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桂丰早龙眼开花习性和果实生长模型研究

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摘 要:【目的】探究龙眼新品系桂丰早在南宁产区的开花习性和果实生长数学模型,为制定高产优质栽培管理措施提供理论依据。**【方法】**通过系统研究桂丰早龙眼的开花习性、果实生长发育和主要品质指标的动态变化规律,选用4种理论生长方程对果实纵径、横径、果形指数、单果质量、果皮质量、果皮厚度、果核质量、果肉质量、可食率、可溶性固形物含量(TSS)10个指标进行拟合,以花后天数(x),各指标生长变化(y)构建非线性回归方程,以各指标增长速率(g)绘制导函数方程,确定果实生长和品质指标动态变化的最优数学模型。**【结果】**在南宁桂丰早的花期约为24 d,先开雄花,花后12 d雌花开放量达到最高峰,在雌花开花数量较多的花期开放的雄雌花比例为2∶1;各指标的最优拟合方程如下:果实纵径(y_2)、单果质量(y_4)、果肉质量(y_8)、可食率(y_9)和TSS(y_{10})为一元二次项方程($y_2=-0.001\,x^2+0.285\,x+3.094$、$y_4=-0.002\,x^2+0.445\,x-17.962$、$y_8=-0.002\,x^2+0.399\,x-17.953$、$y_9=-0.02\,x^2+4.182\,x-151.845$和$y_{10}=-0.012\,x^2+2.380\,x-94.493$);果实横径($y_1$)、果形指数($y_3$)和果皮厚度($y_6$)为一元三次项方程($y_1=-2.405\times10^{-5}x^3+0.003\,x^2+0.146\,x+2.067$、$y_3=7.822\times10^{-7}x^3-5.878\times10^{-5}x^2-0.009\,x+1.542$和$y_6=6.551\times10^{-7}x^3-0.019\,x+1.610$);果皮质量($y_5$)和果核质量($y_7$)为Logistic方程[($y_5=2.75/(1+11.80\,e^{-0.024\,x})$和$y_7=1.94/(1+1.70\,e^{-0.031\,x})$)];果实发育期间各指标的增长速率为:果实横径和果皮质量为逐渐递增到最高值后就逐渐递减;果形指数为逐渐递减到最低值后逐渐递增;果实纵径、单果质量、果核质量、果肉质量、可食率和TSS为逐渐递减;果皮厚度逐渐递增。相关和偏相关分析表明,除果皮厚度外,其余指标两两间大都呈显著或极显著相关。**【结论】**基于果实发育天数构建果实发育的曲线拟合方程和导函数能较好地反映桂丰早龙眼果实的生长发育动态,该生长模型的建立在桂丰早生产上可用于品质预测和指导制定合理的优质栽培技术措施。

关键词:龙眼;桂丰早;开花习性;果实生长数学模型

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A study on the flowering characteristics and fruit growth models of Guifengzao longan

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Abstract:【Objective】To provide theoretical basis for formulating high-yield and high-quality cultivation and management measures, the flowering characteristics and fruit growth mathematical models of Guifengzao, a new line of longan were studied. Guifengzao was an excellent mutant strain with early maturity, high TSS, high edible rate and other excellent characteristics. The development patterns of reproductive organs were closely related to the yield formation. The dynamic models of fruit growth and development were established by using linear, quadratic, cubic and Logistic equations, which could be used as the evaluation and prediction method of important indicators such as fruit growth and yield. 【Methods】From April 3 to 27, 2019, the number of male and female flowers was counted every day. From April 27, 2019 [0 days after flowering (DAF)] to August 17, 2019 (110 DAF), the change patterns

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of fruit transverse and longitudinal diameters were traced using an electronic vernier caliper every 10 days. From July 1, 2019 (64 DAF) to August 22, 2019 (116 DAF), the single fruit weight, peel weight, peel thickness, kernel weight, flesh weight, edible rate and soluble solids (TSS) were measured every 5 or 7 days. The weights of single fruit, peel and kernel were measured with an electronic scale. The peel thickness at fruit equator was obtained with an electronic vernier caliper. The flesh weight was calculated by subtracting peel and kernel weight from single fruit weight. The edible rate was the ratio of flesh weight to single fruit weight. Four equations were used to fit the above 10 growth indexes, including transverse diameter, longitudinal diameter, fruit shape index, single fruit weight, peel weight, peel thickness, kernel weight, flesh weight, edible rate and TSS. The dynamic change pattern of fruit growth and development was established with the regressed equations of growth indexes against DAF and the derivative equation displayed change pattern of the growth rate (g). Meanwhile, the linear and partial correlation analyses were carried out among the 10 fruit growth indexes. The SPSS 21.0 software was used to analyze the data. 【Results】 The flowering period of Guifengzao in Nanning was about 24 days. The male flowers bloomed first and the number of blooming female flowers reached a peak 12 days after initial blooming. The ratio of male to female flowers was 2∶1. The changes in longitudinal diameter (y_2), single fruit weight (y_4), flesh weight (y_8), edible rate (y_9) and TSS (y_{10}) were fitted well with quadratic equations ($y_2=-0.001x^2+0.285x+3.094$, $y_4=-0.002x^2+0.445x-17.962$, $y_8=-0.002x^2+0.399x-17.953$, $y_9=-0.02x^2+4.182x-151.845$ and $y_{10}=-0.012x^2+2.380x-94.493$, respectively). The changes in fruit transverse diameter (y_1), fruit shape index (y_3) and peel thickness(y_6) could be fitted to cubic equations ($y_1=-2.405\times10^{-5}x^3+0.003x^2+0.146x+2.067$, $y_3=7.822\times10^{-7}x^3-5.878\times10^{-5}x^2-0.009x+1.542$, and $y_6=6.551\times10^{-7}x^3-0.019x+1.610$, respectively). Peel weight (y_5) and kernel weight (y_7) fitted well with Logistic equation [$y_5=2.75/(1+11.80e^{-0.024}x)$ and $y_7=1.94/(1+1.70e^{-0.031}x)$, respectively]. After flower falling and fruit setting, the transverse diameter, longitudinal diameter, single fruit weight, peel weight, kernel weight, flesh weight and edible rate of Guifengzao showed “S” or near “S” growth pattern, while fruit shape index and peel thickness showed an inverse “S” pattern. TSS increased first and then decreased. The fruit diameter and peel weight increased rapidly until 41 DAF and 99 DAF, respectively. The inflection points of fruit shape index occurred at 25 DAF, after which fruit gradually changed from oval shape to nearly round shape. The fruit longitudinal diameter, single fruit weight, kernel weight, flesh weight and edible rate grew slowly, and the single fruit weight, flesh weight and edible rate gradually increased until 111 DAF, 99 DAF and 104 DAF, respectively. The peel thickness was lowest from 85 DAF to 99 DAF, and gradually increased after 99 DAF. TSS gradually increased till 85 DAF and then gradually decreased, reaching >18% from 85 DAF to 106 DAF. The highest value was at 92 DAF, and the inflection point occurred at 99 DAF. Correlation analysis showed that there was significant correlation between the other indexes except peel thickness. 【Conclusion】 In Nanning, the male and female flowers of Guifengzao bloomed in order; the pollen source for the female flowers was sufficient. In the process of fruit development and maturity, quadratic equation could accurately describe the growth of fruit longitudinal diameter, single fruit weight, flesh weight, edible rate and TSS; cubic equation could accurately describe the growth of fruit transverse diameter, fruit shape index, and peel thickness; and Logistic equation could accurately describe the growth of peel weight and kernel weight.

Key words: Longan; Guifengzao; Flowering characteristics; Fruit growth mathematical models

龙眼（*Dimocarpus longan* Lour.）原产于中国，因果实口感爽脆、营养丰富，颇受消费者喜爱，其品种资源、栽培面积、产量均居世界之首，“十四五”规划继续将高可溶性固形物含量（TSS）、大果、高可食率作为优良龙眼种质资源的基本评判标准，且将比石硖早于1周以上的成熟龙眼果实划分为特早熟优良种质资源[1-2]。桂丰早是近几年在广西崇左市龙州县发现的优良变异单株，具有特早熟、高糖、高可食率等优良特性，是一个值得发展的优良新品系[3]，对桂丰早龙眼的开花习性、果实生长发育和品质变化规律进行研究，绘制该品系的果实生长数学模型，可为制定桂丰早的高产优质栽培管理措施提供理论依据。果实生长发育随时空的变化而变化，果树生殖器官发育规律与产量形成有着密切关系，在果实生长发育理论研究中，利用散点图构建绘制果实生长动态模型，可以作为果实生长和产量等重要指标的评估预测手段[4-6]。线性方程、一元多项式方程和Logistic方程等数学模型常用来绘制描述果实的生长发育动态，Yuan等[7]采用线性方程较好地拟合了猕猴桃果实的生长发育动态，一元多项式方程可以较好地拟合荔枝[8]、杏[9]、油橄榄[10]、台湾凤梨释迦[11]的果实生长发育动态，Logistic方程能较好地拟合杨梅[12]、番石榴[13]、槟榔[14]、澳洲坚果[15]、脐橙[16]、蜜橘[17]等果实的生长发育动态，可采用一元多项式和Logistic方程等绘制石硖[6]、储良[18]、大乌圆[19]、四季蜜[20]等龙眼品种的果实生长发育动态。这些果实生长模型的构建，可以确定果实生长的关键拐点，为果树的高产优质生产提供有力依据。但桂丰早龙眼的果实生长模型还未有研究，本试验借鉴前人研究成果，系统研究桂丰早的开花结果习性和果实生长发育及主要品质指标的动态变化，选用4种理论生长方程对果实生长和品质指标变化规律（果实横径、纵径、果形指数、单果质量、果皮质量、果皮厚度、果核质量、果肉质量、可食率、TSS）进行拟合，建立该品系的果实生长数学模型；根据桂丰早龙眼的开花习性和果实生长发育规律构建拟合曲线变化方程，求导分析各指标的增长速率规律，对果实各生长指标间进行相关和偏相关分析，确立最优的桂丰早果实生长数学模型，以期掌握桂丰早的开花习性、果实生长发育规律及其关键拐点，为完善桂丰早挂果期的栽培管理技术进而获得优质商品果实提供科学参考依据。

1　材料和方法

1.1　试验材料与地点

供试材料为龙眼优良品系桂丰早，砧木为2 a生广眼，2017年1月用大苗定植于广西大学农学院教学科研基地龙眼园（东经108°17′24″，北纬22°51′10″，海拔80 m），株行距为3 m×5 m。土壤为红壤土，灌溉条件良好，肥水按常规管理。

1.2　试验设计方法

选取长势一致、有代表性的植株3株，单株小区，设置3个重复，每株树在树冠外部按东南西北4个方向各挂牌2个花穗或果穗，每株树共8个花穗或果穗。2019年4月3日至2019年4月27日每天统计雌雄花开放数；2019年4月27日（花后0 d）至2019年8月17日（花后110 d）每隔10 d定期观察果实横纵径生长发育动态，2019年7月1日（花后64 d）至2019年8月22日（花后116 d）每隔5~7 d定期测定单果质量、果皮质量、果皮厚度、果核质量、TSS等指标。

1.3　试验指标及其观察测定方法

1.3.1　开花数量记录　自开花当天起至落花结束后，每日进行观察计数，对当日开放的雄花用镊子夹落并计数，对当日开放的雌花用金属笔进行标记并计数。

1.3.2　果实指标观察　每果穗根据先前金属笔的颜色标记，选取坐果时间、大小和色泽一致、无任何机械伤及病虫害的3粒果实，采摘后及时置于冰盒后带回实验室测定。果实的横纵径、果皮厚度采用游标卡尺测定，单果质量、果皮质量、果核质量采用电子秤测定，TSS采用电子糖度计测定，其中果皮厚度选择果皮赤道面3个位点测定取平均值，果形指数=纵径/横径，果肉质量=单果质量-果皮质量-果核质量，可食率/%=（果肉质量/单果质量）×100。

1.4　数据统计分析

采用SPSS 21.0进行统计和建模并进行最优拟合分析，采用Pearson法进行线性和偏相关分析。以花后天数为x、果实各生长和品质指标为y，作一元线性回归、一元多项式回归和Logistic方程拟合分析。以花后天数为x，果实各指标为g采用Wolfram Alpha在线求导获得各指标的增长速率方程，拐点（T_{IP}）采用$-b/2a$（适用二次项方程）、二阶导数$f''(x)=0$（适用三次项方程）和$\ln a/b$（适用Logistic方程）计

算获得。

2 结果与分析

2.1 桂丰早开花习性观察

由图1和图2可见，桂丰早总花期为24 d，雄花先开，雄花有4个开放高峰，分别在4月的10日、13日、15日和20日，其中4月20日的单穗雄花开花数量最多，达676朵•穗$^{-1}$；雌花有3个开放高峰，分别在4月的11日、15日和23日，其中4月15日出现单穗雌花最高峰，为69朵•穗$^{-1}$；雌花比雄花晚于5 d开放，4月12日只开雌花，雌雄花相遇主要在4月13—17日，雌花开花数量较多且与雄花相遇的花期是4月13—15日，期间开放的雄雌花比例接近2∶1，4月14日雌雄花开放数量几乎相等，接近1∶1。桂丰早主要以雄花为主，雌雄花的比例为1∶15.7，单株雄花和雌花变异系数分别为19%和42%。说明雄雌花按顺序开放，花期授粉源充足，授粉正常。

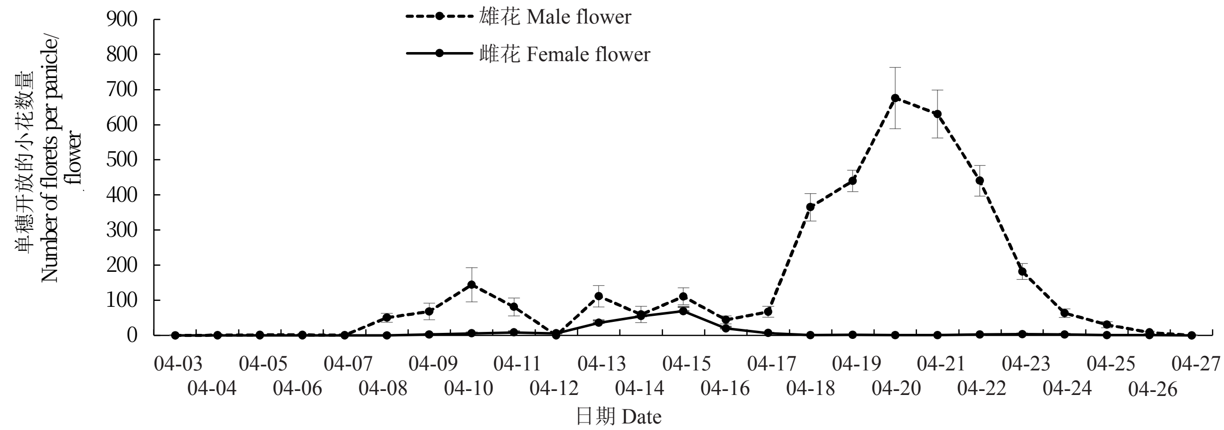

图1 桂丰早花期每日单穗开放的雌雄花数量

Fig. 1 Dynamics of the numbers of female and male flowers per panicle of Guifengzao during flowering

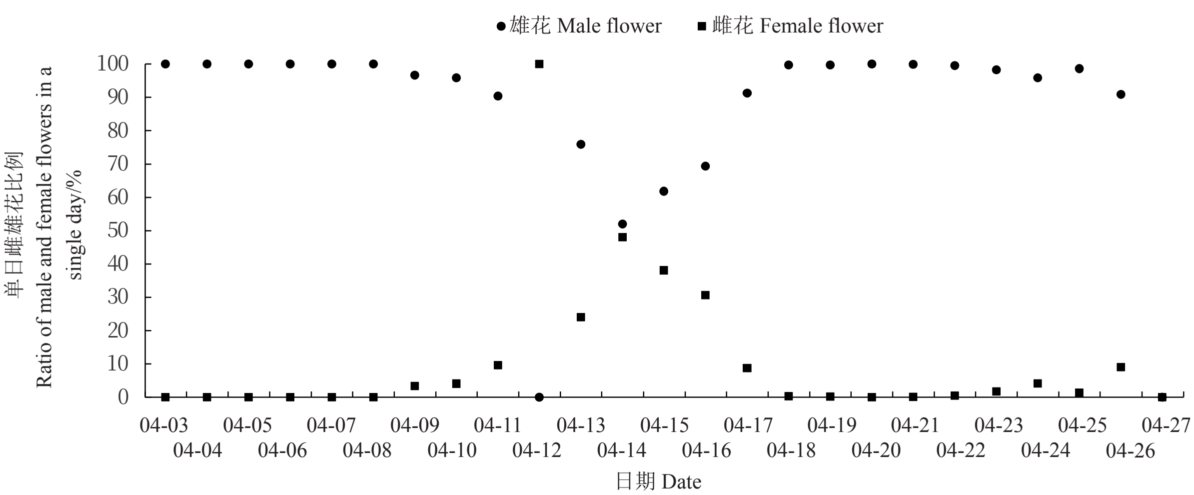

图2 桂丰早单日雌雄花开放的比例

Fig. 2 Changes in the ratio of female flowers to male flowers in Guifengzao

2.2 桂丰早果实生长数学方程模型搭建

图3~图12绘制了桂丰早果实生长发育指标的最优数学模型，可见，果实纵横径、单果质量、果肉质量和可食率呈近“S”形增长，果皮质量和果核质量呈“S”形增长，果形指数和果皮厚度呈反“S”形下降，TSS呈先上升后下降趋势。果实横径和果皮质量快速增长至花后41 d和99 d后缓慢增长，日增长量分别是0.001~0.4 mm·d^{-1}和0.02~0.03 g·d^{-1}；果形指数的拐点是花后25 d，果实由原来的椭圆形逐渐变为近圆形；果实纵径、单果质量、果核质量、果肉质量、可食率一直呈缓慢增长趋势，日增长量分别是0.03~0.3 mm·d^{-1}、0.03~0.22 g·d^{-1}、0.000 8~0.02 g·d^{-1}、0.03~0.2 g·d^{-1}、0.01~1.5 %·d^{-1}，单果质量、果肉质量和可食率分别逐渐增长至花后111、99和104 d后趋于平缓变化。果皮在花后85~99 d最薄，花后99 d

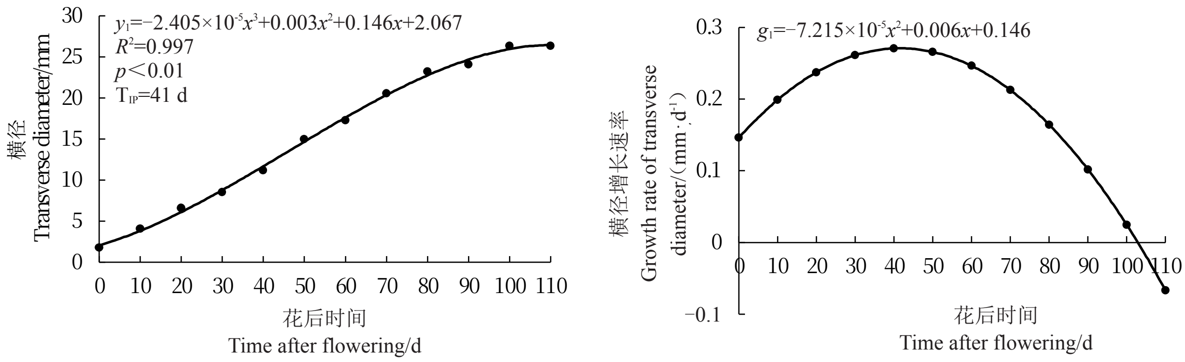

图 3　桂丰早果实横径生长动态变化规律

Fig. 3　Dynamic change in transverse diameter in Guifengzao

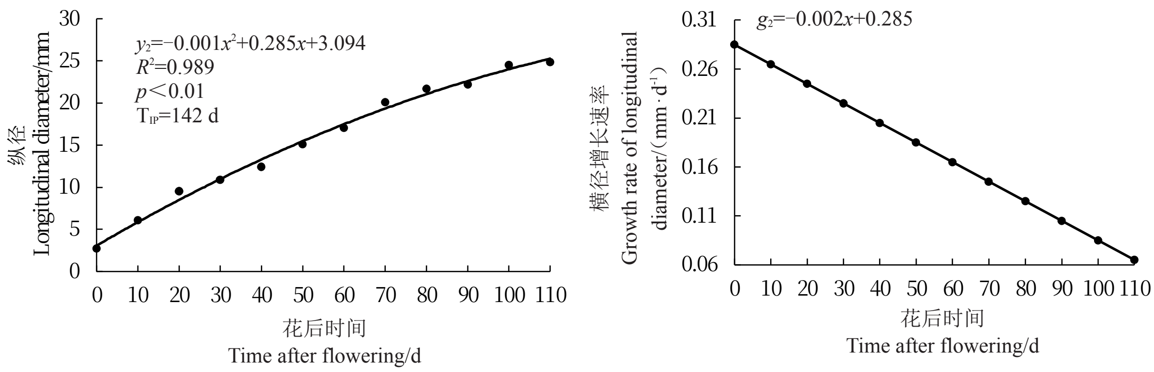

图 4　桂丰早纵径生长动态变化规律

Fig. 4　Dynamic change in longitudinal diameter in Guifengzao

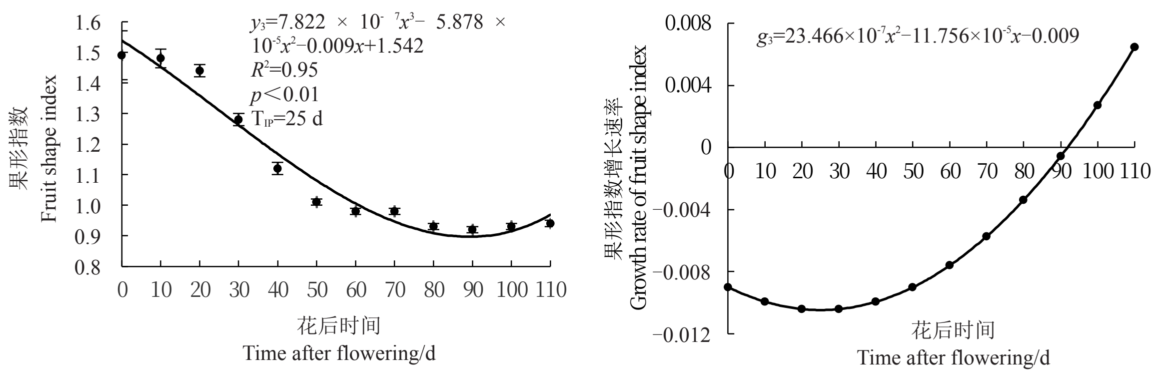

图 5　桂丰早果形指数生长动态变化规律

Fig. 5　Dynamic change in fruit shape index in Guifengzao

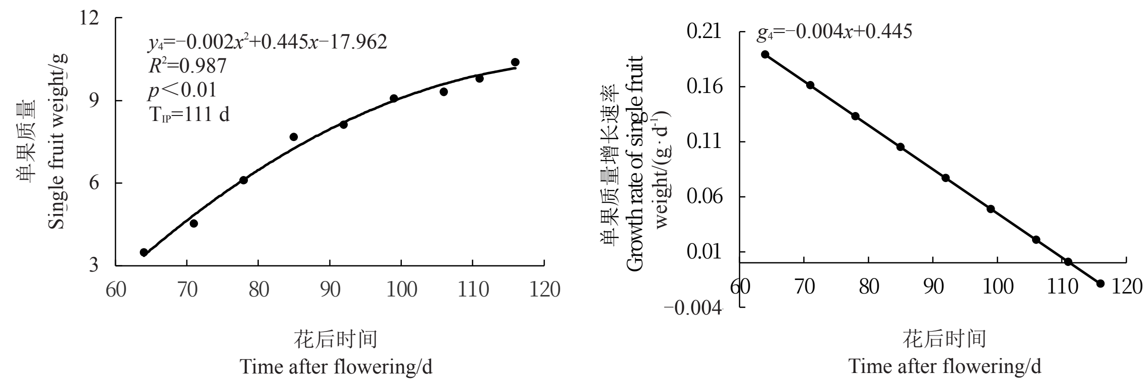

图 6　桂丰早单果质量生长动态变化规律

Fig. 6　Dynamic change in single fruit weight in Guifengzao

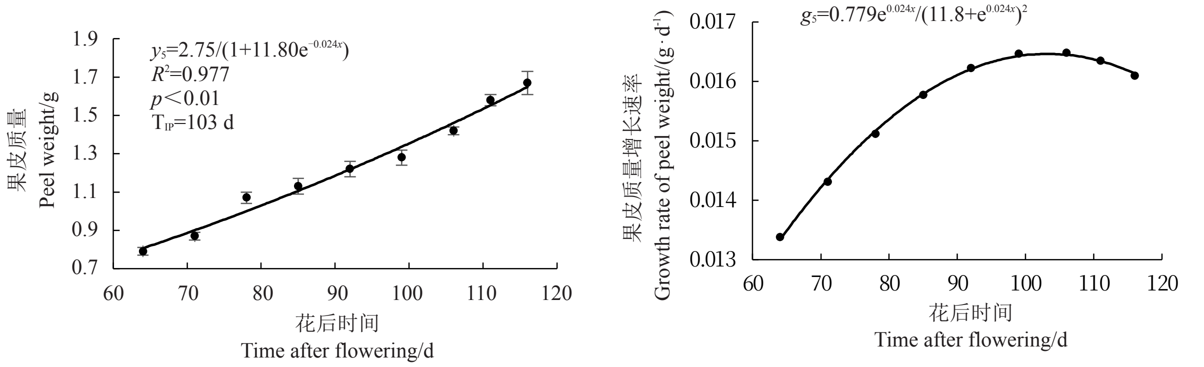

图 7　桂丰早果皮质量生长动态变化规律

Fig. 7　Dynamic change in peel weight in Guifengzao

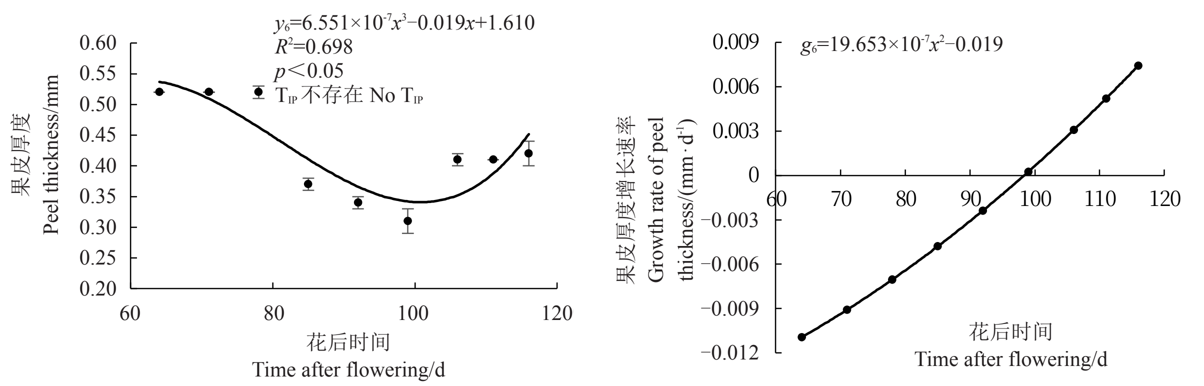

图 8　桂丰早果皮厚度生长动态变化规律

Fig. 8　Dynamic change in peel thickness in Guifengzao

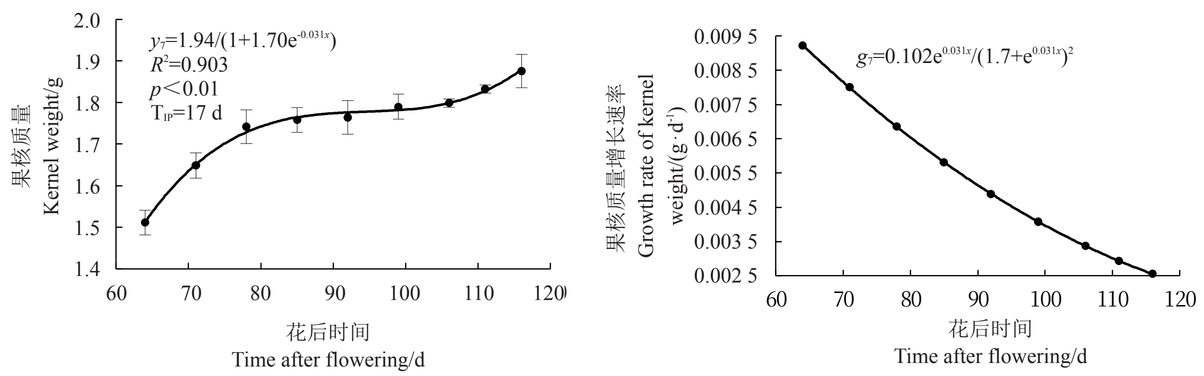

图 9　桂丰早果核质量生长动态变化规律

Fig. 9　Dynamic change in kernel weight in Guifengzao

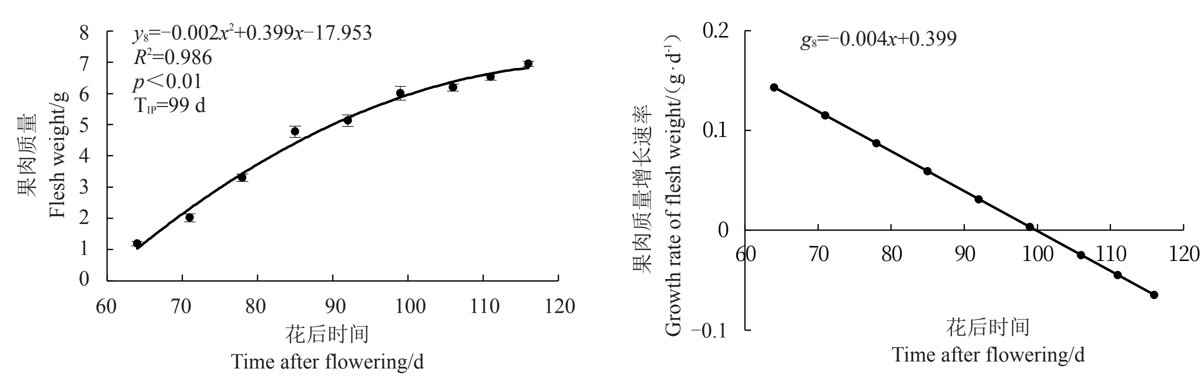

图 10　桂丰早果肉质量生长动态变化规律

Fig. 10　Dynamic change in flesh weight in Guifengzao

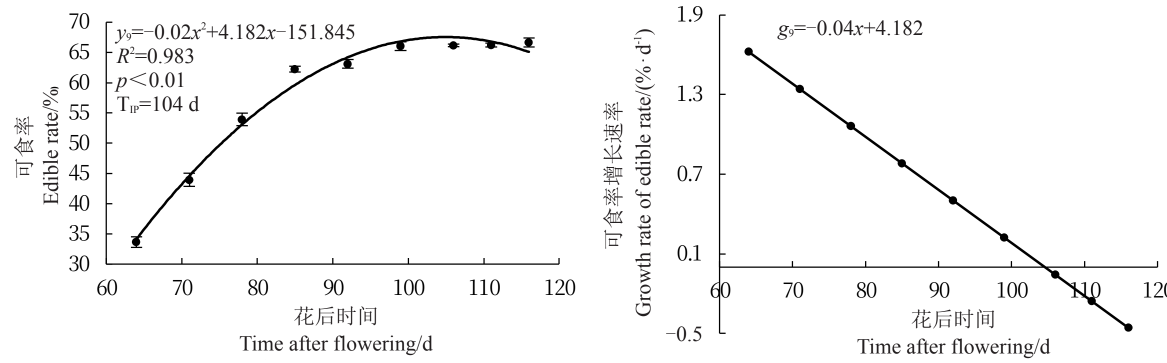

图 11　桂丰早可食率生长动态变化规律

Fig. 11　Dynamic change in flesh recovery of Guifengzao

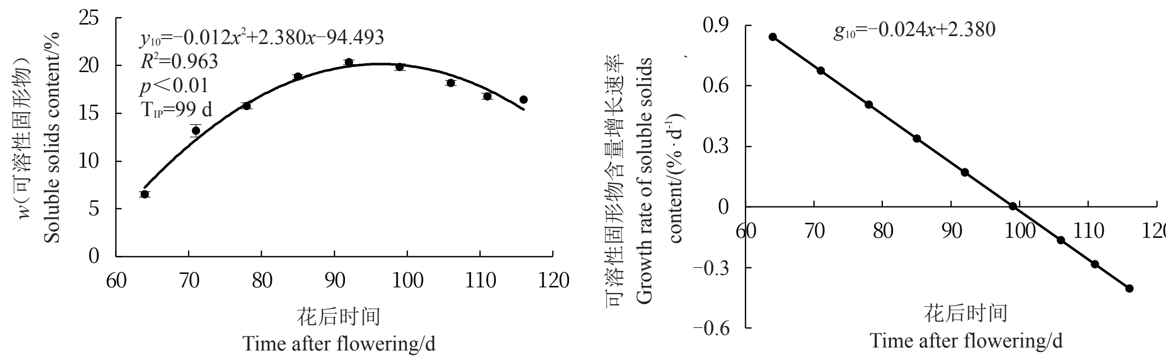

图 12　桂丰早可溶性固形物生长动态变化规律

Fig. 12　Dynamic change in soluble solids in Guifengzao

后逐渐递增，日增长量为−0.0006~0.014 mm·d^{-1}。TSS逐渐增加至花后85 d后缓慢变化再逐渐下降，在花后85~106 d都超过18%，花后92 d为最高值，花后99 d为拐点，日增长量是−2.34~0.95 %·d^{-1}。说明花后99 d是桂丰早果实生长的关键拐点。

2.3　桂丰早龙眼果实生长指标间的相关性

相关和偏相关分析结果见表1。果实纵横径与单果质量、果肉质量、果皮质量、果核质量、可食率间呈极显著正相关，单果质量、果肉质量、果皮质量、果核质量和可食率间也呈极显著正相关，TSS与单果质量、果肉质量、果核质量和可食率呈显著或极显著正相关，果形指数与果实纵横径、单果质量、果肉质量、果皮质量和果核质量间呈极显著负相关；偏相关分析表明，果皮厚度与其他指标的相关性大都不显

表 1　桂丰早果实生长指标间的相关和偏相关分析

Table 1　Analysis on the whole or part correlation between various fruitindexes of Guifengzao

	横径 Transverse diameter	纵径 Longitudinal diameter	果形指数 Fruit shape index	单果质量 Single fruit weight	果皮质量 Peel weight	果核质量 Kernel weight	果肉质量 Flesh weight	可食率 Eible rate
纵径 Longitudinal diameter	0.915**							
果形指数 Fruit shape index	−0.942**	−0.935**						
单果质量 Single fruit weight	0.954**	0.973**	−0.961**					
果皮质量 Peel weight	0.991**	0.995**	−0.933**	0.961**				
果核质量 Kernel weight	0.895**	0.942**	−0.847**	0.953**	0.922**			
果肉质量 Flesh weight	0.949**	0.967**	−0.965**	0.999**	0.954**	0.946**		
可食率 Edible rate	0.845**	0.893**	−0.879**	0.963**	0.868**	0.956**	0.964**	
可溶性固形物含量 Soluble solids content	0.558	0.634	−0.653	0.763*	0.588	0.807**	0.769*	0.903**

注：**表示在 0.01 水平（双侧）上显著相关，*表示在 0.05 水平（双侧）上显著相关。

Note: ** indicates extremely significant correlation at 0.01 level (bilateral); * indicates significant correlation at 0.05 level (bilateral).

著,说明所测定的指标两两之间大都相互关联。

3 讨 论

桂丰早单株雄花和雌花变异系数分别为19%和42%,在南宁产区总花期为24 d,雌雄花相遇期达5 d,雄花间隔3~5 d共出现4个开放高峰,雌花有3个开放高峰,其中4月15日出现单穗雌花最高峰且雌花开花数量较多的花期开放的雄雌花比例为2∶1,有利于授粉受精。

在生产上,前人比较倾向运用多项式回归分析果实生长各指标与发育时间的拟合关系以及求导分析各指标增长速率与发育时间的关系方程[20-24],前人在对龙眼果实生长发育各指标模型的建立中,选择Logistic方程预测红孩子横纵径[25]、石硖果核质量[6]的生长,二次项方程预测四季蜜横纵径[21]、石硖果肉质量[6]、大乌圆果皮质量[20]的生长。三次项方程预测石硖[6]和四季蜜[18]果皮质量、四季蜜TSS[21]的生长。本试验中,二次项方程能更好地描述果实纵径、单果质量、果肉质量、可食率和TSS的生长动态,三次项方程能更好地描述果实横径、果形指数、果皮厚度的生长动态,Logistic方程能更好地描述果皮质量和果核质量的生长动态。这说明龙眼果实拟合曲线构建可能受到树种、品种、栽培管理措施、气候条件以及其动态变化规律不一致[20]的影响。

自谢花坐果后,桂丰早的纵横径、单果质量、果皮质量、果核质量、果肉质量、可食率呈"S"形或近"S"形增长,果形指数和果皮厚度呈反"S"形下降。本研究中桂丰早果实各指标拟合方程及其导函数模型显示,横径在花后40 d前增长较快,纵径增长在花后142 d后出现拐点,果形指数在25 d左右出现拐点,最终果形呈近圆形,这与依嚣、四季蜜果形相似[21,26];花后99 d之前为果实单果质量、果肉质量、可食率、TSS主要增长阶段,且花后85~99 d为果皮最薄的阶段。鲜食和近销的龙眼果实宜在成熟期采摘[27],TSS可作为判断龙眼果实成熟的标准[28],桂丰早龙眼的TSS在花后92 d达到最高点,花后99 d为拐点,同时花后99 d是单果质量、果肉质量、可食率指标较佳时期,故花后99 d是桂丰早果实生长的重要分水岭,在生产上,应于上年12月底至1月中下旬施促花肥,遇上花穗冲梢,选择乙烯利加多效唑混合溶液喷洒以及人工辅助防治。花期为清明节前后至劳动节前,共24 d,应在花前花后补施速效氮、钾肥,果实膨大期间(花后99 d前)要施足肥料和加强水分管理。

果实生长发育过程中指标之间相互关联且呈现先后顺序变化的趋势[29]。桂丰早果实生长以果核为先,然后是果肉生长,从而影响单果质量,与前人研究一致[25],同时相关性分析表明,单果质量和果肉质量的相关系数(0.999)较高,表明桂丰早是以果肉增重为主的果实,表现肉厚,这与东良一致[30];桂丰早果皮由厚向薄转变,与石硖果皮的变化相类似[31],这一现象的原因可能是果肉的生长导致果皮变薄[25],这与桂丰早在果肉主要生长阶段果皮变薄的情况相符。

4 结 论

在南宁,根据构建的曲线拟合方程和导函数,表明桂丰早果实横径快速增长是花后40 d前,主要性状单果质量、果肉质量、可食率、TSS生长关键时期是花后99 d前。基于果实发育天数搭建果实发育的曲线拟合方程和导函数能较好地反映桂丰早龙眼果实的生长发育动态,故桂丰早龙眼果实生长模型的建立在生产上可用于果实品质预测和指导制定合理的栽培技术措施。

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