



Research article

Late harvesting enhances granulation incidence in ‘Khao Yai’ pummelo (*Citrus maxima* (Burm.) Merr.) fruit

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Abstract

Granulation is an unfavorable characteristic found in citrus fruit including pummelo due to the juice sacs becoming hard, dry and tasteless, leading to poor fruit quality. The degree of granulation and fruit quality were compared of ‘Khao Yai’ pummelo harvested at three different stages: 1) early-harvest (1 mth before the optimum harvest for local market), 2) optimum-harvest and 3) late-harvest (1 mth after the optimum harvest for local market) in two consecutive crops (January and April) from the same set of trees. Granulation was detected in most fruit (84–100%) from all three harvesting stages. The degree of granulation was relatively low with less variation (0–38.8%) in fruits of early- and optimum-harvests and it increased significantly with more variation (1.9–81.7%) in late-harvest fruits. A similar trend was observed in both the January and April crops. The N, K, Mg and Na concentrations in the juice sac tissues were not significantly different among fruits with various degree of granulation. The Ca concentration (0.06–0.95%) in the juice sac tissues increased significantly with an increased degree of granulation in the April crop but not in the January crop within the range 0.08–0.20%. The degree of granulation tended to increase with increased fruit height, fruit circumference and fruit weight. Fruits from the April crop had higher total soluble solids (TSS) and lower titratable acidity (TA) than those from January crop. Normal juice sacs of fruits with different degrees of granulation had a relatively stable TSS (approximately 11°Brix) while the TA decreased with the progression of harvesting stages.

Introduction

One of the unfavorable characteristics often associated with pummelo and other citrus is granulation wherein juice sacs in a segment become tough, dry and assume the white color of rice grain leading to poor fruit quality (Sharma and Saxena, 2004). The tough texture is a result of thickened walls of individual parenchyma cells within the granulated juice sacs and the development of secondary walls in cases of severe granulation (Burns and Achor, 1989). The dry appearance of granulated juice sacs is not caused by dehydration but

by gel formation (Bartholomew et al., 1941). Granulated juice sacs are generally tasteless due to their lower content of soluble sugars and acids which is a consequence of the increased respiration by the granulated juice sacs (Burns, 1990). Lacerna et al. (2017) reported that postharvest yellowing of fruit peel and the degree of granulation further increased in pummelo fruits stored for 12 wk at ambient temperature and high relative humidity. Hence, granulation may be a part of the fruit senescence process as suggested by Chen et al. (2005).

Although the true causes of citrus granulation have not been fully understood, several factors are reported to be associated with granulation incidence, including: frequent irrigation, higher application rate of nitrogenous fertilizers, vigorous growth after heavy pruning or fertilization, delayed harvesting, shade inside the canopy, tree age,

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over fruit size, low crop load, growing location and some climatic factors (Singh, 2001; Ritenour et al., 2004; Sharma and Saxena, 2004). Increased granulation was reported in late harvested ‘Thong Dee’ (pink flesh) and ‘Khao Nam Phueng’ (light yellow flesh) pummelo grown in the same orchard and the degree of granulation was significantly greater in the ‘Khao Nam Phueng’ cultivar (Thammarat et al., 2010). The granulation symptom was clearly identified by eye in ‘Khao Nam Phueng’ but it was difficult to distinguish without carefully examining and touching in ‘Thong Dee’ where the granulated juice sacs were still translucent. Studies on citrus granulation mostly scored the degree of granulation by eye based on the appearance of the whole segments which tended to underestimate the symptom as the hard translucent juice sacs inside the segments were ignored.

‘Khao Yai’ pummelo is a seedless cultivar with light yellow flesh and a relatively large in fruit size; it is mainly produced on alluvial soil in the Mae Klong river basin, Samut Songkhram province, in the central region of Thailand and its superior quality is well known domestically. The climatic conditions in this region allow the ‘Khao Yai’ pummelo to flower and set fruit almost all year round with two peaks of harvest in January and April, though differences in the fruit size, yield and quality between January and April crops have been reported (Tongleaw and Phavaphutanon, 2011). As a non-climacteric fruit, a fully mature pummelo fruit can be left on the tree without ripening for a certain period to expand the marketing window. However, delayed harvesting may increase the granulation incidence and lower the overall fruit quality. Whether granulation is influenced by harvesting stages has not been reported for this cultivar.

The objectives of this study were to compare the degree of granulation and fruit quality of ‘Khao Yai’ pummelo harvested at three different stages: 1) early-harvest (1 mth before the optimum harvest for local market), 2) optimum-harvest and 3) late-harvest (1 mth after the optimum harvest for local market) in two consecutive crops (January and April crops) from the same set of trees. Whether concentrations of certain nutrients in juice sac tissues and the fruit characteristics associated with granulation were also investigated.

Materials and Methods

Description of study site and cultural practice

The study was conducted in an orchard with a good record of production and fruit quality in Bang Khon Tee district, Samut Songkhram province, Thailand. The ‘Khao Yai’ pummelo trees were aged 17 yr and were growing in a double-row system. Each planting bed was alternated by a furrow that served for irrigation and drainage—a typical practice in lowland orchards with alluvial clayey soil. The orchard soil was slightly acidic with pH (1:2.5) of 6.1, low electrical conductivity (0.2 dS/m), low organic matter (1.1–1.5%), high available phosphorus (31 mg/kg), very high exchangeable potassium (304.8 mg/kg) and high exchangeable calcium (2,924.5 mg/kg), magnesium (915.3 mg/kg) and sodium (156.6 mg/kg). Manure was applied once a year at the rate of 15–20 kg per tree. Chemical fertilizer was applied as compound fertilizer (400 g of 25N-7P-7K per tree) every month to promote vegetative growth. In addition, 1 kg of 12N-24P-12K per tree was applied to promote flowering and 1–2 kg per tree of scraped out material from the salt field at 2 mth

before harvesting was applied to improve fruit quality. This sheathed material is a byproduct of salt production in ponds and was composed of dried algae, lichen and sediment and was rich in P and K.

Fruit sample collection and handling

Five uniform representative trees with canopy size of 6.1 m × 6.6 m were selected. Trees were allowed to flower naturally and two crops could be expected in January and April on the same trees. In each crop, fruits were harvested at three different stages: 1) early-harvest (1 mth before the optimum harvest for local market; fruits were aged 7 mth), 2) optimum-harvest (fruits were aged 8 mth) and 3) late-harvest (1 mth after the optimum harvest for domestic market; fruits were aged 9 mth). The average fruit counts were 55 and 30 fruits per tree for the January and April crops, respectively. The optimum harvesting stage for the domestic market was confirmed by orchard owners and professional fruit collectors. In each harvest, five fruits per tree were randomly hand-picked from the entire canopy. These fruits were transported to a laboratory on the same day as harvesting and weighed individually. The fruit surface was cleaned using 0.1 N HCl solution and distilled water.

Measurement of fruit characteristics

The fruit circumference and height were recorded. Peel color was determined by a color difference meter (Tricolor LFM3 Instrument, DR Lange, Germany) based on the Hunter scale and the peel thickness was recorded. After peeling, the peel and pulp were weighed separately.

Determination of granulation

The number of fruits with granulation was recorded in each harvesting stage. Granulation was determined in each segment in detail by observation and touch. Granulated juice sacs which were clearly identified by their white opaque color were separated out first. Any remaining translucent juice sacs which were hard and dry to touch were considered as having granulation and were also separated out. The firmness scores of long juice sacs (mostly found in the middle of the segment) and short juice sacs (mostly found at the ridge, stem end and bottom end of the segment) with and without granulation were measured using a fruit hardness tester (N.O.W., model FHR-5, Japan) with a puncture head of 0.5 cm diameter. The granulated juice sacs were weighed and the degree of granulation was calculated from the proportion of fresh weight of granulated juice sacs and the total fresh weight of pulp of the whole fruit and expressed as a percentage. The pattern of granulation was described based on the amount of granulated juice sacs found in different positions in each segment.

Determination of nutrients in juice sac tissues

Composite samples of pulp from groups of fruits showing different degrees of granulation (< 5%, 5–20 % and > 20%) were collected and dried at 70°C for 7–10 d until each dry weight was constant. Dried samples were ground to pass through a 40-mesh screen for further nutrient analysis. Total nitrogen (N) was determined using the combustion with a using LECO Protein/nitrogen determinator (model FP-528, LECO, USA). The potassium (K), calcium (Ca), magnesium

(Mg) and sodium (Na) concentrations were determined using atomic absorption spectrophotometry (Analytic Jena, Vario 6, Germany) after samples had been digested to eliminate organic matter using an acid mixture (12.21 N HClO₄ + 15.77 N HNO₃ at 2:1 ratio) under high temperature.

Statistical analysis

Data were subjected to analysis of variance and the comparison of means was done based on Tukey's test. Correlation analysis was performed to determine the relationship between the degree of granulation and certain fruit characteristics. The differences were considered as significant at $p < 0.05$ and as highly significant at $p < 0.01$. All statistical analyses were performed using the SPSS software version 11 (SPSS Inc., USA).

Results and Discussion

Granulation was detected in almost every fruit (84–100%) examined from all three harvesting stages. Granulated juice sacs of 'Khao Yai' pummelo were white opaque, hard and dry as previously reported in other citrus fruits (Agusti et al., 2004; Ladaniya, 2008; Singh, 2001). The symptom occurred in both long and short juice sacs with increased firmness values of 1.0–1.3 kg/cm² while the normal juice sacs had firmness values in the range 0.2–0.5 kg/cm². The symptom was mainly found in juice sacs near the stem-end and along the ridge of the segments and less commonly in juice sacs near the fruit bottom (styler) end. In severe cases, granulation occurred in whole segments. The pattern of granulation in segments of 'Khao Yai' pummelo was similar to that described in another light yellow-pulp pummelo cultivar, 'Khao Nam Pheung' (Thammarat et al., 2010). Fruits harvested in January and April had comparable numbers of fruits with granulation and degree of granulation. The numbers of fruits with granulation and degree of granulation tended to increase with the progression of harvesting stages. The degree of granulation had greater variation in late-harvest fruit (in the range 4.5–81.7% in the January crop and 1.9–62.1% in the April crop) compared to the early- and optimum- harvest ones (in the range 0–14.2%

for the January crop and 0–38.8% for the April crop), as shown in Table 1.

Fruits harvested in January had comparable sizes and weights to those harvested in April with a lower percentage of peel (38.7% versus 41.3%) and a higher percentage of pulp (54.9% versus 50.7%). The fruit size and weight tended to increase with the progression of harvesting stages in the January crop but not in the April crop. The percentage of peel was not significantly different among different harvesting stages (average = 40%) while the percentage of pulp slightly increased from 50.07% in the early harvesting stage to 53.3–54.5% in the last two harvesting stages (Table 2).

The peel color of 'Khao Yai' pummelo fruit was highly significantly different between the January and April crops and among the three harvesting stages. Fruits harvested in January had lower green (-a) values, higher brightness (L) and yellow (+b) values and less peel thickness than those harvested in April. The L and +b values tended to increase with the progression of harvesting stages in both crops. The green color of the peel remained relatively stable in the April crop but not in the January crop (Table 3).

The January crop had slightly lower TSS values ($11.1 \pm 0.7^\circ\text{Brix}$ versus $11.6 \pm 0.7^\circ\text{Brix}$) and higher TA values ($0.7 \pm 0.1\%$ versus $0.6 \pm 0.1\%$) than the April crop, resulting in a lower TSS:TA ratio. In each crop, the TSS was not significantly different among the three harvesting stages (average = 11.3°Brix). The TA tended to decrease with the progression of harvesting stages, leading to an increased TSS:TA ratio (Table 4). However, the late-harvest fruit of both crops started to have a fermented odor which could be unacceptable to consumers. The overall fruit size and quality of 'Khao Yai' pummelo at the optimum harvesting stage in the current study agreed well with a previous study of both January and April crops (Tongleaw and Phavaphutanon, 2011) and suggested that delaying harvesting of this cultivar is detrimental and increases the granulation incidence, even though fruit appearance is still acceptable. Although the tolerance level of granulation has not been established as a quality standard for Thai pummelo, tasters in the current experiment agreed that a degree of granulation above 20% was not acceptable. However, this opinion cannot be compared to other studies directly as the methods of granulation assessment were different.

Table 1 Fruit with granulation and degree of granulation of 'Khao Yai' pummelo crops harvested in January and April at early (1), optimal (2) and late (3) harvesting stages, where data are shown as mean $\pm$ SD

Trait	Harvesting stage within crop (A)						Significance
	1		2		3		
Granulated fruit (%)	88.0 ± 25.3 ^b		94.0 ± 13.5 ^{ab}		100.0 ± 0.0 ^a		*
Granulation degree (%)	4.9 ± 3.5 ^b		8.8 ± 10.8 ^b		19.0 ± 18.6 ^a		**
Trait	Crop (B)						B
	January crop			April crop			
Granulated fruit (%)	94.6 ± 20.7 ^a			92.3 ± 12.3 ^a			ns
Granulation degree (%)	12.6 ± 16.8 ^a			9.2 ± 9.8 ^a			ns
Trait	Interaction (A×B)						A×B
	January crop			April crop			
Harvesting stage	1	2	3	1	2	3	
Granulated fruit (%)	84.0±35.6 ^b	100.0±0.0 ^a	100.0±0.0 ^a	92.0±0.0 ^a	88.0±0.0 ^{ab}	100.0±0.0 ^a	ns
Granulation degree (%)	5.0 ^b	8.6 ^b	24.1 ^a	4.7 ^b	9.0 ^b	13.9 ^b	ns
	(0–10.4)	(0–14.2)	(4.5–81.7)	(0–15.4)	(0–38.8)	(1.9–62.1)	

ns = not significant; *, ** = significance at $p < 0.05$ and $p < 0.01$, respectively;

Values in parentheses show minimum and maximum range of degree of granulation. Mean $\pm$ SD values within a row follow by different lowercase superscripts are significantly different ($\alpha < 0.05$).

Table 2 Fruit height, circumference, weight and percentage of peel and pulp of ‘Khao Yai’ pummelo crops harvested in January and April at early (1), optimal (2) and late (3) harvesting stages, where data are shown as mean $\pm$ SD

Trait	Harvesting stage within crop (A)			Significance		
	1	2	3			
Height (cm)	15.5 ± 1.3 ^b	16.0 ± 1.3 ^{ab}	16.3 ± 2.0 ^a	*		
Circumference (cm)	50.7 ± 3.1 ^b	52.0 ± 3.0 ^{ab}	53.2 ± 5.7 ^a	**		
Weight (g)	1,402.0 ± 224.1 ^b	1,573.0 ± 262.4 ^a	1,682.2 ± 482.7 ^a	**		
Peel (%)	40.8 ± 6.2 ^a	38.9 ± 4.5 ^a	40.3 ± 9.3 ^a	ns		
Pulp (%)	50.7 ± 5.6 ^b	54.5 ± 4.9 ^a	53.3 ± 7.5 ^{ab}	**		
Trait	Crop (B)			B		
	January crop		April crop			
Height (cm)	16.1 ± 1.3 ^a		15.8 ± 1.5 ^a	ns		
Circumference (cm)	52.5 ± 4.7 ^a		51.4 ± 3.7 ^a	ns		
Weight (g)	1,600.0 ± 407.5 ^a		1,504.8 ± 298.9 ^a	ns		
Peel (%)	38.7 ± 7.3 ^b		41.3 ± 6.6 ^a	*		
Pulp (%)	54.9 ± 5.5 ^a		50.7 ± 6.1 ^b	**		
Trait	Interaction (A×B)			A×B		
	January crop		April crop			
Harvesting stages	1	2	3	1	2	3
Height (cm)	15.4 ± 1.3 ^b	15.9 ± 1.2 ^{ab}	17.0 ± 2.1 ^a	15.6 ± 1.2 ^a	16.2 ± 1.4 ^{ab}	15.6 ± 1.7 ^a
Cir. (cm)	50.5 ± 3.3 ^b	51.7 ± 2.8 ^b	55.6 ± 5.7 ^a	50.9 ± 2.9 ^b	52.3 ± 3.3 ^b	50.9 ± 4.6 ^b
Weight (g)	1396.0 ± 239.4 ^b	1,521.6 ± 229.2 ^b	1,882.4 ± 519.0 ^a	1,408.0 ± 212.5 ^b	1,624.4 ± 287.1 ^{ab}	1,482.0 ± 350.4 ^b
Peel (%)	37.0 ± 4.8 ^b	37.3 ± 3.7 ^b	41.8 ± 10.5 ^{ab}	44.6 ± 5.1 ^a	40.4 ± 4.9 ^{ab}	38.9 ± 8.1 ^b
Pulp (%)	53.4 ± 5.6 ^{ab}	56.8 ± 8.1 ^a	54.8 ± 14.5 ^{ab}	48.0 ± 4.6 ^c	52.2 ± 6.3 ^{abc}	51.8 ± 9.8 ^{bc}

ns = not significant; *, ** = significance at $p < 0.05$ and $p < 0.01$, respectively;

Mean $\pm$ SD values within a row followed by different lowercase superscripts are significantly different ($p < 0.05$).

Table 3 Peel color and peel thickness of ‘Khao Yai’ pummelo crops harvested in January and April at early (1), optimal (2) and late (3) harvesting stages, where values are shown as mean $\pm$ SD

Trait	Harvesting stage with crop (A)						Significance
	1		2		3		
Peel color							
L	52.5 ± 4.6 ^b		50.7 ± 4.5 ^b		56.1 ± 6.1 ^a		**
a	-13.1 ± 1.2 ^b		-14.7 ± 3.7 ^c		-10.3 ± 2.5 ^a		**
b	32.8 ± 3.9 ^c		34.9 ± 4.7 ^b		36.1 ± 4.7 ^a		**
Peel thickness (cm)	1.9 ± 0.4 ^a		1.7 ± 0.3 ^a		1.8 ± 0.5 ^a		ns
Trait	Crop (B)						B
	January crop			April crop			
Peel color							
L	54.7 ± 6.4 ^a			51.5 ± 4.1 ^b			**
a	-13.4 ± 4.3 ^b			-12.1 ± 1.1 ^a			**
b	37.3 ± 4.5 ^a			32.6 ± 3.8 ^b			**
Peel thickness (cm)	1.7 ± 0.4 ^b			1.9 ± 0.5 ^a			*
Trait	Interaction (A×B)						A×B
	January crop			April crop			
Harvesting stage	1	2	3	1	2	3	
Peel color							
L	55.2 ± 4.4 ^{ab}	50.3 ± 5.5 ^{cd}	58.4 ± 6.4 ^a	49.7 ± 2.7 ^d	51.0 ± 3.2 ^{cd}	53.9 ± 5.0 ^{bc}	**
a	-13.5 ± 1.3 ^b	-17.8 ± 2.5 ^a	-8.8 ± 2.6 ^d	-12.7 ± 1.0 ^{bc}	-11.7 ± 1.1 ^c	-11.8 ± 0.8 ^c	**
b	35.5 ± 2.9 ^b	36.5 ± 5.5 ^b	39.9 ± 3.8 ^a	30.1 ± 2.6 ^c	33.5 ± 3.3 ^b	34.3 ± 4.1 ^b	ns
Peel thickness (cm)	1.7 ± 0.3 ^b	1.6 ± 0.3 ^b	1.9 ± 0.4 ^{ab}	2.1 ± 0.4 ^a	1.9 ± 0.4 ^{ab}	1.8 ± 0.6 ^{ab}	*

L = brightness value (0–100), 0 = dark and 100 = white; +a = red and -a = green; +b = yellow and -b = blue; ns = not significant; *, ** = significance at $p < 0.05$ and $p < 0.01$, respectively;

Mean $\pm$ SD values within a row followed by different lowercase superscripts are significantly different ($p < 0.05$).

Table 4 Total soluble solids (TSS), titratable acidity (TA) and TSS:TA ratio of ‘Khao Yai’ pummelo crops harvested in January and April at early (1), optimal (2) and late (3) harvesting stages, where values are shown as mean $\pm$ SD

Trait	Harvesting stage within crop (A)			Significance A			
	1	2	3				
TSS (°Brix)	11.4 ± 0.7 ^a	11.3 ± 0.6 ^a	11.3 ± 0.9 ^a	ns			
TA (%)	0.7 ± 0.07 ^a	0.6 ± 0.08 ^b	0.5 ± 0.09 ^c	**			
TSS:TA	15.2 ± 1.9 ^c	17.7 ± 2.5 ^b	20.1 ± 3.7 ^a	**			
Trait	Crop (B)			Significance B			
	January crop		April crop				
TSS (°Brix)	11.1 ± 0.7 ^b		11.6 ± 0.7 ^a	**			
TA (%)	0.7 ± 0.1 ^a		0.6 ± 0.1 ^b	**			
TSS:TA	16.3 ± 2.5 ^b		19.1 ± 3.7 ^a	**			
Traits	Interaction (A×B)						A×B
	January crop			April crop			
Harvesting stage	1	2	3	1	2	3	
TSS (°Brix)	11.3 ± 0.8 ^{abc}	11.1 ± 0.6 ^{bc}	10.8 ± 0.6 ^c	11.5 ± 0.7 ^{ab}	11.5 ± 0.7 ^{ab}	11.8 ± 0.8 ^a	**
TA (%)	0.8 ± 0.07 ^a	0.7 ± 0.09 ^b	0.6 ± 0.08 ^c	0.7 ± 0.08 ^{ab}	0.6 ± 0.06 ^c	0.5 ± 0.08 ^d	ns
TSS:TA	14.6 ± 1.7 ^d	16.3 ± 1.9 ^{cd}	17.9 ± 2.6 ^{cd}	15.8 ± 1.9 ^d	19.1 ± 2.3 ^b	22.4 ± 3.3 ^a	**

ns = not significant; *, ** = significance at $p < 0.05$ and $p < 0.01$, respectively;

Mean $\pm$ SD values within a row followed by different lowercase superscripts are significantly different ($p < 0.05$).

Pummelo fruits with various degrees of granulation from both the January and April crops did not show any significant differences in the N and K concentrations in the juice sac tissues. The Ca concentration in the juice sacs was also not significantly different in the January crop (Ca in the range 0.08–0.20%) but its concentration increased highly significantly with increased degree of granulation in the April crop (Ca in the range 0.06–0.95%). It was reported that the Ca concentration in juice sacs of ‘Khao Yai’ pummelo was in the range 0.11–0.12%, which was much lower than the concentration in other fruit parts including the flavedo, albedo and segment membrane (Tongleaw et al., 2012). An increase in Ca could be a consequence of the thickened cell wall of the granulated juice sacs, as Ca is an essential component of cell wall materials (Marschner, 1995). Relatively large variations in the Mg and Na concentrations were observed among fruits with comparable degrees of granulation and between fruits with different degrees of granulation. Consequently, the mean concentrations of Mg and Na in the juice sac tissues of fruits with different degrees of granulation were not significantly different in both the January and April crops (Table 5). Analysis of selected nutrients in the juice sac tissues of pummelo in the current study did not demonstrate that any particular nutrient influenced granulation. In another study, monthly spray of 1% urea solution on

‘Khao Nam Phueng’ pummelo fruits, starting when the fruits were aged 3 mth significantly enhanced the juice sac tissue N concentration and the degree of granulation of fruits at the optimum harvesting stage (Thammarat et al., 2011). High N fertilizer was reported to increase the number of over-sized fruit with rough peel, to delay maturity and to increase granulation in grapefruit (He et al., 2003).

Correlation analysis indicated that the degree of granulation correlated well (significant at the 99% confidence level) with increased fruit height (correlation coefficient, $r = 0.49$), fruit circumference ($r = 0.56$), fruit weight ($r = 0.59$), peel thickness ($r = 0.43$) and decreased green color of fruit peel ($r = -0.33$) in the January crop. For April crop, the degree of granulation correlated well (significant at the 99% confidence level) with only fruit height ($r = 0.32$), fruit circumference ($r = 0.43$) and fruit weight ($r = 0.49$), as shown in Table 6. A common trend observed in both crops suggested that ‘Khao Yai’ pummelo fruits of larger size and fruit height than the norm tended to have more granulation. A similar observation was reported in other kinds of citrus (Burns and Albrigo, 1998; Sharma et al., 2006). Larger fruits which tended to have more granulation may have had a more advanced age. Typically, they arise from the terminal florets of the cymose inflorescence and their development is initiated in advance of that of the lateral florets (Lord and Eckard, 1985).

Table 5 Concentrations of nitrogen, potassium, calcium, magnesium and sodium in juice sac tissues of ‘Khao Yai’ pummelo fruits with different degrees of granulation harvested in January and April

Degree of granulation (%)	Nutrient concentration				
	N (%)	K (%)	Ca (%)	Mg (mg/kg)	Na (mg/kg)
January crop					
< 5	0.9	1.1	0.12 ^a	553.8	524.2
5–20	0.8	1.1	0.08 ^a	522.2	572.4
> 20	0.9	1.2	0.20 ^a	702.0	706.0
F test	ns	ns	ns	ns	ns
April crop					
< 5	0.8	1.1	0.06 ^b	438.8	608.5
5–20	0.9	1.2	0.45 ^{ab}	751.2	1,071.2
> 20	0.9	1.2	0.95 ^a	388.0	454.8
F test	ns	ns	**	ns	ns

** = significant at $p < 0.01$; ns = not significant.

mean values in a column within each crop followed by different lowercase superscripts are significantly different ($p < 0.05$).

Table 6 Correlation coefficients between degree of granulation and certain fruit characteristics of ‘Khao Yai’ pummelo crops harvested in January and April.

Characteristic	January crop	April crop
Fruit height	0.49**	0.32**
Fruit circumference	0.56**	0.43**
Fruit weight	0.59**	0.49**
Peel color		
L	0.11	0.09
-a	-0.33**	-0.05
b	0.06	0.09
Peel thickness	0.43**	0.15

** = correlation significant at 99% confidence level

The current results demonstrated that granulation of ‘Khao Yai’ pummelo occurred before the fruit reached the optimum harvesting stage for the domestic market, and that late harvesting enhanced granulation incidence. In mature Satsuma mandarin fruit, the respiration rate and weight of peel increased during storage while the pulp weight decreased, indicating that the peel was still growing with advanced fruit age and it was suspected that certain substances and water might transfer from pulp to peel to support the growth and respiration of the peel and cause granulation of the juice sacs (Ke et al., 1989). Chen et al. (2005) provided evidence for the transport of C-14-glucose from juice sacs to peel tissue in ‘Huyou’ citrus fruit before the commencement of granulation was recorded. Sethapakdee (1997) proposed that a developing pummelo fruit was a strong sink of photoassimilate and it became a source after reaching full maturity. Therefore, draining of food reserves from late-harvest fruit to other strong sinks such as developing leaves could happen and might be related to increased granulation incidence. However, it cannot explain the cause of granulation found in early-harvest fruit. How the transfer of water and substances relates to cell wall thickening and gel formation of granulated juice sacs is still not known.

From the current study, a low level of granulation was detected readily in ‘Khao Yai’ pummelo fruits at 1 mth before the optimum harvesting stage for the local market in both the January and April crops. The number of fruits with granulation increased significantly and the degree of granulated juice sacs increased highly significantly in late harvesting fruits (1 mth after the optimum harvest for the local market). Analysis of selected nutrients in the juice sac tissues did not identify that any particular nutrient influenced granulation except for Ca in that its concentration increased significantly with increased degree of granulation in the April crop but not in the January crop. The degree of granulation tended to increase with increased fruit size and fruit weight regardless of harvesting times but its relationship with peel color and peel thickness was inconsistent. Fruits from the April crop generally had higher TSS and lower TA values than those from the January crop. With the progression of harvesting stages, fruits with different degrees of granulation had relatively stable levels of TSS in the normal juice sacs (approximately 11°Brix) while their TA decreased.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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