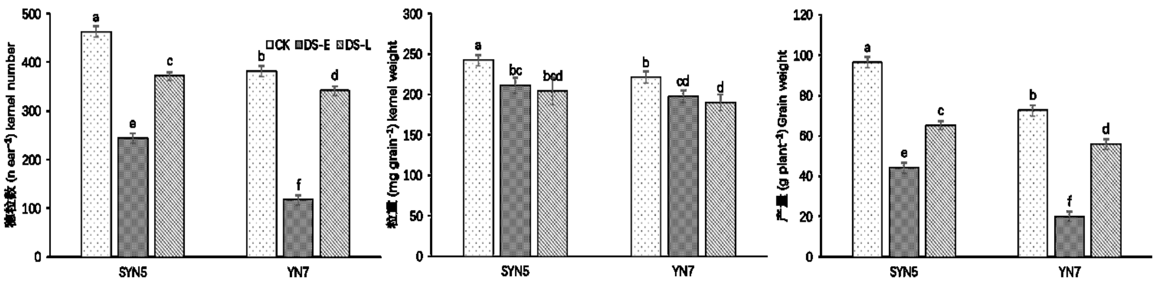
1.4　数据分析

使用DPS 7.05软件进行数据分析,Microsoft Excel 2016软件作图。

2　结果与分析

2.1　子粒产量

结实期不同阶段干旱胁迫均显著降低两个品种的穗粒数、千粒重,进而降低子粒产量(图1)。结实期干旱胁迫下穗粒数和产量显著降低,且降幅子粒建成期大于灌浆充实期。结实期干旱胁迫下两个品种粒重显著降低,降幅时期间无显著差异。子粒建成期和灌浆充实期干旱胁迫下,SYN5分别减产54.1%和32.5%,YN7分别减产72.6%和23.1%。



注:图中不同字母表示处理间在5%水平上差异显著。SYN5为苏玉糯5号;YN7为渝糯7号;CK为对照;DS-E为子粒建成期干旱;DS-L为灌浆充实期干旱。下图同。

Note: Values in the same column followed by different letters are significantly different at the 5% probability levels. SYN5, Suyunuo5, YN7, Yunuo7; CK, control; DS-E, drought stress at grain formation stage; DS-L, drought stress at grain filling stage. The same as follows.

图1　吐丝后不同阶段干旱胁迫对糯玉米子粒产量的影响

Fig.1　Effect of drought at different grain filling stages on waxy maize yield

2.2　子粒蛋白质组分、可溶性糖和淀粉含量

表1　结实期不同阶段干旱胁迫对糯玉米子粒组分含量的影响

Table 1　Effect of drought at different grain filling stages on grain components of waxy maize　　g/kg

品 种 Variety	处 理 Treatment	总蛋白 Total protein	清蛋白 Albumin	球蛋白 Globulin	醇溶蛋白 Glutenin	谷蛋白 Zein	可溶性糖 Soluble sugar	淀 粉 Starch
SYN5	CK	82.7 d	13.2 c	9.6 e	17.7 d	17.6 d	42.0 b	679.6 a
	DS-E	97.2 b	11.3 e	10.5 c	24.3 b	19.3 a	36.9 cd	595.0 c
	DS-L	94.0 c	12.8 c	10.0 d	22.6 bc	18.1 bcd	42.2 b	642.5 b
YN7	CK	92.6 c	12.1 d	10.9 c	19.7 cd	17.9 cd	49.3 a	692.5 a
	DS-E	103.6 a	14.0 b	12.0 b	31.0 a	18.5 b	34.4 d	587.8 c
	DS-L	97.6 b	15.5 a	12.9 a	28.3 a	18.3 bc	38.4 c	621.2 b
*F*值								
品种 V		108.6**	101.5**	337.3**	28.2**	0.5	0.2	0.4
处理 T		137.1**	51.6**	56.3**	35.6**	22.8**	42.9**	44.0**
品种×处理 V×T		8.3**	79.0**	25.8**	2.5	5.9*	15.8**	1.4

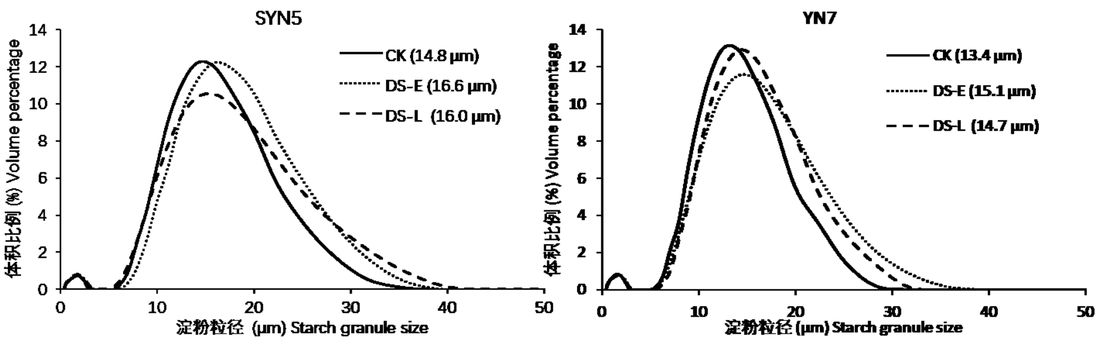
注:同一列中不同字母表示处理间在5%水平上差异显著,*、**分别表示差异达显著(P<0.05)和极显著(P<0.01)水平。下表同。

Note: Values in the same column followed by different letters are significantly different at the 5% probability levels, * P<0.05; ** P<0.01. The same below.

结实期不同阶段干旱胁迫对糯玉米子粒蛋白质组分、可溶性糖和淀粉含量有显著影响(表1)。与对照相比,干旱胁迫下两个品种子粒淀粉含量显著降低,总蛋白、球蛋白、谷蛋白含量显著增加,且子粒建成期干旱胁迫影响大于灌浆充实期。SYN5清蛋白含量受灌浆充实期干旱胁迫影响较小,子粒建成期干旱胁迫下显著降低。YN7清蛋白含量干旱胁迫下显著增加,且增幅灌浆充实期干旱胁迫下较大。两个品种的醇溶蛋白含量干旱胁迫下显著增加,但增幅不同阶段干旱胁迫下无显著差异。可溶性糖含量两品种子粒建成期干旱胁迫下显著降低,灌浆充实期干旱胁迫下YN7降低,SYN5不变。

2.3 淀粉粒分布

两个品种淀粉粒体积分布在各处理下均呈双峰分布,与对照相比,结实期两个阶段干旱胁迫增大了糯玉米淀粉的平均粒径(图2)。



注:括号中数据是淀粉粒平均粒径。

Note: The data in the bracket are average starch granule size.

图2 结实期不同阶段干旱胁迫对糯玉米淀粉体积分布的影响

Fig.2 Effect of drought stress at different stages on waxy maize starch granule volume distribution

2.4 最大吸收波长和碘结合力

两个品种的最大吸收波长变幅分别为532.2~533.8 nm 和 532.6~534.5 nm,均为典型的糯性特征,淀粉的碘结合力和最大吸收波长在两个阶段干旱胁迫下变化有所不同(图3)。最大吸收波长SYN5在子粒建成期干旱胁迫下显著降低,受灌浆充实期干旱胁迫影响不大;YN7在两阶段干旱胁迫下均显著下降,且灌浆充实期干旱胁迫下降幅最大。碘结合力SYN5受灌浆充实期干旱胁迫影响较小,子粒建成期干旱胁迫下显著增加;YN7两阶段干旱胁迫下均显著增加,子粒建成期干旱胁迫下增幅最大。

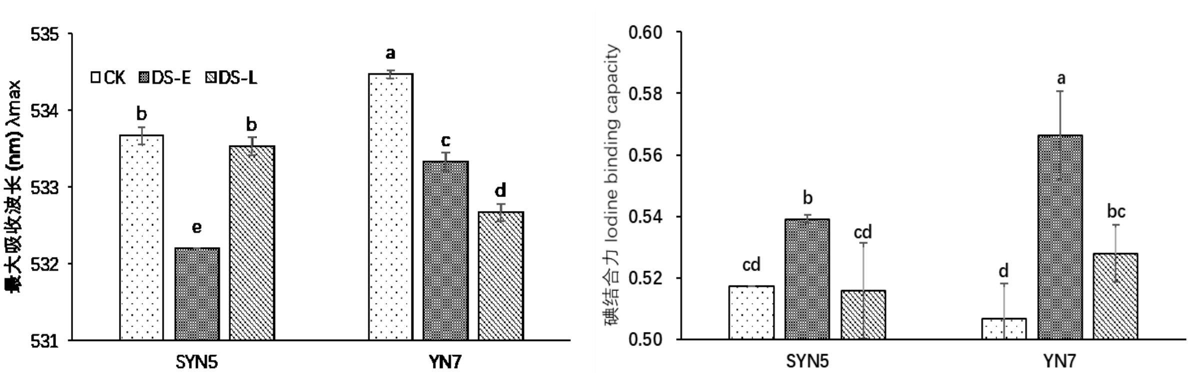


图3 结实期不同阶段干旱胁迫对糯玉米淀粉最大吸收波长和碘结合力的影响

Fig.3 Effect of drought stress at different stages on waxy maize starch maximum absorption wavelength and iodine binding capacity

2.5 晶体结构

两个品种淀粉晶体衍射类型在各处理下均相似,在 2θ=15°、17°、18°和 23°左右有显著的尖峰,为典型的"A"型衍射特征;在 2θ=20°的尖峰峰值较低,全部表现为典型的糯性特征。子粒建成期干旱胁迫均增加两个品种的淀粉相对结晶度(图4)。灌浆充实期干旱胁迫显著增加SYN5的相对结晶度,对YN7的相对结晶度影响不显著。

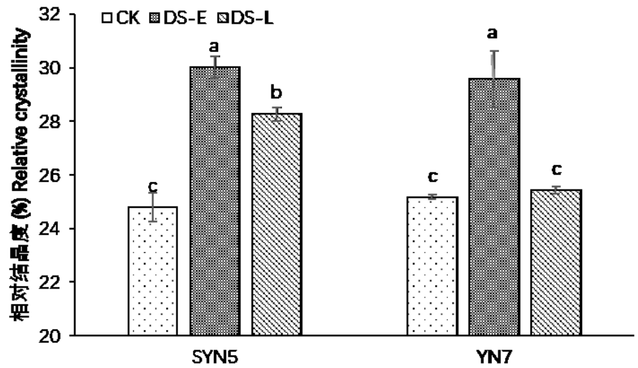


图4　结实期不同阶段干旱胁迫对糯玉米淀粉晶体结构的影响

Fig.4　Effect of drought stress at different stages on waxy maize starch diffraction pattern

2.6　糊化特性

结实期干旱胁迫对糯玉米粉糊化特性有显著影响(表2)。与对照相比,峰值黏度两品种受灌浆充实期干旱胁迫影响较小,子粒建成期干旱胁迫下显著降低;谷值黏度YN7受干旱胁迫影响较小,SYN5受灌浆充实期干旱胁迫影响较小,子粒建成期干旱胁迫下显著降低;崩解值YN7干旱胁迫下显著降低,降幅子粒建成期干旱胁迫下较大,SYN5子粒建成期干旱胁迫下增加,灌浆充实期干旱胁迫下降低;终值黏度YN7受干旱胁迫影响较小,SYN5子粒建成期干旱胁迫下降低,灌浆充实期干旱胁迫下增加;回复值YN7受干旱胁迫影响较小,SYN5受子粒建成期干旱胁迫影响较小,灌浆充实期干旱胁迫下显著增加;糊化温度SYN5受干旱胁迫影响较小,YN7号干旱胁迫下显著增加。总体上,SYN5较YN7具有较高的黏度特征值。与子粒建成期干旱胁迫相比,两个品种的峰值黏度、谷值黏度和终值黏度在灌浆充实期干旱胁迫下较高,表明前期干旱胁迫下对子粒糊化特性的影响大于后期。

表2　结实期不同阶段干旱胁迫对糯玉米粉糊化特性的影响

Table 2　Effect of drought stress at different grain filling stages on flour pasting properties of waxy maize

品 种 Variety	处 理 Treatment	峰值粘度(cP) PV	谷值黏度(cP) TV	崩解值(cP) BD	终值黏度(cP) FV	回复值(cP) SB	糊化温度 P_{temp}
SYN5	CK	1 883 a	1 306 a	577 b	1 592 b	286 b	79.6 a
	DS-E	1 750 b	1 226 b	624 a	1 518 c	292 b	79.5 a
	DS-L	1 841 a	1 341 a	501 c	1 668 a	328 a	78.7 ab
YN7	CK	1 533 c	1 093 cd	441 d	1 328 de	235 c	77.9 b
	DS-E	1 224 d	1 081 d	143 f	1 302 e	221 c	79.9 a
	DS-L	1 513 c	1 121 c	392 e	1 361 d	240 c	79.1 ab
*F*值							
品种 V		366.1**	555.2**	178.1**	294.3**	30.4**	0.7
处理 T		43.5**	30.3**	15.9**	15.6**	1.8	2.6
品种×处理 V×T		8.9*	8.7*	43.7**	3.0	0.7	3.2

2.7　热力学特性

子粒胶凝温度两个品种间无显著差异,热焓值、回生热焓值和回生值SYN5显著高于YN7(表3)。热焓值两品种子粒建成期干旱胁迫下显著降低,灌浆充实期干旱胁迫下显著升高;起始温度两个品种子粒建成期干旱胁迫下显著降低,灌浆充实期干旱胁迫下YN7不变,SYN5增加;峰值温度两个品种受子粒建成期干旱胁迫影响较小,灌浆充实期干旱胁迫下显著升高;终值温度两个品种干旱胁迫下显著增加,增幅以灌浆充实期较高。糊化样品冷藏后回生,回生热焓值两个品种子粒建成期干旱胁迫下降低,灌浆充实期干旱胁迫下SYN5降低,YN7升高;回生值SYN5干旱胁迫下显著降低,降幅灌浆充实期较大,YN7受子粒建成期干旱胁迫影响较小,灌浆充实

表3 结实期不同阶段干旱胁迫对糯玉米粉热力学特性的影响

Table 3 Effect of drought stress at different grain filling stages on flour thermal properties of waxy maize

品 种 Variety	处 理 Treatment	热焓值(J/g) ΔH_{gel}	峰值温度(℃) T_p	起始温度(℃) T_o	终值温度(℃) T_c	回生热焓值(J/g) ΔH_{ret}	回生值(%) R
SYN5	CK	8.1 c	77.9 b	72.0 b	84.9 c	4.7 a	58.4 a
	DS-E	6.6 e	77.7 b	71.3 c	86.0 b	3.0 c	45.7 b
	DS-L	10.6 a	78.5 a	72.8 a	86.7 a	4.4 b	41.1 cd
YN7	CK	7.5 d	78.0 b	72.9 a	84.8 c	3.0 d	40.1 d
	DS-E	6.6 e	77.7 b	71.3 c	86.0 b	2.9 e	44.2 bcd
	DS-L	9.6 b	78.5 a	72.8 a	86.7 a	4.3 b	45.3 bc
*F*值							
品种 V		28.4**	0.2	4.5	0.0	10.4*	25.3**
处理 T		225.1**	22.5**	42.0**	69.8**	74.5*	12.0**
品种×处理 V×T		7.2*	0.3	4.5	0.1	7.3*	43.3**

期增加。

3 结论与讨论

本研究结果表明，结实期不同阶段干旱胁迫显著影响子粒产量，粒重两个品种不同阶段干旱胁迫下无显著差异，但每穗粒数和子粒产量均以子粒建成期干旱胁迫下降幅最大。与在普通玉米上的研究结果相似[40,41]，主要是因为子粒建成期是胚乳细胞分裂分化和淀粉粒开始形成的关键时期，该时期干旱增加子粒败育数，同时影响胚的形成与胚乳细胞分裂分化，减少胚乳细胞数量和淀粉体数量，进而降低粒重[42]。子粒可溶性糖和淀粉含量在子粒建成期干旱胁迫下显著低于灌浆充实期干旱胁迫，这种降低主要是由于淀粉合成相关酶活性和IAA等生长促进类激素含量降低以及灌浆抑制类激素如ABA含量增加所致[43,44]。结实期干旱胁迫下子粒总蛋白、醇溶蛋白和谷蛋白含量增加，且增幅以子粒建成期干旱胁迫下较大。然而这种增加多为浓度效应，因为干旱胁迫下淀粉含量降幅较大(子粒建成期和灌浆充实期淀粉积累量降幅分别23.9%和21.7%，蛋白质积累积累量降幅分别为-1.3%和6.9%)，导致蛋白相对含量增加。

淀粉在子粒中以颗粒态存在，其粒度形态大小和分布显著影响玉米淀粉理化特性，淀粉粒是由结晶区和非结晶区两部分组成的多晶体系，相对结晶度可以直接影响淀粉的应用性能[45]。碘结合力可简单评价支链淀粉中长链比例的指标，碘结合力越大，长链比例越高。本研究结果表明，子粒建成期干旱胁迫显著增加淀粉的平均粒径、碘结合力和相对结晶度，灌浆充实期干旱胁迫下淀粉粒径增大，碘结合力SYN5不变，YN7增加，而相对结晶度SYN5增加，YN7不变，结果与课题组前期对结实期全生育期的干旱胁迫下淀粉粒径变小、碘结合力和相对结晶度降低的结果不同。其原因主要是子粒建成期干旱胁迫显著影响了胚乳细胞的分裂分化和淀粉体形成，淀粉粒数量显著减少，复水后的光合产物更多运输到较少的淀粉体上，导致淀粉粒径增加[46]。灌浆充实期干旱胁迫下淀粉粒径两个品种亦显著增加，但增幅显著低于子粒建成期干旱胁迫。其可能原因可能是淀粉粒发育是一个动态过程，课题组前期对子粒胚乳结构发育表明，授粉后15 d时的子粒胚乳淀粉尚存在着较大的空间[47]，此时进行干旱胁迫仍对子粒胚乳细胞中淀粉体分裂分化有显著影响，导致淀粉粒仍有所增大。

本研究表明，子粒建成期干旱胁迫显著降低两个品种糯玉米粉的峰值黏度，子粒建成期干旱胁迫下较低的峰值黏度可能与其具有较高的蛋白质含量、较低的淀粉含量、较大的淀粉粒以及较长的支链淀粉链长有关，较高的蛋白质含量包裹在淀粉粒表面，限制了淀粉粒的膨胀，进而影响黏度。亦有研究表明，干旱胁迫下较小的淀粉粒有利于增加淀粉的峰值黏度。不同的结果可能与样品(淀粉或子粒粉样)不同、水分胁迫程度(轻度、中度、重度)以及胁迫时间(前期、中期、后期)以及品种抗逆性不同有关。因此进一步细化处理有利于阐明相关研究结果的异同。回生值两个品种在结实期不同阶段干旱胁迫下表现不同。SYN5干旱胁迫下降低，而YN7胁迫条件下升高，SYN5号回生值子粒建成期干旱胁迫下高于灌浆充实期，而YN7不同时期干旱胁迫下无显著差异，课题组前期对淀粉研究的结果亦发现结实期

干旱胁迫下淀粉回生值对干旱胁迫的响应存在年度间差异,表明外界气候(光照、温度)条件等参数亦可能参与影响了淀粉品质。两个品种间比较,SYN5号具有较高的糊化黏度,而对照条件下YN7号的回生值较低。因此,根据用途选择产品时如需要高黏度应选择SYN5,而需要较低的回生特性时建议选择YN7。

本研究结果表明,子粒建成期干旱胁迫对子粒产量,子粒组分含量,淀粉结构和淀粉品质的影响总体上大于灌浆充实期,证实了子粒建成期是子粒产量和淀粉品质形成的敏感时期。在生产中应在开花期进行灌水,减轻后期胁迫影响。干旱胁迫是渐进性胁迫,因此,进一步研究不同程度干旱胁迫、不同胁迫持续时间对子粒产量和淀粉品质的影响有利于深化对干旱胁迫的认知。

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