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研究简报

不同胚乳类型玉米籽粒淀粉粒的粒度分布特征

崔丽娜[1,2] 张 红[1] 孟佳佳[1] 石德杨[1] 董树亭[1,*]

[1] 山东农业大学农学院 / 作物生物学国家重点实验室, 山东泰安 271018; [2] 山东德州市农业局, 山东德州 253000

摘 要: 以超甜玉米(华威 6 号)、爆裂玉米(特爆 2 号)、糯玉米(西星黄糯 6 号)及普通玉米(郑单 958)为材料, 利用激光衍射粒度分析仪及投射电镜, 分析其籽粒淀粉粒粒度分布特征。结果表明, 玉米淀粉粒体积分布均为三峰曲线。粒径<2 μm 淀粉粒所占的体积最小; >15 μm 玉米淀粉粒所占体积较大(超甜 2~15 μm 淀粉粒体积占的比例最大)。淀粉粒平均粒径为糯>爆裂>普通>超甜。单粒重及总淀粉含量与>2 μm 的淀粉粒体积百分比显著相关; 其他籽粒品质与淀粉粒分布相关性不显著。普通及超甜玉米淀粉粒大多呈圆形, 淀粉粒折叠的花纹多, 普通玉米淀粉粒排布稀疏, 脂滴含量较丰富, 超甜淀粉粒分布非常松散, 脂滴较少; 爆裂玉米淀粉粒相互挤压成长条形或方形, 淀粉粒折叠的花纹粗大, 数量少, 淀粉粒排布非常致密, 脂滴含量非常丰富; 糯玉米淀粉粒呈圆形或椭圆形, 淀粉粒折叠成的花纹浅且少, 淀粉粒分布致密, 脂滴含量丰富。由扫描图片知, 普通、超甜及糯玉米淀粉粒呈球形, 普通玉米凹陷的淀粉粒数量少; 糯玉米淀粉粒大小均匀, 具凹陷的淀粉粒数量大; 超甜玉米淀粉粒表面分布了许多网状结构, 淀粉粒未见凹陷, 淀粉粒及淀粉粒之间的填充物未充满整个细胞; 爆裂玉米淀粉粒为多面体, 有凹陷的淀粉粒极少。

关键词: 玉米; 淀粉粒; 胚乳

Starch Granule Size Distribution in Maize Kernel with Different Endosperm Types

CUI Li-Na[1,2], ZHANG Hong[1], MENG Jia-Jia[1], SHI De-Yang[1], and DONG Shu-Ting[1,*]

[1] College of Agriculture of Shandong Agricultural University / State Key Laboratory of Crop Biology, Tai'an 271018, China; [2] Dezhou Agriculture Bureau, Dezhou 253000, China

Abstract: Maize (*Zea mays* L.) kernel dry weight contains about 70% starch. Many studies have focused on the effects of sowing date, variety and nitrogen top-dressing on starch granule distribution in single variety or two varieties. But starch granule size distribution in grains of different endosperm types of maize has not been clear yet. Four maize varieties including super-sweet corn (Huawei 6), popcorn (Tebao 2), waxy corn (Xixinghuangnuo 6) and dent corn (Zhengdan 958) were used to study the starch granule size distribution and the starch granule arrangement in grains by laser diffraction grain size analyzer, transmission electron and scanning electron microscopy. The results showed that distribution of starch granules volume in grains of the maizes were changed in a triple humped curve. The volume proportion of starch granules with diameter lower than 2 μm was the least, while that with diameter higher than 15 μm was the more (that with diameter from 2 to 15 μm in super-sweet corn grain was the most). The average diameter showed following order: the waxy>the pop>the dent>the super sweet. Correlation analysis indicated that the grain weight and starch content were significantly correlated with the volume percentage of starch granules with diameter higher than 2 μm; while the contents of protein, amino acid, crude fat and test weight had no correlation with volume of starch granule with all size ranges. Transmission electron microscopy showed that the starch granules in grains of dent and super sweet corn were rotund mostly, with a great deal of drapes. Starch granule arrangement of dent corn was sparse, with abundant lipid droplet, while that of super sweet corn was very sparse; with rich lipid droplet. The starch granule in grains of pop corn was square and oblong, and extruded one another, with thick and skimp drapes, with was highly compact with abundant lipid droplet. The starch granule in grains of way corn was rotund and elliptic, with low and skimp drapes, compact arrangement and abundant lipid droplets. Scanning electron microscopy showed that the starch granules in grains of dent, super sweet and waxy corn were spherical. A

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* 通讯作者(Corresponding author): 董树亭, E-mail: stdong@sdau.edu.cn

第一作者联系方式: E-mail: cuilina2008@163.com, Tel: 15318140919

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small quantity of depressed starch granules were demonstrated in dent corn, while none of depressed starch granules were detected in super sweet corn with reticulate configuration in surface of starch granules. Moreover the cell did not be filled with starch granules and filling agent. The starch granule was polyhedral in pop corn with a very few depressed starch granules.
Keywords: Maize (*Zea mays* L.); Starch granule; Endosperm

玉米是制造淀粉的重要原料之一[1]。淀粉占玉米籽粒干重的 70%左右, 主要以淀粉粒的形式存在于籽粒胚乳中, 淀粉粒大小分布是淀粉重要的品质性状之一, 玉米淀粉粒形态存在显著的基因型差异[2-4], 不同大小的淀粉粒对淀粉特性有显著影响。研究玉米籽粒淀粉粒的分布特性, 有助于揭示玉米淀粉品质差异的内在原因[5]。糯玉米所含淀粉全为支链淀粉, 超甜玉米含糖量较为丰富, 爆裂玉米淀粉粒排列紧密。玉米籽粒胚乳淀粉粒的直径一般为 7~25 μm, 形状不规则[6], 平均直径在 10 μm 左右[7-9]。相关研究表明, 玉米淀粉粒大小与淀粉颗粒的起始糊化温度、峰值糊化温度及终止糊化温度等热力学性状间存在显著正相关性[10]; 大淀粉粒所含的直链淀粉含量高于小淀粉粒[7], 且粒度分布差异对淀粉的理化特性有重要影响[11]。前人的研究只是集中在单一胚乳类型的玉米淀粉粒分布的研究[4]及高低淀粉含量玉米籽粒淀粉粒的分布[12]上, 对不同胚乳型玉米的系统比较研究, 尚未见报道。本试验比较研究淀粉粒的体积分布, 以揭示不同胚乳类型玉米与普通类型玉米间的差异。

1 材料与方法

1.1 供试材料

华威 6 号为超甜玉米、特爆 2 号为爆裂玉米、西星黄糯 6 号为糯玉米, 普通玉米品种为郑单 958。

1.2 试验方法

试验于 2010—2011 年在山东农业大学玉米科技园进行。分别于每年的 6 月 17 日播种, 种植密度为每公顷 75 000 株。采用完全随机区组排列, 重复 3 次, 小区面积为 3 m× 10 m=30 m^2。试验地土壤质地为壤土, 0~20 cm 土壤 pH 7.40, 含全碳 12.76 g kg^{-1}、全氮 1.06 g kg^{-1}、碱解氮 79.45 mg kg^{-1}、速效磷 74.16 mg kg^{-1}、速效钾 94.45 mg kg^{-1}。基施复合肥(N-P-K: 16%-16%-16%) 300 kg hm^{-2}, 大喇叭口期追施尿素 675 kg hm^{-2}, 田间管理同高产田。试验期间玉米生长发育正常, 分别于每年的 10 月 18 日收获, 取玉米穗中部籽粒保存备用。

1.3 测试项目与方法

1.3.1 *淀粉粒提取及测定* 参照 Peng 等[13]、Ji 等[2]和 Malouf 等[14]的方法提取淀粉粒。取成熟期 15 粒玉米籽粒(穗中部)在 40 mL 浓度为 0.5 mol L^{-1} 的 NaCl 溶液中浸泡 16 h 后, 剥去种皮, 去掉胚, 在研钵中研成匀浆, 再用 200 μm 筛布过滤, 固体部分继续研磨过滤, 重复 3 次。将淀粉匀浆在 4 000×*g* 离心 5 min, 去上清液, 加 25 mL 浓度为 2 mol L^{-1} 的 NaCl, 旋涡混合, 在 4 000×*g* 再离心, 去上清液, 然后分别加 2%SDS、2%NaOH 溶液及蒸馏水, 匀浆后再离心, 重复 4 次, 再用丙酮清洗 1 次, 然后风干, 贮存于–20℃备用。

用贝克曼库尔特公司的 LS13320 激光衍射粒度分析仪分析淀粉粒。取 50 mg 淀粉放入离心管, 加 10 mL 蒸馏水悬浮, 旋涡混匀后置 4℃下 1 h, 每 10 min 振荡 1 次, 在吸取样品前摇匀, 吸取 2 mL 左右转移至激光衍射粒度分析仪的分散盒中, 测量淀粉粒的体积、表面积及体积分布状况。

1.3.2 *淀粉粒透射电镜及扫描电镜观测* 取人工授粉的玉米(授粉后 20 d)穗部籽粒, 切取顶部籽粒, 横切面用 4%戊二醛前固定, 磷酸缓冲液冲洗。再用 1%锇酸后固定, 乙醇梯度脱水。Epon-812 (环氧树脂)浸透与包埋。以瑞典 LKB-7800 型超薄切片机切片, 切片厚 0.6 μm。将部分材料重新建断层后喷金属粉, 用日本 JSM-660LV 扫描电镜观察照相。部分材料在定位后用醋酸双氧铀-柠檬酸铅双重染色, 日本 JEM-1200EX 型透射电镜下观察照相, 用于淀粉粒超微结构研究。

2 结果与分析

2.1 玉米淀粉粒粒度分布特征

各胚乳类型玉米籽粒淀粉粒体积分布均为三峰曲线, 爆裂玉米的峰值为 2.107、5.355 和 18.000 μm; 糯玉米峰值为 16.40 (18.00)、45.76 和 96.49 μm; 超甜玉米峰值为 1.919、5.355 和 14.940 μm; 普通玉米郑单 958 峰值为 1.919、5.355 和 18.000 μm。爆裂玉米籽粒淀粉粒表面积分布为三峰曲线, 其峰值分别为 1.593、5.355 和 18.000 μm。

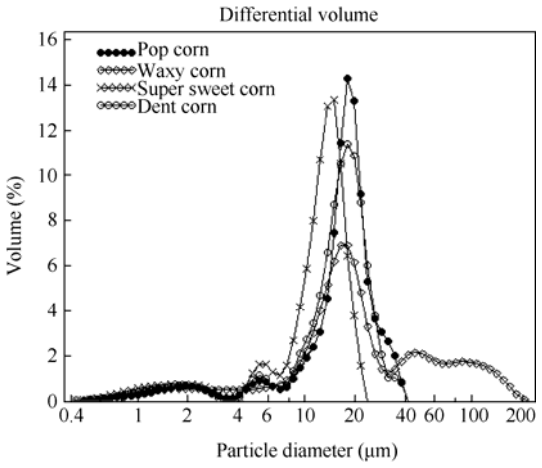

图 1 不同胚乳类型玉米籽粒淀粉粒体积的分布
Fig. 1 Distribution of starch granule volume in the grain of different endosperm types of maize

2.2 玉米淀粉粒粒度体积分布

由表 1 可知, 爆裂、糯、超甜及郑单 958<2 μm 的淀

粉粒体积比例很小分别为 5.0%、5.5%、7.6%和 6.2%。>15 μm 的淀粉粒体积比例分别为 68.9%、61.3%、28.5%和 60.3%。超甜 2~15 μm 淀粉粒体积占的比例最大。总之, 各玉米品种<2 μm 淀粉粒所占的体积最小; >15 μm 玉米淀粉粒所占体积较大(超甜 2~15 μm 淀粉粒体积占的比例最大)。各品种玉米淀粉粒的体积平均粒径为糯>爆裂>普通>超甜。

2.3 玉米籽粒品质性状

表 2 表明, 不同胚乳类型玉米单粒重为普通>糯>超甜>爆裂; 总淀粉含量为爆裂>普通>糯>超甜; 容重为爆裂>普通>糯>超甜; 蛋白质含量为普通>糯>超甜>爆裂; 氨基酸含量为糯>超甜>普通>爆裂; 粗脂肪含量为普通>爆裂>糯>超甜。

由表 3 可知, 单粒重与>2 μm 的淀粉粒体积百分比显著相关; 总淀粉含其他籽粒品质与淀粉粒分布相关性不显著, 淀粉粒的平均粒径与玉米籽粒各品质性状相关性不显著(除总淀粉量与>2 μm 淀粉粒体积百分比显著正相关外)。

2.4 玉米淀粉粒透射及扫描图

将籽粒胚乳深层细胞的透射及扫描观察并照相, 以对比不同胚乳类型玉米籽粒淀粉粒的差异。由图 2 可知, 普通玉米籽粒淀粉粒大多呈圆形, 投射图花纹较多、较浅, 淀粉粒排布比较稀疏, 脂滴含量较丰富; 爆裂玉米淀粉粒较大, 较普通玉米大, 且相互挤压成长条形或方形, 淀粉粒折叠的花纹较粗大, 数量较少, 淀粉粒排布非常致密, 脂滴含量非常丰富; 超甜玉米籽粒淀粉粒较普通玉米小, 数量较大, 多呈圆形, 淀粉粒折叠的花纹颜色较深, 淀粉粒分布非常松散, 细胞中的淀粉粒未充满整个细胞, 脂滴较少; 糯玉米籽粒淀粉粒呈圆形或椭圆形, 较普通玉米淀粉粒大, 淀粉粒折叠成的花纹较少、较浅, 淀粉粒分布较致密, 脂滴含量丰富。淀粉粒表观大小为爆裂>糯>普通>超甜。由图 3 可知, 普通玉米淀粉粒几乎都成球形, 有凹陷的淀粉粒数量少, 淀粉粒之间有大量填充物; 爆裂玉米淀粉粒为多面体, 有凹陷的淀粉粒极少, 淀粉粒排布致密; 超甜玉米淀粉粒多为球形, 淀粉粒表面分布了一些网状结构, 淀粉粒未见凹陷, 淀粉粒之间空隙大, 淀粉粒及淀粉粒之间的填充物未充满整个细胞; 糯玉米淀粉粒呈球形, 且大小均匀, 具凹陷的淀粉粒数量大。

3　讨论

禾谷类作物淀粉含量占胚乳细胞的 90%左右, 对作物品质起决定作用。淀粉以淀粉粒的形式存在, 其大

表 1　不同胚乳类型玉米淀粉粒体积分布

Table 1　Starch granule volume distribution in different endosperm types of maize (%)

品种类型 Variety type	<2 μm	2–15 μm	>15 μm	均值 Mean
爆裂 Pop corn	4.95±0.203 d	26.13±0.697 c	68.90±2.036 a	17.18±0.263 b
糯 Waxy corn	5.55±0.167 c	31.48±1.236 b	63.06±2.117 ab	33.86±0.524 a
超甜 Super sweet corn	7.65±0.315 a	63.78±1.679 a	28.49±0.379 c	11.90±0.236 c
普通 Dent corn	6.22±0.219 b	33.49±0.964 b	60.30±2.069 b	16.02±0.224 b

表 2　供试玉米品种籽粒的品质性状

Table 2　Grain quality traits of the tested cultivars

品种类型 Variety type	单粒重 Grain weight (mg)	总淀粉含量 Starch content (%)	容重 Test weight (g L^{-1})	蛋白质含量 Protein content (%)	氨基酸含量 Amino acid content (g kg^{-1})	粗脂肪含量 Crude fat content (%)
爆裂 Pop corn	109.3±3.22	71.37±2.69	0.722±0.013	2.371±0.132	5.680±0.136	5.882±0.346
糯 Waxy corn	249.4±13.64	57.63±1.49	0.683±0.009	4.292±0.162	9.192±0.267	5.193±0.267
超甜 Super sweet corn	134.8±14.22	49.90±1.57	0.647±0.008	3.673±0.129	6.629±0.155	5.074±0.436
普通 Dent corn	348.9±21.37	67.60±3.11	0.712±0.011	5.224±0.137	5.817±0.209	6.290±0.419

表 3　淀粉粒的体积分布与籽粒品质的相关性分析

Table 3　Correlation coefficients between starch granule volume and grain quality traits

品质指标 Quality index	淀粉粒直径 Diameter of starch granule			平均粒径 Average diameter (μm)
	<2 μm	2–15 μm	>15 μm	
单粒重 Grain weight (mg)	0.362	0.649*	–0.672*	0.467
总淀粉含量 Starch content (%)	0.444	0.764*	0.569*	0.794*
容重 Test weight (g L^{-1})	0.202	0.526	0.336	0.511
蛋白质含量 Protein content (%)	0.310	0.084	0.091	0.261
氨基酸含量 Amino acid content (%)	0.094	0.049	0.010	0.123
粗脂肪含量 Crude fat content (%)	0.198	0.558	0.082	0.517

*, **显著性水平分别为 0.05 和 0.01。*, ** represent significance at 0.05 and 0.01 probability levels, respectively.

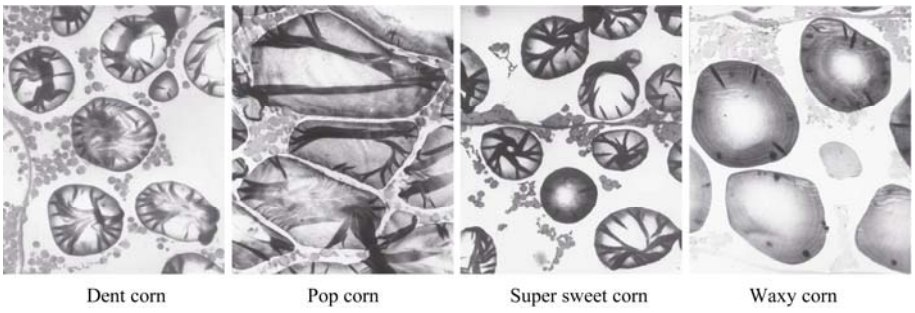

图 2 不同胚乳类型玉米淀粉粒投射图(×2500)

Fig. 2 Transmission electron microscopy showing the starch granule arrangement in grains of different endosperm types of maize (×2500)

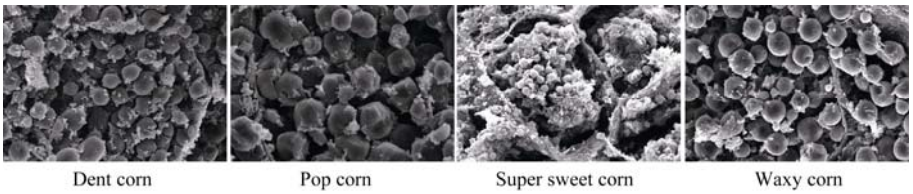

图 3 不同胚乳类型玉米淀粉粒扫描图(×1500)

Fig. 3 Scanning electron microscopy showing the starch granule arrangement in maize with grains of different endosperm types (×1500)

小和分布对淀粉理化性质起重要作用, 受品种、栽培措施及环境的共同调控[15-16]。玉米籽粒胚乳淀粉粒的直径一般为 7~25 μm, 形状不规则[6], 平均直径在 10 μm 左右[7-9]。Bechtel 等[17-19]以 5 μm 和 16 μm 为分界点把小麦淀粉粒划分为了 A (>16 μm)、B (5~16 μm)和 C (<5 μm) 3 种类型; 张丽等[20]在研究不同淀粉含量玉米籽粒淀粉粒度的分布特征中将玉米籽粒分为小型(粒径<2 μm 的淀粉粒)、中型(2~15 μm)和大型(>15 μm)三类。依据不同胚乳玉米籽粒淀粉粒体积、表面积及数目的峰值特征, 上述分类可以在本试验中应用, 即将大中小淀粉粒的分界点为 2 μm 和 15 μm。小型淀粉粒数目最大, 而占的体积最小。陆大雷等[5]、张丽等[20]和 Sandhu 等[21]研究表明, 单一类型玉米品种间的变异均小于 5%。所以本试验采用一个品种作为一类胚乳类型玉米的代表具有现实性和可行性。

淀粉粒由支链淀粉、直链淀粉和少量蛋白质和脂类组成[22], 爆裂玉米胚乳几乎全为角质胚乳[23], 淀粉粒排列紧密、无空隙, 这可能是导致爆裂玉米籽粒膨胀系数高的原因之一。超甜玉米可溶性糖含量高[24], 其胚乳淀粉粒排列稀疏, 空间大, 导致其淀粉含量低。普通玉米及糯玉米淀粉含量在爆裂与超甜玉米之间, 其淀粉粒的排列差异不大, 而外形差异较大。淀粉粒下限均为 0.375 μm, 上限的大小顺序为糯>爆裂=普通>超甜; 淀粉粒表观大小为爆裂>糯>普通>超甜。即淀粉粒上限与淀粉粒表观大小非一一对应关系; 淀粉粒体积及表面积均值大小顺序一致, 糯>爆裂>普通>超甜; 淀粉粒体积、表面积两者与淀粉粒数目均值非一一对应关系; 玉米淀粉粒数目均值为爆裂>普通>超甜>糯。

淀粉粒透射及扫描图存在许多差异, 淀粉粒大小、外形及皱褶深浅、大小以及淀粉粒排布的稀疏与致密程度差异显著, 且脂滴的分布差异较大。

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