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特色热带作物淀粉研究进展

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摘要 淀粉作为自然界来源最广泛的碳水化合物, 最基本的生理功能是为人体生命活动提供能量. 作为木薯、香蕉等典型特色热带作物的主要组成成分, 特色热带作物淀粉因具有区别于传统淀粉资源的多尺度结构, 从而表现出不同的理化性质、加工性能和应用领域而受到广泛的关注. 本文按照淀粉的来源归纳现有特色热带作物淀粉的研究进展, 综述了木薯、香蕉、菠萝蜜、面包果、芒果、蛋黄果等特色热带作物淀粉的提取工艺、直链淀粉含量、多尺度结构、理化性质、加工技术及其产品应用等, 讨论了特色热带作物淀粉的未来发展方向、应用前景, 给出了研究建议, 以期为特色热带作物淀粉的研究、相关产品的加工水平的提升等提供理论指导.

关键词 特色热带作物淀粉, 结构, 性质, 应用前景

特色热带作物淀粉即存在于热带植物中的淀粉, 其主要特色热带作物来源包括木薯、香蕉、菠萝蜜、面包果、芒果、蛋黄果等(图1). 木薯是热带地区的主要块根作物, 其富含淀粉的块根为全球5亿多人的能量来源[1]. 香蕉是一种热带水果作物[2], 青香蕉果肉和香蕉皮中含有淀粉. 菠萝蜜是热带和亚热带常绿树种之一[3], 其果实由外皮, 可食用的黄色果肉, 鳞茎和种子组成[4]. 菠萝蜜种子占整个果实重量的8%~15%[5], 通常作为加工副产物被废弃[6]. 面包果原产于马来西亚, 南太平洋和加勒比海地区[7], 目前在非洲、亚洲和加勒比海的大部分地区生长茂盛[8], 是非洲人民的主食之一. 芒果是第二大贸易热带水果, 也是全球第五大产量的热带水果[9,10], 每年有超过100万吨的芒果种子被丢弃[11], 造成大量浪费. 蛋黄果原产于东南亚和南美洲的热带和亚热带地区, 因其果肉的颜色、风味、质地与蛋黄相似而得名[12]. 这些作物是热带地区的主食[13]或主要水果, 对增加食物供应具有积极作用[14].

淀粉是特色热带作物的主要成分之一, 其含量和分布如下: 新鲜木薯块根中淀粉含量16.55%~34.00%[15], 干木薯中淀粉含量高达65%以上[16]. 青香

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图 1 六种特色热带作物果实
Figure 1 Fruit of six characteristic tropical crops

蕉果肉中含有高达70%~80%(干重)的淀粉[17]，而青香蕉皮中的淀粉含量约为22.6%[18]．菠萝蜜淀粉主要来源于其种子, 种子中淀粉含量高于60%[5]. 面包果果肉是良好的淀粉来源，淀粉含量在53%~86%(干基)[19~21]. 芒果种子占到整个水果重量的10%~25%[22]，是芒果淀粉的主要提取原料，芒果种仁中淀粉的湿基含量为32%左右，折算干基后高达58%以上[9]．与芒果相似, 成熟的蛋黄果果肉中淀粉含量较低(8%[23]~15.6%[24], 干基), 而未成熟的蛋黄果果肉以及其种子中的淀粉含量较高, 干基含量分别为93.12%和68.17%[23].

淀粉是一种在生产和生活中极为重要的原料和产品. 近年来, 特色热带作物淀粉等新型淀粉资源因具有区别于传统淀粉资源的性质和功能而受到广泛的关注．如青香蕉淀粉中直链淀粉含量和抗性淀粉含量较高[25], 分别达到30%以上和40%; 而菠萝蜜淀粉则表现出不易糊化和抗性淀粉含量高的特点[26~30]．此外，不同品种和不同成熟时期的特色热带作物淀粉的精细结构、加工性质和营养特性均存在差异. 然而, 热带地区国家主要为低收入国家，对特色热带作物淀粉的开发利用研究十分有限，这严重制约了热带淀粉的开发和利用．目前除木薯淀粉外，其他特色热带作物淀粉的应用主要停留在研究阶段，尚未见大规模商业化生产和利用．特色热带作物淀粉的开发意义重大，不仅可以满足食物需求，还能促进相关产业的发展，对于热带地区的可持续发展具有重要意义．因此，本文对特色热带作物淀粉进行综述，以明确特色热带作物淀粉的研究进展和发展不足，为特色热带作物淀粉的开发和研究指出发展方向和应用前景, 提出研究建议.

1 提取工艺

特色热带作物淀粉的提取是其开发利用的前提. 木薯淀粉主要从新鲜薯肉中获得，也有从木薯渣中提取的相关报道．香蕉淀粉多从果肉中提取，从香蕉皮中提取的研究相对较少．菠萝蜜淀粉的提取部位是菠萝蜜种子，面包果淀粉提取于其果肉，分为鲜果肉和干果肉．芒果淀粉主要提取于种仁，少数提取于青芒果果肉. 蛋黄果淀粉主要提取于未成熟的果肉和种子. 本文汇总了特色热带作物淀粉的提取情况(表1)．在上述几种特色热带作物中，木薯淀粉的提取率处于最高水平，芒果淀粉的提取率略低于木薯淀粉；面包果淀粉和菠萝蜜淀粉的提取率相近，排在第三和第四位; 排第五位的是香蕉淀粉, 而蛋黄果淀粉的提取率(根据淀粉含量和得率估算)排在最末位.

特色热带作物淀粉的提取方法主要有干法[31]、水提法[32~37]、碱提法[5,26,32,33,35]、酶法[32,35,38]、超声提取法[39,40]、表面活性剂提取法[32]等．新鲜木薯一般经过去皮、清洗、粉碎、调浆、过滤、沉降、洗涤、干燥和磨粉等工艺后得到木薯淀粉[1,41]，为提高淀粉的提取率, 可使用酶法处理[42]. 为减少资源浪费, 很多研究者也从木薯皮渣中提取淀粉，主要利用酶法[43,44]和均质法[45]．香蕉淀粉的提取往往使用湿磨工艺[36,37], 具体流程为去皮、切块、亚硫酸钠溶液/抗坏血酸溶液/水浸泡、粉碎、过滤、洗涤、干燥和磨粉．此外, 有报道使用液氮粉碎香蕉果肉并使用果胶酶去除细胞壁从而提取淀粉[46]．不同香蕉品种[47,48]、成熟度[49]、提取部位等造成了香蕉淀粉得率的差异[17,50]．菠萝蜜

表 1　特色热带作物淀粉的提取工艺a)

Table 1　Extraction technology of starch from characteristic tropical crops

特色热带作物	提取部位	提取工艺	淀粉纯度	淀粉提取率	淀粉得率
木薯	薯肉	新鲜木薯→去皮→清洗→粉碎→调浆→过滤→沉降→洗涤→干燥→磨粉→木薯淀粉[1,41]	—	—	19.1%(以鲜薯计)
		在调浆步骤后使用果胶酶与蛋白酶对浆料进行处理[42]	—	提高约10%	—
	渣皮	使用混酶(果胶酶、纤维素酶、酸性蛋白酶)对木薯渣进行处理[43]	—	约45%	—
		使用复合酶(纤维素酶、β-葡聚糖酶、木聚糖酶、戊聚糖酶、果胶酶、蛋白酶、多酚氧化酶、脂肪酶、α-淀粉酶)处理木薯渣[44]	—	97.84%	—
		将木薯皮磨碎后经过均质提取得到淀粉[45]	—	—	6.5%
香蕉	果肉	湿磨工艺[36,37]: 去皮→切块→亚硫酸钠溶液/抗坏血酸溶液/水浸泡→粉碎→过滤→洗涤→干燥→磨粉	86.3%以上[50]	33.8%[48](干基)	18.73%~32.22%(干基)[50] 43.8%和11.8%[47]
		使用液氮粉碎香蕉果肉并使用果胶酶去除细胞壁从而提取淀粉[46]	—	—	—
		湿磨法和酶法处理不同成熟度的香蕉[48]	—	—	20%~60%
菠萝蜜	种子	提取程序: (去皮)→与溶剂混合→磨浆→(均质)→筛分→(浸泡)→洗涤→分离→干燥→粉碎[5,26,32~35,38]	—	—	—
		水提法[32~35]	—	18.92%[32]	—
		碱提法[5,26,32,33,35]	—	63.82%~64.46%[32]	—
		酶提法[32,35,38]	—	43.57%~66.68%[32]	—
		表面活性剂提取法[32]	—	70.55%[32]	—
面包果	鲜果	去皮→切片→(浸泡)→磨浆→过滤→洗涤→离心分离→干燥→粉碎[21,54,55]	84.48%[54]		13.60%[21](湿基)
		水提法[52]、碱提法[52]和酶提法[52,53]	—	23.90%~66.25%	—
	干果切片	粉碎→分散→浸泡→离心除杂→过滤→洗涤→干燥[56]	—	—	—
芒果	种仁	磨粉→混浆→过滤→离心→洗涤→干燥→粉碎	—	—	—
		碱法	—	42.05%[40]、91.72%[63]	—
		碱法协同超声法	94.95%[39]	45.2%~54.0%[40]	50.34%[39]
		蒸馏法[63]	—		—
		沉淀法[63]	—	81.87%	—
		离心法[63]	—	74.82%	—
	青芒果肉	芒果去皮→切片→(干燥)→打浆→离心/静置/过滤分离→洗涤→干燥→磨粉[31,64]	—	—	—
		干法和湿法[31]	87%以上	49%~90%	—
蛋黄果	未成熟的蛋黄果果肉	碱法: 去皮→干燥→湿磨→分离(离心、过滤)→碱泡→洗涤→干燥→磨粉[23,65~67]	96.12%[65]、63.8%[68]	—	17.19%[65]
	种子	碱法	99.07%[65]、98.09%[67]、85.7%[68]	—	22.98%[65]、19.75%[66]

a) “—”表示未报道

淀粉的提取方法有水提法[32~35]、碱提法[5,26,33,35]、酶提法[29,33]和表面活性剂提取法[26]. 提取程序主要包括(去皮)、与溶剂混合、磨浆、(均质)、筛分、(浸泡)、洗涤、分离、干燥、粉碎[5,26,32~35,38](括号中步骤在有些报道中被省略). 研究认为, 菠萝蜜种子中的蛋白质是造成淀粉提取困难的主要原因, 碱法能够溶解蛋白质从而提高淀粉的纯度[32], 酶法则能够提高淀粉的提取率[51]. 研究者通过水提法[52]、碱提法[52]和酶提法[52,53]提取面包果淀粉, 淀粉提取率为23.90%~66.25%. 面包果淀粉的提取原料一般为鲜果, 少数情况为干燥后的面包果切片. 以鲜果为原料的提取流程为: 去皮、切片、(浸泡)、磨浆、过滤、洗涤、离心分离、干燥、粉碎[21,54,55], 浸泡时所用溶液有亚硫酸氢钠溶液[21]和水等. 以干果切片为原料的提取流程为: 粉碎、分散、浸泡、离心除杂、过滤、洗涤、干燥[56], 此流程中洗涤所用溶液一般为氢氧化钠[56]、石油醚[19]、乙醇[19]和水等. 提取产量可能与果实成熟阶段, 植物品种和气候条件以及所使用的提取方法等几个因素有关[21,54]. 芒果淀粉的提取一般要先将种壳去掉, 然后再对种仁进行进一步处理, 少数研究者提出了直接带壳粉碎芒果种子的方式进行淀粉提取[57]. 得到种仁后, 芒果淀粉的一般提取流程如下: 磨粉→混浆→过滤→离心→洗涤→干燥→粉碎. 在混浆过程中, 研究者往往会调节浆液的pH至碱性以达到提高淀粉提取率的目的[39,58~61], 提取过程中常见的碱性试剂有氢氧化钠[39]、亚硫酸氢钠[59~61]、硫代硫酸钠[62]. 有些研究者在混浆过程中采用超声处理[39,40]以增加淀粉的提取率. Shahrim等人[63]比较了蒸馏、碱法、沉淀法、离心法提取芒果种子淀粉, 发现碱法的淀粉提取率最高(91.72%), 高于蒸馏法、沉淀法(81.87%)和离心分离法(74.82%). 除从芒果种仁中提取淀粉外, 一些研究者也从青芒果果肉中提取淀粉[31,64]. 将芒果去皮、切片、干燥、打浆, 离心/静置/过滤分离、洗涤、干燥、磨粉后得到芒果果肉淀粉. Lagunes-Delgado等人[31]利用干法和湿法从青芒果果肉提取淀粉, 其研究发现对同一品种的青芒果干法比湿法提取到的淀粉纯度略高, 但降低了淀粉提取率, 增加了淀粉损伤. 蛋黄果淀粉的提取研究较少, 主要为碱法, 提取流程有去皮、干燥、湿磨、分离(离心、过滤)、碱泡、洗涤、干燥、磨粉, 其中常用的碱性药品为硫代硫酸钠[23,65~67]. Agama-Acevedo等人[68]报道了稍有差别的提取工艺: 分别对蛋黄果果肉和种子淀粉进行提取, 在果肉进行湿磨时使用了柠檬酸溶液, 在种子进行脱皮和湿磨时使用了亚硫酸氢钠溶液, 洗涤时使用了石油醚. 总体来看, 6种淀粉的提取方法较为相似, 在今后的研究中可能需要根据提取原料的特点, 有针对性地设计提取方法.

2 直链淀粉含量

淀粉主要由直链淀粉和支链淀粉构成, 直支链淀粉含量的差异将导致淀粉结构、性质的差异, 进而影响其应用. 直链淀粉因其易回生、具有优异的成膜能力和更高的抗消化、抗溶胀性等特点, 近年来广受关注[69]. 表2总结了特色热带作物淀粉的直链淀粉含量, 木薯淀粉的直链含量常见范围为14.8%~28.2%[70,71], 转基因品种淀粉中的直链淀粉含量可达50%[72], 甚至接近100%[72]. 香蕉淀粉的直链淀粉含量范围为14.4%~36.87%, 菠萝蜜淀粉为26.33%~38.11%, 芒果淀粉为9.1%~36.56%. 面包果淀粉的直链淀粉含量一般为18.58%~31.85%, 蛋黄果为16.63%~35.5%. 也偶有例外, *apyrena*品种的面包果直链淀粉含量可达50%[55], 海南栽培的蛋黄果种子淀粉直链淀粉含量可达45.50%[66].

直链淀粉含量受到品种、基因型、株系、产地、提取部位、提取方法、处理方式、施肥情况和成熟度的影响. 木薯淀粉的直链含量与木薯的品种[73]、株系[71]、产地[70]、提取部位[45]和处理方式[74~79]有关. 研究发现木薯皮淀粉比木薯薯肉淀粉直链含量低[45]. 对木薯淀粉进行超微粉碎[75]或搅拌球磨机活化[76]、微波[77,78]和超声波[77,79]处理均能使直链淀粉含量增加, 而使用碱/盐对木薯淀粉进行处理一般会降低淀粉中直链淀粉含量 (硝酸锂处理后直链淀粉含量增加)[74]. 此外, 目前研究者还通过转基因手段培育出高直链或蜡质木薯, 如Zhou等人[72]开发了直链淀粉含量高达50%的转基因木薯, 泰国Siam变性淀粉公司生产了直链含量仅为1.2%的蜡质木薯淀粉[80]. 香蕉的品种[81~85]、基因型[86]、成熟度[25,46]、施肥情况[87]和提取部位[18]等均对香蕉淀粉的直链含量造成影响. Schmitz等人[26]发现未成熟的香蕉皮淀粉中直链淀粉含量随着香蕉的成熟而增高, 而果肉中的直链淀粉含量往往随着香蕉成熟而大幅降低[46]. Mesquita等人[87]发现磷酸

表 2　特色热带作物淀粉的直链淀粉含量

Table 2　The amylose content of starch from characteristic tropical crops

热带作物淀粉	品种/处理方式	直链淀粉含量
木薯淀粉	品种: 华南9号/桂热911	22.56%/27.49%[73]
	SC6和SC8不同株系	15.494%~24.726%和14.879%~21.905%[71]
	两个产地(泰国Sikhio和Soeng Sang) 5种木薯: *Huay Bong 55*、*Rayong 25*、*Rayong 102*、*Rayong 60*和*Rayong 2018*	21.0%~27.8%、23.7%~28.2%[70]
	来源部位不同	来源于木薯皮的淀粉<来源于木薯薯肉的淀粉[45]
	碱/盐处理	碱处理使木薯淀粉中直链淀粉含量降低, 而硝酸锂处理后直链淀粉含量增加, 其他盐处理使直链淀粉含量降低[74]
	超微粉碎[75]	增加
	搅拌球磨机活化[76]	增加
	微波处理[77,78]	增加
	超声波处理[77,79]	增加
	转基因手段	直链淀粉含量高达50%的转基因木薯[72], 直链含量仅为1.2%的蜡质木薯淀粉[80]
香蕉淀粉	9个品种: *Ney Poovan*、*Robusta*、*Rasthali*、*Poovan*、*Pachanadan*、*Nendran*、*Karpuravalli*、*Monthan*和*Saba*	24.41%~36.87%[81]
	香蕉果肉淀粉	16.36%[82]
	不同基因型的绿色香/大蕉淀粉	*Dominico*、*Hembra*、*Macho*和*Manzano*约为24%~25%, 而*Enano-gigante*的直链淀粉比例较低(17.6%), *Manzano*的直链淀粉比例最高(27.7%)[86]
	韩国南部*Songkibab*香蕉淀粉和常见的东南亚品种*Cavendish*香蕉淀粉	14.4%和14.9%[83]
	5个品种: *Grand Naine*、*Monthan*、*Saba*、*Nendran*和*Popoulu*	25.05%~31.86%[84]
	5个品种: *Mzuzu*、*Malindi*、*Mshale*、*Bukoba*和*Moshi*	16.67%~23.11%[85]
	不同磷酸盐施肥速率	29.01%~31.12%[87]
	未成熟的/成熟的香蕉皮淀粉	22.65%/29.31%[31]
	不同成熟度香蕉果肉淀粉	随着香蕉成熟而大幅降低[46]
	香蕉果肉淀粉/果皮淀粉	21.3%/25.7%[18]
菠萝蜜淀粉	海南本地品种/马来西亚4个品种	26.33%/32.58%~38.11%[5]
	碱提法	能够提高直链淀粉的含量 且随着碱浓度的增加, 直链淀粉含量增加[33]
	酶提法	降低淀粉中的直链淀粉含量[88]
面包果淀粉		18.58%~22.52%[54,89,90]
	以干果切片为原料	30.18%[19]
	碱提法	31.85%[21]
	水提法, 品种*apyrena*	50%[55]
芒果淀粉	碱法, 种仁, 埃塞俄比亚巴赫达尔	19.28%[62]
	—	25.90%[39]
	碱法, 印度阿姆利则, 五个芒果品种(*Chausa*, *Totapuri*, *Kuppi*, *Langra*和*Dashehari*)种仁	9.1%、16.3%、11.3%、14.0%和9.7%[59]
	希尔萨地区, 芒果果肉	16.9%[60]
	碱法/碱法+超声, 种仁, *Corazón*, 玻利瓦尔	28.46%/32.58%~36.56%[40]
蛋黄果淀粉	果肉淀粉/种子淀粉 品种: 中国海南香料饮料研究所, 成熟度较高	16.63%/33.65%[65]
	果肉淀粉/种子淀粉 墨西哥莫雷洛斯州, 未成熟	20.6%~21.3%/31.5%~35.5%[68]
	海南栽培的蛋黄果种子淀粉	45.50%[66]

盐施肥速率对香蕉淀粉的直链淀粉含量有显著影响. Li等人[18]发现香蕉果肉淀粉的直链淀粉含量明显低于果皮淀粉. Lemos等人[82]研究发现香蕉果肉淀粉中直链淀粉含量低于马铃薯和玉米淀粉, 高于木薯淀粉.

菠萝蜜淀粉的直链含量随其产地、品种和提取方式的不同而有差异. Zhang等人[5]的研究显示海南本地品种菠萝蜜淀粉的直链含量远低于马来西亚的品种. 研究显示使用碱提法提取菠萝蜜淀粉能够提高直链淀粉的含量, 且随着碱浓度的增加, 直链淀粉含量增加[33], 而酶提法提取淀粉会降低淀粉中的直链淀粉含量[88]. 面包果淀粉的直链含量通常在18.58%~22.52%[54,89,90], 然而近年来提取到的面包果的直链淀粉含量均高于此范围[19,21,55], 这主要与品种有关.

芒果淀粉的直链含量由于产地、品种和提取方法的不同有较大差异. 同为碱法提取, 从埃塞俄比亚巴赫达尔获得的芒果种仁淀粉中直链含量为19.28%[62], 从希尔萨地区的芒果中提取的淀粉直链淀粉含量为16.9%[60], 而从印度阿姆利则当地的五个芒果品种的种仁中所提取淀粉的直链含量分别为9.1%、16.3%、11.3%、14.0%和9.7%[59]. 同一种芒果种仁, 使用碱法和超声协同的手段提取的淀粉直链含量远高于碱法提取的淀粉[40].

蛋黄果淀粉直链含量受品种、成熟度和提取部位的影响较大. Li等人[65]和Agama-Acevedo等人[68]发现蛋黄果果肉淀粉直链淀粉含量低于种子淀粉[65,68]. Li等人[65]和Agama-Acevedo等人[68]所使用的蛋黄果品种和成熟度不同, 前者来自于中国海南香料饮料研究所(第202007号), 后者来源于墨西哥莫雷洛斯州, 前者的成熟度较高, 而后者为未成熟的蛋黄果.

3 多尺度结构

淀粉的多尺度结构是淀粉基础研究的主要内容之一, 通常将淀粉的结构分为五级, 分别为颗粒结构、半结晶层和无定形层交替形成的生长环结构、小块结构、螺旋结构和分子结构, 涉及指标包括颗粒形貌和粒径、晶型、结晶度、半结晶片层厚度、短程有序性、链长分布、相对分子量等.

3.1 颗粒结构

特色热带作物淀粉颗粒大多都呈现出球形[91~105], 但也呈现其他形状(表3): 木薯淀粉颗粒还呈现椭球形[87,88,91,96,102~104]、或球形缺陷(截断)状[95,103,106~111]; 香蕉淀粉颗粒还呈现扁平状、不规则椭圆形、细长杆状和锥形等[2,48,50,112,113]; 菠萝蜜淀粉颗粒还呈现椭圆形和钟形[114~118], 也有呈现三角形和四边形[3,119,120]; 面包果淀粉还呈亚球形[8]或椭圆形[121], 有些则会同时出现不规则形状[19,56]; 芒果淀粉还呈卵形或椭圆形[31,61,122~124], 有部分报道其还呈长方形或不规则的立方体形[63,125,126]; 蛋黄果淀粉还呈椭圆形到钟形[65,67,68,127]. 特色热带作物淀粉大多数颗粒表面光滑[91,92,96,98,99,101,102,110,126,128~132], 面包果淀粉颗粒表面光滑但有孔[104], 芒果淀粉表面光滑程度不一, 大部分报道其表面光滑, 部分报道其表面有孔或凹痕[61,124,133].

淀粉颗粒大小一般不均一[93,99,100,107,108,134], 香蕉淀粉的粒径尺寸差异很大[48,112], 在6~80 μm[87]. 木薯淀粉、芒果淀粉和蛋黄果果肉淀粉的颗粒尺寸在30 μm以下, 木薯淀粉颗粒尺寸在7~20 μm[92~94,97~99,101,103,111,135~143]变化, 蛋黄果果肉的淀粉颗粒粒径为5.03~30.15 μm[65,68,127]. 芒果淀粉的粒径为5.62~36.48 μm, 大多数集中在13.0~19.2 μm[39,61,63,130~133,146~148]. 此外, Patiño-Rodríguez等人[122]发现芒果淀粉的平均粒径为50 μm. 菠萝蜜淀粉、芒果淀粉、面包果淀粉和蛋黄果种子淀粉的颗粒较普通玉米淀粉小, 可能可以用作脂肪替代物. 菠萝蜜淀粉绝大多数粒径为3~15 μm[3,33,115,116,144], 仅见Choy等人[145]报道了菠萝蜜淀粉的粒径范围为1.1~41.6 μm. 面包果淀粉颗粒直径介于1.5~16.5 μm之间[8,19], 一般小于10 μm[56,104,105,121], 而蛋黄果种子淀粉粒径为4~11.93 μm[65,67,68]. 与淀粉颗粒形状和粒径相比, 比表面积的报道相对较少. 木薯淀粉的比表面积差异较大, Zhou等人[93]报道的为0.44 cm^2/g, 而Mutungi等人[142]报道的却为1 m^2/cm^3. 面包果淀粉颗粒比表面积较大, Adebayo等人[8]报道了一种来源于牙买加曼彻斯特教区的面包果淀粉, 其比表面积为4410 cm^2/g. 淀粉颗粒的比表面积大有助于提高其酶解效率, 有助于生物乙醇、糖类等的生产.

3.2 结晶结构

三种晶型(表4)均在特色热带作物淀粉中出现, 相对结晶度范围较广, 大多数为10%~40%. 木薯淀粉的晶型一般为A型[92,93,95,97,98,101,106,107,109~111,149~152]或C型[91,94,96,99,106,142,143], 其相对结晶度范围为21.3%[100]

表 3　特色热带作物淀粉的颗粒结构a)

Table 3　The granule structure of starch from characteristic tropical crops

热带作物淀粉	颗粒形貌	粒径	比表面积
木薯淀粉	球形[91~103]、椭球形[91,92,95,100,106~108]、或球形缺陷(截断)状[95,103,106~111], 颗粒表面光滑[91,92,96,98,99,101,102,110]	木薯淀粉颗粒大小不均一[93,99,100,107,108,134]颗粒尺寸在7~20 μm[92~94,97~99,101,103,111,135~143]	0.44 cm^2/g[93]、1 m^2/cm^3[142]
香蕉淀粉	颗粒形状多样, 包括球状、扁平状、不规则椭圆形、细长杆状和锥形等[2,48,50,112,113], 颗粒表面光滑[128,129]	粒径尺寸差异很大[48,112], 在6~80 μm[87]	—
菠萝蜜淀粉	颗粒表面光滑, 主要为球形、椭圆形和钟形[114~118], 也有呈现三角形和四边形[3,119,120]	该淀粉颗粒分布较为集中, 绝大多数粒径为3~15 μm[3,33,115,116,144], 也见粒径范围为1.1~41.6 μm[145]的报道	—
面包果淀粉	呈球形[104,105]、亚球形[8]或椭圆形[121], 有些则会同时出现不规则形状[19,56], 表面光滑但有孔[104]	淀粉颗粒较小, 直径介于1.5~16.5 μm之间[8,19], 一般小于10 μm[56,104,105,121]	4410 cm^2/g[8]
芒果淀粉	多为球形、卵形或椭圆形[37,61,122~124], 有部分报道其还呈现长方形或不规则的立方体形[63,125,126]. 该淀粉表面光滑程度不一, 大部分报道其表面光滑[126,130~132], 部分报道其表面有孔或凹痕[61,124,133]	芒果淀粉的粒径为5.62~36.48 μm, 大多数集中在13.0~19.2 μm[39,61,63,130~133,146~148]. 此外, 有研究发现芒果淀粉的平均粒径为50 μm[122]	—
蛋黄果淀粉	球形、椭圆形到钟形[65,67,68,127]	颗粒较小, 来源于果肉的淀粉颗粒粒径为5.03~30.15 μm[65,68,127], 来源于种子的淀粉粒径为4~11.93 μm[65,67,68]	—

a) “—”表示未见报道

~45.78%[107]. C型木薯淀粉中, 蜡质木薯淀粉的 A/B 型比例为75/25~95/5, 普通木薯淀粉为80/20~85/15[139], 且蜡质木薯淀粉的相对结晶度高于普通木薯淀粉[106]. 菠萝蜜淀粉[3,33,34,115]、芒果淀粉[60,61,63,122,125,130~132,153]和蛋黄果淀粉[65,67,68]的晶型为A型, 也有极个别报道芒果淀粉为C型结晶[37,132]. 菠萝蜜淀粉的相对结晶度为9.3%~40.64%[3,33,34,115], 大多数在20%以上[32,35,154,155]. 芒果淀粉的相对结晶度主要集中于24.50%~26.70%[133,156]和35.4%~41.30%[39,61,130,148]这两个范围. 对同一种蛋黄果, 来源于种子的淀粉结晶度高于来源于果肉的淀粉, 果肉淀粉的结晶度17.15%~21.40%, 种子淀粉则为22.68%~39.20%[65,67,68]. 面包果淀粉为B型结晶, de Carvalho Batista Muniz等人[21]报道了产自巴西伊列乌斯市的apyrena 品种的绿色面包果中分离的淀粉的相对结晶度为32.54%. Tan等人[56]报道的产自马达加斯加去皮和干燥的面包果片中分离出的淀粉相对结晶度则14.3%. 香蕉淀粉的晶型大多数为B型[18,37,87,112,113,128,157~160]和C型[48,50,112,161~165], 也有少量报道其为A型[2,83,166], 相对结晶度变化范围为18.4%~41.1%[2,50,160,161]. 总体来说, 特色热带作物淀粉的结晶度较普通玉米淀粉高, 这可能是导致特色热带作物淀粉抗消化的原因之一.

特色热带作物的半结晶结构研究相对较少, 木薯淀粉的散射峰位置q一般在0.6~0.7 nm^{-1}, 半结晶片层的平均厚度在9.39~9.905 nm[93,95,143]. 香蕉果肉淀粉和果皮淀粉在小角散射光谱中, 散射峰分别在0.071和0.072 $Å^{-1}$处出现, 对应的层状结构厚度分别为8.79和8.71 nm[18]. Chen等人[25]报道了菠萝蜜淀粉的散射峰位置q为0.6934 nm^{-1}, 则其半结晶片层的厚度为9.061 nm. Tan等人[56]还报道了面包果淀粉在小角散射测定中散射峰的位置在0.6932 nm^{-1}, 半结晶片层厚度为9.06 nm. Li等人[23]报道了蛋黄果淀粉的层状结构和螺旋结构, 果肉淀粉和种子淀粉的散射峰位置为0.692和0.709 nm^{-1}, 对应半结晶片层厚度为9.074和8.858 nm, 其中结晶层平均厚度分别为5.422和5.243 nm.

3.3　螺旋结构

表5显示了特色热带作物淀粉的螺旋结构. 从955/1022 cm^{-1}的比值来看, 木薯淀粉与香蕉淀粉相似, 大于蛋黄果淀粉和面包果淀粉. 从1047/1022 cm^{-1}的比值

表 4 特色热带作物淀粉的结晶和半结晶结构a)

Table 4 The crystalline and semi-crystalline structure of starch from characteristic tropical crops

特色热带作物淀粉	晶型	结晶度	散射峰位置	半结晶片层厚度
木薯淀粉	A型[92,93,95,97,98,101,106,107,109~111,149~152]或C型[91,94,96,99,106,142,143]	21.30%[100]-45.78%[107]	0.6~0.7 nm^{-1}[93,95,143]	9.390~9.905 nm[93,95,143]
香蕉淀粉	大多数为B型[18,37,87,112,113,128,157~160]和C型[48,50,112,161~165], 也有少量报道其为A型[2,84,166]	18.4%~41.1%[2,50,160,161]	果肉淀粉: 0.071 Å^{-1} 果皮淀粉: 0.072 Å^{-1}[18]	果肉淀粉: 8.79 nm 果皮淀粉: 8.71 nm[18]
菠萝蜜淀粉	A型[3,33,34,115]	9.3%~40.64%[3,33,34,115], 大多数在20%以上[32,35,154,155]	0.6934 nm^{-1}[25]	9.061 nm[25]
面包果淀粉	B型[21,56]	32.54%[21]、14.3%[56]	0.6932 nm^{-1}[56]	9.06 nm[56]
芒果淀粉	A型[56,60,63,122,125,130~132,153], 极个别报道其为C型[37,132]	主要集中于24.50%~26.70%[133,156]和35.4%~41.30%[39,61,130,148]	—	—
蛋黄果淀粉	A型[65,67,68]	果肉淀粉: 17.15%~21.40%, 种子淀粉: 22.68%~39.20%[65,67,68]	果肉淀粉: 0.692 nm^{-1}, 种子淀粉: 0.709 nm^{-1}[23]	果肉淀粉: 9.074 nm, 种子淀粉: 8.858 nm[23]

a) "—"表示未见报道

表 5 特色热带作物淀粉的螺旋结构

Table 5 The helical structure of starch from characteristic tropical crops

特色热带作物淀粉		短程有序性		游离侧链/双螺旋/V型晶型/无定形态含量(%)	α-1,4/α-1,6糖苷键的含量(%)
		955 cm^{-1}/1022 cm^{-1}	1047 cm^{-1}/1022 cm^{-1}		
木薯淀粉		1.180~1.393[100,108,152]	0.72~1.12[91,100,108,110,149]	—	—
香蕉淀粉		0.894~1.69[18,112,164]	0.55~1.12[18,112,164]	—	—
面包果淀粉		0.521[21]	1.617[21]	—	—
蛋黄果淀粉	果肉淀粉	0.68[68]	0.675[65]	9.88/39.24/3.33/57.43[23]	91.25/8.75[23]
	种子淀粉	0.72[68]	1.27[67] 0.740[65]	11.14/44.70/4.78/50.52[23]	90.02/9.98[23] 88.31/11.69[67]

a) "—"表示未见报道

来看, 由大到小的顺序为面包果淀粉, 蛋黄果种子淀粉, 木薯淀粉, 香蕉淀粉和蛋黄果果肉淀粉. 不同报道关于蛋黄果淀粉的955 cm^{-1}/1022 cm^{-1}和1047 cm^{-1}/1022 cm^{-1}的比值差异较大, Agama-Acevedo等人[68]报道了果肉淀粉的955 cm^{-1}/1022 cm^{-1}的值为0.68, 而种子淀粉则为0.72, 果肉和种子淀粉的1047 cm^{-1}/1022 cm^{-1}的值均为0.13; Li等人[65]报道了果肉和种子淀粉的1047 cm^{-1}/1022 cm^{-1}的值分别为0.675和0.740, 而Luo等人[67]报道种子淀粉的1047 cm^{-1}/1022 cm^{-1}的值则为1.27.

特色热带作物淀粉的双螺旋、无定形态等的含量和α-1,4/α-1,6糖苷键的含量信息相对缺失, 仅见蛋黄果的相关报道: 蛋黄果果肉和种子淀粉的游离侧链分别为9.88%和11.14%, 双螺旋含量为39.24%和44.70%, V型晶型含量分别为3.33%和4.78%, 无定形态含量为57.43%和50.52%[23]. Li等人[23]报道了果肉和种子淀粉的α-1,4糖苷键的含量为91.25%和90.02%, α-1,6糖苷键的含量为8.75%和9.98%, 而Luo等人[67]报道的种子淀粉的α-1,4和α-1,6糖苷键的含量分别为88.31%和11.69%.

3.4 分子结构

表6显示了特色热带作物淀粉的分子结构. 特色热带作物淀粉的A链(DP 6-12)、B1链(DP 13-24)、B2链(DP 25-36)和B3链(DP≥37)含量分别集中在20%~30%、40%~50%、10%~20%和20%以下. 但也有一些比较特殊的淀粉, 如Xu等人[152]报道了一种较为特殊的木薯淀粉, 其A链、B1链B2链和B3链的含量分别

表 6 特色热带作物淀粉的分子结构[a)]

Table 6 The molecular structure of starch from characteristic tropical crops

特色热带作物淀粉	链长分布(%)				分子量	回旋半径
	A链	B1链	B2链	B3链		
木薯淀粉	21.1%~30.9%[70,103,167,170] 16%[152]	43.4%~49%[70,103,167,170] 27%[152]	12.5%~14.6%[70,103,167,170] 12%[152]	7.2%~16.5%[70,103,167,170] 45%[152]	普通木薯: Mw, 2.0×10^8 g/mol[168] Mn: 1.5×10^5 g/mol, Mw: 5.3×10^5 g/mol[142] Mw: 0.628×10^7~2.64×10^7 g/mol[143] 蜡质木薯支链淀粉的Mw为4.08×10^6 g/mol[139]	51.3~58.45 nm, 其中直链淀粉为18.1~20.55 nm, 支链淀粉为59.8~90.4 nm[70,167] 174.1 nm[168] 96.6~150.0 nm[143]
香蕉淀粉	25.06%~33.3%[50,83,157,165]	40.27%~49.2%[50,83,157,165]	10.50%~18.30%[50,83,157,165]	6.40%~16.42%[50,83,157,165]	Mw: 1.70×10^8~5.65×10^8 g/mol[169] 3.109×10^7~4.820×10^7 g/mol[165]	184.80~239.55 nm[169] 93.3~109.2 nm[165]
菠萝蜜淀粉	20.8%~25.9%[3,33,171] 33.89%~38.33%[5]	42.7%~50.1%[3,33,171] 39.06%~39.58%[5]	12.30%~16.04%[3,33,171] 17.13%~18.43%[5]	10.36%~20.70%[3,33,171] 4.96%~8.62%[5]	Mw: 1.74×10^7~4.61×10^7 g/mol[5], Mn: 1.10×10^7~2.34×10^7 g/mol[5]	115.4~144.2 nm[5]
面包果淀粉	—	—	—	—	Mw: 2.386×10^7 g/mol[56]	105.5 nm[56]
芒果淀粉	16.36%[156] 支链淀粉: 25.70%~39.19%[124,130]	26.33%[156] 支链淀粉: 46.10%~53.24%[124,130]	10.48%[156] 支链淀粉: 8.36%~13.74%[124,130]	46.81%[156] 支链淀粉: 2.35%~16.60%[124,130]	直链淀粉Mw: 2.79×10^5~6.20×10^6 g/mol[130,148], 支链淀粉Mw: 1.14×10^6~5.01×10^7 g/mol[37,124,130,148,156]	直链淀粉: 124~134 nm[148], 支链淀粉: 141~317 nm[124,148]
蛋黄果淀粉 果肉	29.4%[68]	41.5%[68]	14.9%[68]	15.0%[68]	Mn: 2.08×10^7 g/mol, Mw: 2.79×10^7 g/mol[23]	89.4 nm[23]
蛋黄果淀粉 种子	20.3%[68]	48.8%[68]	13.8%[68]	16.5%[68]	Mn: 2.14×10^7~2.5×10^7 g/mol, Mw: 3.64×10^7~6.43×10^7 g/mol[23,67]	107.0~118.9 nm[23,67]

a) "—"表示未见报道

为16%、27%、12%和45%. Zhang等人[5]报道的来自中国的5种菠萝蜜淀粉的链长分布则为33.89%~38.33%(A链)、39.06%~39.58%(B1链)、17.13%~18.43%(B2链)、4.96%~8.62%(B3链). Casarrubias-Castillo等人[156]报道了产自墨西哥的芒果淀粉的A链、B1链B2链和B3链的含量分别为16.36%、26.33%、10.48%和46.81%. Saeaurng和Kuakpetoon130]和Espinosa-Solis等人[124]等报道了4个品种的芒果淀粉，其支链淀粉A链、B1链B2链和B3链的含量范围为25.70%~39.19%、46.10%~53.24%、8.36%~13.74%和2.35%~16.60%. 总体来说，特色热带作物淀粉的长链含量较普通玉米淀粉和大米淀粉高，这可能是导致其糊化黏度高的原因之一. 特色热带作物的聚合度研究较少，仅见对木薯淀粉聚合度的研究. Tappiban等人[70,167]对木薯淀粉的聚合度进行测定，结果表明其中直链淀粉的聚合度分别为1392.5~2000.5、1443.0~1588.5和1296~1529，支链淀粉峰1的聚合度分布分别为16.0~16.4、15.4~16.4和15.9~16.5，支链淀粉峰2的聚合度分布分别为37.3~37.6、37.2~37.7和37.3~37.7.

木薯淀粉、香蕉淀粉和芒果淀粉的分子量分布和回旋半径分布范围较广，而其他三种淀粉的分子量分布和回旋半径分布范围较为集中. 众多研究者对木薯淀粉的相对分子量进行测定，但其结果差异较大，这可能与木薯淀粉来源、生长期以及测定仪器的情况有关. Tappiban等人[70]使用体积排阻色谱测定了两个产地的5种木薯淀粉的平均流体力学半径，分别为54.95~57和51.3~56.35 nm，其中直链淀粉为18.35~19.75和18.2~19.65 nm，支链淀粉为63.2~90.4和59.8~83.05 nm. Tappiban等人[167]还比较了另外七个品种的木薯淀粉,

其平均流体力学半径为53.35~58.45 nm, 直链淀粉为18.1~20.55 nm, 支链淀粉为60.1~87.95 nm. Castanha等人[168]使用高效尺寸排阻色谱和凝胶渗透色谱测得木薯淀粉得回旋半径为174.1 nm, 重均分子量(Mw)为2.0×10^8 g/mol, 分散度为1.1. Mutungi等人[142]测得木薯淀粉的数均分子量(Mn) 和Mw分别为1.5×10^5和5.3×10^5 g/mol. Rolland-Sabaté等人[139]测得的蜡质木薯支链淀粉的Mw为4.08×10^6 g/mol. Tan等人[143]比较了不同生长期的木薯淀粉结构, 显示其Mw为0.628×10^7~2.64×10^7 g/mol, 流体力学半径在96.6~150.0 nm范围变化. Rodriguez-Ambriz等人[169]和Wang等人[160]报道的香蕉淀粉的Mw范围分别为1.70×10^8~5.65×10^8和3.109×10^7~4.820×10^7 g/mol, 分散度分别为2.24~2.82和1.147~1.232, 回旋半径分别为184.80~239.55和93.3~109.2 nm. 菠萝蜜淀粉的Mw, Mn和回转半径分别为1.74×10^7~4.61×10^7, 1.10×10^7~2.34×10^7和115.4~144.2 nm[5]. 面包果淀粉的Mw为2.386×10^7 g/mol, 回旋半径为105.5 nm, 分子量小于1×10^7 g/mol占比7.79%, 分子量介于1×10^7和3×10^7 g/mol之间的占比80.35%, 而大于3×10^7 g/mol占比同为7.79%[56]. 芒果淀粉支链淀粉Mw为1.14×10^6~5.01×10^7 g/mol[31,124,130,148,156], 直链淀粉Mw为2.79×10^5~6.20×10^6 g/mol[130,148], 直支链淀粉的回旋半径分别为124~134 nm[148], 141~317 nm[124,148]. 蛋黄果种子淀粉的Mn, Mw和回旋半径分别为2.14×10^7~2.5×10^7, 3.64×10^7~6.43×10^7和107.0~118.9 nm[23,67]. 果肉淀粉的Mn, Mw和回旋半径分别为2.08×10^7, 2.79×10^7和89.4 nm[23].

4 性质

淀粉的性质是应用研究的基础, 研究者主要考察淀粉的色度、堆积密度、pH、吸水性、溶解度、膨润力、糊化特性、热学特性、凝胶特性、冻融稳定性和消化性等, 然后根据淀粉的性质提出淀粉可能的应用场景.

4.1 白度、pH、堆积密度

特色热带作物淀粉大多数为白色, 当除杂不彻底时, 香蕉淀粉为轻微的黄色且颜色偏暗[48], 面包果淀粉为亮黄色[172], 芒果淀粉淡白色偏黄色[39]. 表7呈现了6种特色热带作物淀粉的亮度值, 均在76%以上[173,174], 大多数在90%以上[104,115,175~180]. 淀粉的酸度可以反映其质量和稳定性, 对其后续加工及加工过程控制具有重要意义. 木薯、香蕉、菠萝蜜、面包果和芒果淀粉均为酸性[105,129], 其中菠萝蜜[181]和芒果淀粉[62]的酸性较弱. 堆积密度的大小可用于判别粉质的细腻程度, 研究发现菠萝蜜淀粉的堆积密度在0.42~0.75 g/cm^3[115,117,145,155,181], 面包果淀粉的堆积密度为0.28~0.33 g/cm^3[8,105,182], 蛋黄果果肉和种子淀粉的堆积密度分别为0.47和0.62 g/cm^3[65], 这说明菠萝蜜淀粉较面包果淀粉更为细腻, 蛋黄果种子淀粉比果肉淀粉更为细腻.

4.2 吸水吸油性、溶解度、膨润力、透明度

本文汇总了特色热带作物淀粉的吸水吸油性、溶解度、膨润力、透明度(表8). 6种淀粉的吸水量一般在0.7~3 g/g[8,21,33,39,54,65,100,115,121,126,133,142,182,183,186,187], 吸油性一般在2 g/g以下[8,21,33,54,55,65,115,117,121,182,183,186]. 香蕉淀粉的吸水/油性与测试温度、品种和成熟度等均有关, 其吸水性一般在2 g/g以下[2,47,48,113,128,159,161], 另外有一些报道发现香蕉淀粉的吸水性在2~16 g/g[109,166], 其吸油性一般在5 g/g以下[161], 大多数不超过2 g/g[2,159,162].

6种淀粉中溶解度大多数为0~27 mg/g, 各淀粉的膨润力有较大差异. 木薯品种、测定的温度等对其淀粉溶解度和膨润力有显著影响, 从0~95℃, 溶解度的变化范围为0.54%[184]~60%[142], 膨润力的变化范围为2~60 g/g[91,97,138,149]. Airlangga等人[91]报道了在85°C下, Budi Jaya(印度尼西亚雅加达)木薯淀粉的溶解度为0.205±0.105 mg/g, 膨润力为7.222±0.348 g/g. Mei等人[149]报道了木薯淀粉在55°C~85°C条件下, 溶解度和膨润力分别在1~25 mg/g和2~23 g/g变化. Ceballos等人[138]比较了3种基因型的木薯淀粉的性质, 发现突变体的木薯淀粉的溶解度(6.0%)显著低于普通木薯淀粉(14.1%和13.4%), 而膨润力较高, 为55.7 g/g. 香蕉淀粉的溶解度和膨润力随着测定温度(50℃~95℃)的变化在0~26.5 mg/g[96,159]和0.5~98 g/g[2,109,112,113,159,161,185]范围内变化, 大多数香蕉淀粉的溶解度在16 mg/g以下[48,161,163,166,188], 膨润力在35 g/g以下[109,112,113,159,161,185]. 菠萝蜜淀粉的溶解度和膨润力与其产地和品种有关, 其溶解度范围为0.13%~20.59%, 其膨润力范围则为3.33%~23.00%[3,33,115,117,179,181,186]. 面包果淀粉的溶解

表 7 特色热带作物淀粉的白度、pH、堆积密度

Table 7 The whiteness, pH and packing density of starch from characteristic tropical crops

特色热带作物淀粉	颜色	亮度值L	pH	堆积密度
木薯淀粉	白色	96.02[175]	4.90±0.12[183]	—
香蕉淀粉	轻微的黄色, 颜色有些发暗[48]	76.30%~89.88%[173,174]	4.60[129]	—
菠萝蜜淀粉	—	90%以上[115,176~179]	6.56~6.70[181]	0.42~0.75 g/cm^3[115,117,145,155,181]
面包果淀粉	白色, 除杂不彻底时为亮黄色[172]	97.5%以上[104,180]	4.73[105]	0.28~0.33 g/cm^3[8,105,182]
芒果淀粉	淡白色偏黄色	79.63[39]	6.26[62]	—
蛋黄果淀粉	—	—	—	果肉淀粉: 0.47 g/cm^3和种子淀粉: 0.62 g/cm^3[65]

a) “—”表示未见报道

表 8 特色热带作物淀粉的吸水吸油性、溶解度、膨润力、透明度a)

Table 8 The water absorption/oil absorption, solubility, swelling power and transparency of starch from characteristic tropical crops

特色热带作物淀粉	吸水性	吸油性	溶解度	膨润力	透明度
木薯淀粉	2~3 g/g[92,100,142]	—	0.54%[184]~60%[142]	2~60 g/g[91,97,138,149]	50%~70%[103]
香蕉淀粉	2 g/g以下[2,47,48,113,128,159,161] 2~16 g/g[109,166]	5 g/g以下[161] 不超过2 g/g[2,159,162]	0~26.5 mg/g[96,159]	0.5~98 g/g[2,109,112,113,159,161,185]	3.5%以下[48,113,129,161,185]
菠萝蜜淀粉	0.89~2.82 g/g[33,115,183,186]	0.70~1.90 g/g[33,115,117,183,186]	0.13%~20.59%[3,33,115,117,179,181,186]	3.33%~23.00%[3,33,115,117,179,181,186]	放置24 h时12.10%, 放置到第7天时透光率为1.20%[176] 刚冷却时: 4.57%[155]
面包果淀粉	0.8~2.2 g/g[8,21,54,55,121,182]	0.39~2.15 g/g[8,21,54,55,121,182]	0~20%[55,121,182] 48.87%~93.5%[54]	1.33~12 g/g[54,55,121,182]	38%[55]
芒果淀粉	0.77~2.04 g/g[39,126,133,187]	0.91~1.02 g/g[153]	2.14%~19%[39,60,62,153] 59%和52%[133]	2.25~21.73 g/g[39,60,126,153] 40.75和44.70 g/g[133]	3%左右[62]
蛋黄果淀粉	果肉淀粉: 1.23 g/g和种子淀粉: 0.95 g/g[65]	果肉淀粉: 93.58%和种子淀粉: 74.71%[65]	—	—	—

a) “—”表示未见报道

度通常在0~20%变化[55,121,182], 膨润力范围为1.33~12 g/g[54,55,121,182]. Adebowale等人[54]报道了来自尼日利亚Elekiri的面包果淀粉, 其溶解度较高, 在50~80℃下从48.87%增加至93.5%. 芒果淀粉溶解度为2.14%~19%[39,60,62,153], 膨润力为2.25~21.73 g/g[39,60,126,153]. Ramírez-Brewer等人[133]报道了两种芒果淀粉, 其溶解度和膨润力较高, 分别为59%、52%及40.75和44.70 g/g. 总体来说, 6种淀粉中, 菠萝蜜淀粉、面包果淀粉、芒果淀粉和蛋黄果淀粉的吸水性和吸油性较差, 膨润力较低, 适用于制作油炸食品(减少食品脂肪含量)、粉丝等. 淀粉糊的透明度对淀粉的应用有重要影响. 6种淀粉中木薯淀粉糊的透明度最高, 其透光率在50%~70%[103], 面包果淀粉糊次之, 透光率为38%[55], 其他淀粉的透明度都比较低, 这说明木薯淀粉和面包果淀粉更适用于淀粉基薄膜的制作. 香蕉淀粉糊在1~5天内透光率均在3.5%以下[48,113,129,161,185]. 菠萝蜜淀粉成糊后, 放置24 h时透光率为12.10%, 放置到第七天时透光率为1.20%[176]. 另一报道显示, 刚冷却时菠萝蜜淀粉糊的透光率为4.57%[155]. 芒果淀粉糊的透明度在3%左右[62].

4.3 糊化特性

6种淀粉的成糊温度(表9)由高到低的顺序为菠萝蜜淀粉、芒果淀粉、蛋黄果淀粉、香蕉淀粉和面包果淀粉、木薯淀粉. 木薯淀粉的成糊温度为60~80℃[80,97,189,190], 主要集中于70~75℃[70,92,100,111]. 木薯淀粉的糊化特性与其测定浓度[80,97,111,141,189]、品种[80]、生长地[70]、基因型[70]和发育期[143]等均有关.

表 9 特色热带作物淀粉的成糊温度

Table 9 The pasting temperature of starch from characteristic tropical crops

特色热带作物淀粉	成糊温度
木薯淀粉	60~80℃[80,97,189,190]
香蕉淀粉	64.6~86.0℃[37,113,129,161]
菠萝蜜淀粉	77.9~91.3℃[6,32,33,115,119,171,176,179]
面包果淀粉	64.6~85.7℃[112,121]
芒果淀粉	71.3~85℃[124,125,131,187]
蛋黄果淀粉	果肉和种子淀粉:70.95℃和74.45℃[65]

同样的浓度下，木薯淀粉的峰值黏度高于玉米淀粉而远低于马铃薯淀粉[168], 蜡质木薯淀粉的回值黏度又远低于普通木薯淀粉[103]. 香蕉淀粉的峰黏、崩解值和回值均低于甘薯淀粉[128]，高于普通玉米淀粉[109,185]和小麦淀粉[185]. 菠萝蜜淀粉的成糊温度较高, 但也有例外, Tran等人[191]报道了一种越南菠萝蜜种子淀粉的起始糊化温度为64.2℃. 菠萝蜜淀粉的峰值黏度、谷值黏度、终值黏度、崩解值和回值一般高于玉米淀粉、木薯淀粉、芒果淀粉，低于马铃薯淀粉[27]. 同一测定浓度下，面包果淀粉的RVA黏度曲线整体低于马铃薯淀粉、玉米淀粉[19]和香蕉淀粉[112,121]. 芒果淀粉的RVA黏度曲线高于普通玉米淀粉而低于香蕉淀粉[124]. 蛋黄果种子淀粉糊的峰值黏度比果肉淀粉糊高，但谷值黏度和终值黏度比果肉淀粉糊低[65]. 整体来说蛋黄果淀粉比菠萝蜜淀粉起始糊化温度低, 糊化黏度高[65].

4.4 热力学特性

表10汇总了6种特色热带作物淀粉通过差示扫描量热仪(DSC)测定的热力学特性. 6种特色热带作物淀粉的开始(*To*), 峰值(*Tp*), 终止温度(*Tc*)整体呈现菠萝蜜淀粉>面包果淀粉≈芒果淀粉>香蕉淀粉>木薯淀粉≈蛋黄果淀粉的趋势. 焓变 (ΔH)的整体趋势为菠萝蜜淀粉>面包果淀粉≈木薯淀粉≈香蕉淀粉≈芒果淀粉>蛋黄果淀粉. 菠萝蜜淀粉和面包果淀粉糊化需要更多的热量，这也是造成这两种淀粉抗性淀粉含量高的原因之一. 蜡质木薯淀粉的DSC参数高于普通木薯淀粉[138]. 菠萝蜜淀粉呈现较宽的*To*, *Tp*, *Tc*和ΔH范围，分别为36.00~87.73℃，55.00~91.80℃，58~130.82℃，0.33~480.05 J/g[6,115,116,145,179,186]. 其中*To*主要集中于40~50℃[115,183,186]和72~88℃[6,117,154,155,176]，*Tp*主要集中于75~90℃[6,115,117,154,176]，*Tc*主要集中于91~116℃[6,25,35,115]，ΔH则主要集中7~20 J/g[26,27,29,115,181]. Tan等人[56]报道了面包果淀粉的*To*, *Tp*, *Tc*和ΔH分别为67.3℃、70.9℃、74.9℃和18.5 J/g，而Oderinde等人[121]报道的结果则为79.3℃、84.7℃、89.4℃和14.1 J/g. 蛋黄果种子淀粉的热力学参数普遍高于果肉淀粉[65,67,68].

4.5 流变及凝胶特性

6种特色热带作物淀粉的流变特性均显示出随着剪切速率的增加，剪切力在一段时间的快速增加后趋于平稳，而表观黏度则下降，这是假塑性流体的典型特征[92,97,133]. 此外, 6%(w/w)的木薯淀粉凝胶表现出类固体行为, 有较好的弹性特征[92,97]. 香蕉淀粉也有类固体行为[161,162,169]，但香蕉淀粉的稠度应远低于木薯淀粉[92,161,162,169]. 6%(w/w)以上的菠萝蜜淀粉溶液经过糊化后即可形成凝胶，浓度超过9%(w/w)即可形成硬凝胶[176]. 面包果淀粉在浓度超过8%(w/w)时即可形成凝胶[21,121], 14%(w/w)以上即可形成硬凝胶[21], 且在pH<3条件下表现出更多的牛顿流体行为[19]. 芒果淀粉糊动态流变显示其表现出更多的弹性特性[123]. 6%(w/w)芒果淀粉糊液形成弱凝胶，其凝胶硬度和凝胶强度显著高于玉米淀粉而显著低于豆类淀粉[132]. 总体来说，木薯淀粉、菠萝蜜淀粉和芒果淀粉在6%(w/w)浓度下即可形成凝胶，而香蕉淀粉和面包果淀粉需要更高的浓度.

4.6 冻融稳定性

普通木薯淀粉的冻融稳定性较差，而蜡质木薯淀粉相对较优[103]. 在1~5个冻融周期内, 5%(w/w)固含量的普通木薯淀粉失水率最高接近50%[149]，而同样固含量的蜡质木薯淀粉几乎不失水[135,192]. Garride等人[193]报道了来自巴西的木薯淀粉的冻融稳定性，10%(w/w)固含量的木薯淀粉在3个冻融周期内其失水率为0.45%~0.7%，而18%(w/w)固含量的淀粉失水率为0~0.5%，但文中未指明是否为蜡质木薯淀粉. 香蕉淀粉的冻融稳定性呈现较大的差异，失水率从2%~72%不等[48,185]，这与淀粉的品种[129,162]、冻融循环次数[48,109]、冻融温度[109]有关. 菠萝蜜淀粉的冻融稳定性一般较差, 失水率在19.7%~55.0%[6,119], 但也有部分品种冻融稳定性较好，如Dutta等人[178]从印度阿萨姆

表 10　特色热带作物淀粉的热特性

Table 10　The thermal properties of starch from characteristic tropical crops

特色热带作物淀粉		*To*	*Tp*	*Tc*	*ΔH*
木薯淀粉		50.9~68.1°C[70,91,92,94,95,141,150,170]	62.62~74.31°C[70,91,92,94,95,141,150,170]	69.56~86.77°C[70,91,92,94,95,141,150,170]	2.07~18.5 J/g[70,91,92,94,95,141,150,170]
香蕉淀粉		57.33~76.02°C[2,48,112,113,128,157,162]	60.64~79.80°C[2,48,112,113,128,157,162]	66.02~89.90°C[2,48,112,113,128,157,162]	1.73~17.5 J/g[2,48,112,113,128,157,162]
菠萝蜜淀粉		36.00~87.73°C[6,115,116,145,179,186]	55.00~91.80°C[6,115,116,145,179,186]	58~130.82℃[6,115,116,145,179,186]	0.33~480.05 J/g[6,115,116,145,179,186]
面包果淀粉		67.3°C[56] 79.3°C[121]	70.9°C[56] 84.7°C[121]	74.9°C[56] 89.4°C[121]	18.5 J/g[56] 14.1 J/g[121]
芒果淀粉		66.5~78.5°C[31,122~124,131,133]	71.3~81.4°C[31,122~124,131,133]	76.1~93.4°C[31,122~124,131,133]	1.10~19.45 J/g[31,122~124,131,133]
蛋黄果淀粉	果肉淀粉	55.90~59.75°C[65,68]	60.90~65.97°C[65,68]	70.20~77.79°C[65,68]	8.00~8.43 J/g[65,68]
	种子淀粉	63.30~68.99°C[65,67,68]	68.70~73.34°C[65,67,68]	71.65~82.92°C[65,67,68]	0.12~11.60 J/g[65,67,68]

邦西部获得的菠萝蜜淀粉在前三个冻融周期基本没有水析出，在第四到第八个冻融周期内析水率在5%~10%. 面包果淀粉在10个冻融周期内失水率为35%~45%, 说明面包果淀粉的抗冻融性较差. 天然芒果淀粉(8%, w/w)凝胶的脱水收缩率为50.58%, 低于玉米、马铃薯和绿豆淀粉，但高于木薯淀粉[187]. 基于以上分析, 以上淀粉在用作冷冻食品配料时, 应选择特定品种的香蕉淀粉和菠萝蜜淀粉.

4.7　消化特性

木薯淀粉的消化性与木薯的产地和生长期等有关，Mei等人[149]从中国广西获得的木薯淀粉的快消化淀粉(RDS)、慢消化淀粉(SDS)和抗性淀粉(RS)含量分别约为87%、8%和5%, 而Mutungi等人[142]从肯尼亚内罗毕获得的木薯淀粉的RDS、SDS和RS含量分别为42.10%、22.4%和35.5%. 在相同的田间条件下生长，并在种植后7、8、9、10和11个月收获SC5木薯，其RDS、SDS和RS含量变化范围为90.2%~93.60%、3.35%~6.37%和2.68%~3.99%，且9月收获期的木薯淀粉拥有最低的RDS含量和最高的SDS含量[143]. 香蕉淀粉的消化性多数是基于未糊化淀粉测定，因此一般表现出高RS含量，RS含量高达56.31%~98.98%[2,162]，RDS含量通常高于SDS含量[84,161,162]. 经过糊化的香蕉淀粉的抗性含量会大幅降低，但某些品种的香蕉淀粉RS含量仍然接近20%[165]，甚至接近30%[157]. 菠萝蜜淀粉的抗性淀粉含量普遍较高, 在75%左右, 这主要是因为消化率的测定是基于未糊化淀粉[32~35]. 面包果淀粉的消化性也有较大差异，Tan等人[56]测得面包果淀粉RDS，SDS和RS的含量分别为88.59%、2.99%和8.42%, 而Otemuyiwa和Aina[182]报道的结果则为32%、20%和48%. 芒果淀粉基于糊化淀粉测定的RS含量接近20%[156]，而蛋黄果淀粉基于糊化淀粉测定的RS含量超过了30%[68]. 综上，除木薯淀粉外，其他5种特色热带作物淀粉一般具有较高的抗性淀粉含量，有作为功能性原料的潜力(表11).

5　加工技术及其产品应用

本文汇总了特色热带作物淀粉的应用及技术手段(表12). 木薯淀粉常用作汤、饮料等的添加剂, 面包、饼干等的原料, 生物乙醇、糖浆生产的底物, 塑料、薄膜和水凝胶的原料, 活性物质的包埋壁材等. 木薯原淀粉可以作为大豆蛋白饮料的稳定剂[194]；通过支链淀粉酶改性制备的木薯淀粉提高了发酵乳饮料的稠度和稳定性[195]；通过柠檬酸盐酯化木薯淀粉，增加了抗性淀粉的含量，且将其应用于饮料中提升了饮料的功能特性和消费者的购买意愿[196]. 研究者将木薯淀粉与其他淀粉混合或者对木薯淀粉进行改性后用作制作面包、面条、饼干等食品，Sanchez等人[197]将玉米淀粉、大米淀粉和木薯淀粉按照74.2%、17.2%、8.6%的比例混合制备了品质较优的无麸质面包；交联和氧化的木薯淀粉二元共混物部分替代小麦面粉制作面包，但其替代量低于10%才能获得较好的面包品质[198]；将羟丙基改性木薯淀粉部分替代(10%~30%)小麦面粉制作乌

表 11　特色热带作物淀粉的消化特性

Table 11　The digestibility of starch from characteristic tropical crops

特色热带作物淀粉		RDS	SDS	RS
木薯淀粉		87%[149] 42.10%[142] 90.2%~93.60%[143]	8%[149] 22.4%[142] 3.35%~6.37%[143]	5%[149] 35.5%[142] 2.68%~3.99%[143]
香蕉淀粉		基于未糊化淀粉测定: 0~32.29%, 基于糊化淀粉测定: 43.65% ~94.10%[50,84,157,165]	基于未糊化淀粉测定: 1.8%~8.7%, 基于糊化淀粉测定: 3.9% ~19.1%[50,84,157,165]	基于未糊化淀粉测定: 56.31% ~98.98%[2,162], 基于糊化淀粉测定: 20%[165], 甚至接近30%[157]
菠萝蜜淀粉(基于未糊化淀粉测定)		3.93%~9.54[32~35]	13.68%~19.82%[32~35]	75%左右[32~35]
面包果淀粉		88.59%[56] 32%[55]	2.99%[56] 20%[55]	8.42%[56] 48%[55]
芒果淀粉		基于未糊化淀粉测定: 4.70% ~6.35%[122,148], 基于糊化淀粉测定: 74.28%[156]	基于未糊化淀粉测定: 15.30% ~19.92%[122,148], 基于糊化淀粉测定: 6.37%[156]	基于未糊化淀粉测定: 73.73% ~80.00%[122,148], 基于糊化淀粉测定: 19.34%[156]
蛋黄果淀粉	果肉淀粉	基于未糊化淀粉测定: 25.0%, 基于糊化淀粉测定: 31.6%[68]	基于未糊化淀粉测定: 29.6%, 基于糊化淀粉测定: 35.1%[68]	基于未糊化淀粉测定: 45.37%, 基于糊化淀粉测定: 33.3%[68]
	种子淀粉	基于未糊化淀粉测定: 22.8%, 基于糊化淀粉测定: 31.6%[68]	基于未糊化淀粉测定: 24.1%, 基于糊化淀粉测定: 35.8%[68]	基于未糊化淀粉测定: 53.1%, 基于糊化淀粉测定: 32.6%[68]

冬面, 增加了面条的柔软性、降低了面条的断条率[199]; 辛烯基琥珀酸酐改性木薯淀粉可用作面包生产中的脂肪替代品, 其面团和面包的特性与起酥油面包相比更好或接近[200]; Miyazaki等人[201]比较了羟丙基、乙酰化和磷酸交联木薯淀粉在冷冻面团和面包中的应用效果, 发现羟丙基木薯淀粉应用效果最好; Dariva等人[202]发现乙酰化和预糊化改性淀粉在奶酪面包生产过程中具有优良的应用效果; 酯化木薯淀粉用于日本白盐面条, 能够降低面条生产过程中的能耗[203]; 用酶法协同超声制备多孔木薯淀粉, 将其以5%的添加量添加到乌冬面中, 减少了烹调时间和蒸煮损失, 面条更为柔软[204]; 使用微波处理木薯淀粉可以获得比水热处理更多的抗性淀粉, 将变性淀粉添加到(10%~40%)饼干中均获得了良好的产品品质和抗消化性[205]; 采用柠檬酸和木薯淀粉湿热处理相结合的方法制备高抗酶解性木薯淀粉, 将其与活性面筋混合可替代小麦粉, 从而获得高抗性淀粉含量和中等GI的面包[206]; 机械活化是木薯淀粉物理改性常用的手段之一, 该技术可以增加淀粉破损程度, 最终提高面团强度[207,208]. 木薯淀粉在酶的作用下发酵生产乙醇, 研究者致力于提高乙醇生产效率和浓度, 主要技术包括常规方法(干磨法破坏淀粉颗粒, 然后液化和同步糖化和发酵)[209]、颗粒淀粉水解法[210]、顺序催化混合研磨和热水解工艺[211]、酶的固定化技术[212,213]、生物反应器技术[213,214]等. 木薯淀粉制作薄膜的制作方法主要有流延法[215]、热熔挤出法[216]、溶剂浇铸法[217]和溶剂置换法[218], 所用原料的相关技术主要有共混技术和淀粉改性技术. 混合材料主要包括纤维类(如木薯渣[217,219]、蓝莓渣[220]、南瓜皮[221]、羧甲基纤维素[222]、纳米纤维素[215,223]等)、天然橡胶[224]、蛋白类(发酵乳清[225]、明胶[226,227]、玉米醇溶蛋白[228]、燕麦麸[221]等)、土类(如蒙脱土[229]、膨润土[230]、纳米黏土[231]等)、精油类[232,233]、多酚[234,235]、多糖[216,227,232]、纳米粒子[236~238]和离子液体[239]等; 淀粉改性主要涉及化学改性和物理改性, 如交联改性[240]、氧化改性[241]、酯化改性[240]、预糊化[242]、辐照改性[243,244]、超声改性[245]等. 目前, 木薯淀粉膜也在向智能化发展, 如pH响应型膜[238,246]的开发. 木薯淀粉基凝胶的制备所涉及的技术与薄膜的制备有一些相似性, 如与多糖、蛋白类物质、纳米颗粒等共混[247~249], 对淀粉进行化学改性[250]和物理改性[251,252]等. 此外, 木薯淀粉基凝胶用到了淀粉的酶改性技术[253,254], 以改善凝胶特性. 木薯淀粉作为活性物质的包埋壁材主要有薄膜、凝胶和颗粒等形式, 薄膜和凝胶型壁材的制备如前所述, 颗粒型壁材的制备一般为先将淀粉进行改性处理[255,256]或提高直链淀粉的含量[257,258], 然后利用喷雾干燥[256,259]、冻

表 12 特色热带作物淀粉的应用及技术手段

Table 12 Application and technical means of starch from characteristic tropical crops

特色热带作物淀粉	用途	产品	技术手段
木薯淀粉	添加剂	汤、饮料[194~196]	—
	原料	面包、饼干等[197,198]	与其他淀粉混合或者对木薯淀粉进行改性: 交联和氧化[198]、羟丙基改性[199]、辛烯基琥珀酸酐改性[200]、乙酰化[201,202]、磷酸交联改性[201,202]、预糊化改性[202]、酯化改性[203,206]、酶法协同超声改性[204]、微波处理改性[205]和机械活化改性[207,208]
		生物乙醇、糖浆	常规方法(干磨法破坏淀粉颗粒, 然后液化和同步糖化和发酵)[209]、颗粒淀粉水解法[210]、顺序催化混合研磨和热水解工艺[211]、酶的固定化技术[212,213]、生物反应器技术[213,214]等
		塑料、薄膜和水凝胶	制作方法主要有流延法[215]、热熔挤出法[216]、溶剂浇铸法[217]和溶剂置换法[218] 所用原料的相关技术主要有共混技术等; 淀粉改性主要涉及化学改性和物理改性, 如交联改性[240]、氧化改性[241]、酯化改性[240]、预糊化[242]、辐照改性[243,244]、超声改性[227,245]和酶改性技术[253,254]
		活性物质的包埋壁材等	颗粒型壁材的制备一般为先将淀粉进行改性处理[255,256]或提高直链淀粉的含量[257,258], 然后利用喷雾干燥[256,259]、冻干[257,260]和真空干燥[257]等干燥方法进行干燥, 此外, 还有通过离子凝胶法进行微胶囊制备[261]
香蕉淀粉	香蕉粉	面包、意面、蛋糕、饼干[2]	—
	增稠剂[262]、抗冻剂[48,263]、食用涂层原料等	发酵产品、冷冻食品	淀粉改性技术
		可食用膜/涂层	改性[264]以及与其他物料共混[265~267]
	功能成分	蛋羹糊、面包和饼干等食物、低GI食品	退火处理、湿热处理[268]、挤压处理[269]、高压处理[270]
	—	化妆品中替代滑石粉[159]	—
	—	膜材料	共混技术[266,271~274] 淀粉改性: 氧化[275]、酯化[271]、酶改性[273]、冷等离子体处理[276]
菠萝蜜淀粉	填充物、食品增稠剂、胶凝剂	冷冻产品、糯性食品[117,277] 辣椒酱[278]	—
	原料	糖果、造纸和纺织工业以及制造口香糖	酸性改性[178]
		面条、面团、烘焙产品、馅饼馅料、汤和香肠的制备	退火和高压灭菌-冷却[186]、原淀粉替代[177]
		麦芽糖浆[279]、红曲色素[280]、β-环糊精[281]、乳酸[144]	—
	胶凝剂	口香糖、奶酪	酸改性
	脂肪替代物	低脂涂抹酱、黄油、人造黄油、蛋黄酱和乳制品(如冰淇淋)[183]	—
	功能成分	抗性淀粉	挤压膨化[154]、湿热处理[282]、退火处理[283]
	赋形剂和崩解剂、壁材	药品	原淀粉[284]或交联改性淀粉[285]、纳米化淀粉[286]
	膜材料	食品保鲜涂层[287,288]和生物降解塑料[289~291]	共混技术和浇铸技术

(表12续1)

特色热带作物淀粉	用途	产品	技术手段
面包果淀粉	面包果粉	制作烘焙食品[292,293]、面条[294~296]、粥[297]、发酵饮料[298,299]、植物肉[300,301]	—
	原料	速溶汤、可生物降解和/或可食用包装的成膜剂、冷冻和冷藏食品	交联改性[55]
		可生物降解的薄膜、需要高黏度凝胶的食品、冰淇淋和甜点等产品中的乳化剂	退火处理[21]
		食品甜味剂、单细胞蛋白生产底物、饮料和乙醇	酶处理[302]
		脂肪替代物和黏合剂	超声辅助提取面包果中的淀粉纳米颗粒[20]
芒果淀粉	原料	生物基塑料和可食用涂膜[62,126,303]	与其他淀粉基膜材料制备的技术相似热湿处理[126]、共混技术[62]、纳米化技术[304]、减压超声处理[305~307]
		乙醇[308]、葡萄糖浆等的生产	—
		食品增稠剂[2]	—
		药物崩解剂	—
		3D打印材料[309]	—
		烘焙食品、罐头食品和冷冻食品等热加工食品	微波处理[40]
	芒果籽淀粉	辣椒酱增稠剂和稳定剂[310]	—
	芒果仁淀粉纳米纤维	组织再生或药物输送系统	静电纺丝法[311]
蛋黄果淀粉	膜材料	检测肉类和水产品的新鲜度	共混技术[66]

a) “—”表示未见报道

干[257,260]和真空干燥[257]等干燥方法进行干燥, 此外, 还有通过离子凝胶法进行微胶囊制备[261].

香蕉淀粉主要应用于食品、化妆品、膜材料等. 香蕉淀粉作为香蕉粉的主要成分在食品中应用, 添加到面包、意面、蛋糕、饼干等食品中, 而单纯香蕉淀粉尚未见商品化食品应用[2]. 香蕉淀粉可用作增稠剂、抗冻剂、食用涂层、低GI食品原料等. 青香蕉淀粉可用作巴鲁杏仁发酵产品的天然增稠剂, 改善了产品的pH和质构品质[262]. 某些品种的原淀粉[263]或者经过改性处理的香蕉淀粉[48]具有良好的冻融稳定性, 有潜力作为食品抗冻剂. 香蕉淀粉可食用膜/图层的制备技术与木薯淀粉类似, 主要是淀粉进行改性[264]以及与其他物料共混[265~267]. 香蕉淀粉经过退火处理、湿热处理[268]、挤压处理[269]、高压处理[270]等增加SDS含量或RS含量, 然后添加到蛋羹糊、面包和饼干等食物中. 香蕉淀粉有潜力用于化妆品中替代滑石粉, 但其添加量一般低于15%[159]. 香蕉淀粉膜材料的制备技术与木薯淀粉类似, 但由于其淀粉糊透明度较低, 远没有木薯淀粉膜材料研究广泛. 共混材料主要包括抗菌物质(如姜黄素[271])、芦荟凝胶[266,271,272]、纳米颗粒[273]、多糖[266,272]、乙烯[274]等, 淀粉改性主要涉及氧化[275]、酯化[271]、酶改性[273], 此外, 对膜进行冷等离子体处理可以提高膜材料的性能[276].

菠萝蜜淀粉以原淀粉或改性淀粉形式被应用于(或有潜力应用于)食品、药品、材料等领域. Zhang等人[117,277]推断菠萝蜜淀粉可用作冷冻产品的填充物、食品增稠剂、胶凝剂或作为糖果或婴儿辅食的原料, 某些品种的菠萝蜜淀粉还可用于糯性食品. Dutta等人[178]认为酸性改性菠萝蜜种子淀粉在糖果、造纸和纺织工业以及制造口香糖方面具有广阔的应用前景. Kushwaha等人[186]则认为通过退火和高压灭菌-冷却处理后的菠萝蜜淀粉可用于面条、面团、烘焙产品、馅

饼馅料、汤和香肠的制备，通过酸改性的淀粉(品种Hadiyava和Bhadaiya)可以作为胶凝剂在口香糖、奶酪中应用，以及可以用作低脂涂抹酱、黄油、人造黄油、蛋黄酱和乳制品(如冰淇淋)生产中的脂肪替代物[183]. Khang等人[177]发现菠萝蜜种子淀粉可替代15%的小麦粉，用于制作纸杯蛋糕. Rengsutthi和Charoenrein[278]将菠萝蜜淀粉成功地用作辣椒酱的增稠剂和稳定剂. 此外，研究者还将菠萝蜜淀粉用于制备麦芽糖浆[279]、红曲色素[280]、β-环糊精[281]、乳酸[144]等. 通过改性可以改变淀粉的消化特性, 如通过挤压膨化[154]提高淀粉消化性，通过湿热处理[282]、退火处理[283]提高抗性淀粉含量. 菠萝蜜淀粉以原淀粉[284]或交联改性淀粉[285]的形式在药品中用作赋形剂和崩解剂, 或者经过纳米化对药物进行包封[286]. 菠萝蜜淀粉膜材料主要作为食品保鲜涂层[287,288]和生物降解塑料[289~291]应用, 菠萝蜜淀粉膜材料的主要通过共混技术和浇铸技术制得.

面包果主要以果肉进行油炸、蒸煮、捣碎等加工方式进行食用或制成面包果粉[312], 面包果粉被用于制作烘焙食品[292,293]、面条[294~296]、粥[297]、发酵饮料[298,299]、植物肉[300,301]等. 然而关于面包果淀粉的应用报道较少，目前的研究集中于对面包果淀粉进行改性并评价改性淀粉的性质，从而给出淀粉的应用潜力. Amorim等人[55]对面包果淀粉进行交联改性, 并认为改性后的淀粉可以用于速溶汤、可生物降解和/或可食用包装中用作成膜剂、冷冻和冷藏食品. de Carvalho Batista Muniz等人[21]对面包果淀粉进行退火处理，推断改性后的淀粉可以用于可生物降解的薄膜、需要高黏度凝胶的食品、冰淇淋和甜点等产品中的乳化剂等的生产. Solomon等人[302]发现面包果淀粉经过高粱麦芽中的酶处理后，产生可观的糖分，可用作食品甜味剂、单细胞蛋白生产底物、饮料和乙醇生产. Andrade等人[20]使用超声辅助提取面包果中的淀粉纳米颗粒, 该纳米颗粒有潜力用作脂肪替代物和黏合剂.

芒果淀粉的主要应用是生物基塑料和可食用涂膜[62,126,303]，其他的应用包括乙醇[308]、葡萄糖浆等的生产、食品增稠剂[2]、药物崩解剂和3D打印材料[309]等. 芒果淀粉生物基塑料和可食用涂膜制备的技术与其他淀粉基膜材料制备的技术相似. 芒果仁淀粉薄膜比玉米淀粉薄膜表现出更高的整体拉伸强度和弹性模量[303]. 热湿处理后的芒果淀粉具有较低的回生率，有潜力用于制备可生物降解的薄膜[126]. 通过添加陶土和甘油可以增加芒果淀粉基薄膜的物理力学和热性能[62]. 将芒果淀粉、芒果淀粉纳米晶体和纤维素纳米晶体混合制成的薄膜的强度和模量和水蒸气阻隔性都获得了提高[304]. 将增塑剂和芒果淀粉糊化悬浮液混合，通过减压超声处理去除形成的气泡获得涂层浆液, 涂抹于杏仁、西红柿和红辣椒表面，可以延长杏仁[305]、西红柿[306]和红辣椒[307]的保质期. 经过微波处理的芒果淀粉有潜力应用于烘焙食品、罐头食品和冷冻食品等热加工食品[40]. 芒果籽淀粉可以作为辣椒酱增稠剂和稳定剂[310]. 此外，使用静电纺丝法可以制备芒果仁淀粉纳米纤维，然后有潜力用于组织再生或药物输送系统[311]. 蛋黄果淀粉的应用报道十分有限, Jiang等人[66]将蛋黄果淀粉和紫色百香果果皮提取物制备的复合膜可用于肉眼检测富含蛋白质的肉类和水产品的新鲜度.

6 结论

相比于大宗作物淀粉，特色热带作物淀粉具有高直链淀粉含量、高抗性淀粉含量、高糊化温度等特性和长链比例高的结构特点. 如菠萝蜜淀粉和蛋黄果淀粉具有较高的直链淀粉含量，除木薯淀粉外的其他5种热带作物淀粉(尤其是未成熟的香蕉淀粉)具有较高的抗性淀粉含量，菠萝蜜淀粉具有较高的糊化温度、较好的冻融稳定性，本文所述的6种淀粉具有较高的B3链含量. 特色热带作物淀粉中，菠萝蜜淀粉、面包果淀粉、蛋黄果淀粉、香蕉淀粉是抗性淀粉的天然来源, 适合制备低GI食品和冷冻食品填充剂的天然原料, 木薯淀粉、芒果淀粉适合作为低水分含量食品(烘焙类食品)与淀粉基膜的原材料.

然而与大宗淀粉相比，特色热带作物淀粉研究的深度和广度还十分有限. 特色热带作物淀粉的提取多数处于实验室研究阶段，除木薯淀粉外未见商业化生产; 研究者部分地报道了淀粉的结构和性质, 特色热带作物淀粉的研究系统性不足；不同产地、不同品种的淀粉性质差异较大，目前尚未有商业化的成熟的应用品种; 特色热带作物淀粉的应用研究, 大多与大宗淀粉的应用类似, 但全面性又不足. 特色热带作物淀粉的应用多集中于膜材料的研究，既未突出特色热带作物淀粉的特点，也未根据特色热带作物淀粉的特点开发新

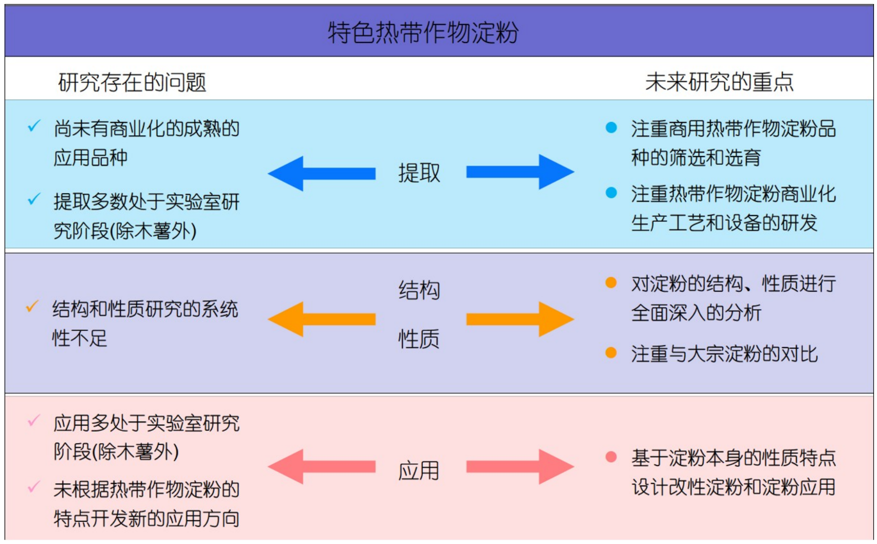

图 2 特色热带作物淀粉研究不足与发展方向
Figure 2 Deficiencies and development directions of research on starch from characteristic tropical crops

的应用方向. 因此, 在今后的研究中应注重特色热带作物淀粉商业化生产工艺和设备的研发; 应注重商用特色热带作物淀粉品种的筛选和选育, 并对其淀粉结构、性质进行全面、深入的分析, 同时注重与大宗淀粉的对比; 要根据淀粉的性质进行应用方向提炼, 基于淀粉本身的性质特点设计改性淀粉和淀粉应用(图2).

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Research progress of starch from characteristic tropical crops

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Starch, being the predominant carbohydrate in nature, serves as a fundamental energy source for various physiological activities in human life. The characteristic tropical crop starch, found in typical tropical crops such as cassava, banana, jackfruit, and breadfruit, has garnered significant attention due to its diverse multi-scale structure, distinct physicochemical properties, processing characteristics, and wide-ranging applications. This paper provides a comprehensive summary of the research progress on starch in tropical crops from various sources. Specifically, it reviews the extraction technology, amylopectin content, multi-scale structure, physical and chemical properties, processing technology and product application of starch in cassava, banana, jackfruit, breadfruit, mango and *Pouteria campechiana*. The future development direction, application prospects, and research suggestions of characteristic tropical crop starch are also discussed to provide crucial theoretical guidance for enhancing the processing level of related products and diversifying food sources.

characteristic tropical crop starch, Structure, property, application prospect

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