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Physical properties of fresh young Thai coconut for maturity sorting

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Young mature coconut is a widely consumed fruit consisting of soft white flesh and sweet white transparent aromatic juice. Judging the maturity of young coconut is difficult and thus a harvested crop typically features fruit of varying levels of maturity, which currently require manual grading. In an attempt to help reduce the time and costs associated with the grading process, the correlations between the physical, mechanical, physiological and acoustic properties of coconuts and their maturity levels were investigated. The analyses showed that specific gravity, husk rupture force and husk firmness showed a decreasing trend with progressing days after pollination. Other properties including resonant frequency, shell rupture force, shell firmness, total soluble solids, flesh thickness, wet flesh weight and dry flesh weight indicated an increase in values with days after pollination. The flesh thickness was the parameter best correlated with days after pollination. Maturity index based on the flesh thickness can be quantitatively predicted by multivariate partial least squares model. The best model used a combination of husk rupture force, shell firmness, shell rupture force, wet flesh weight and husk firmness ($R^2 = 0.991$, standard error of prediction of 0.133 and bias of 0.004). A non-destructive model based on resonant frequency gave relatively good accuracy of prediction with $R^2 = 0.927$, standard error of prediction 0.386 and bias of 0.034.

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1. Introduction

Young coconut is highly nutritious and is one of the most popular export fruits from Southeast Asian countries (Jarimopas and Ruttanadat, 2007; Gatchalian et al., 1994). The fruit structurally comprises a green skin, a fibrous husk, and a shell which encloses the flesh and juice. The “Nahm Wahn”

(“sweet liquid”) cultivar is generally preferred by consumers because of its taste. The maturity of the young coconut fruit strongly affects the fruit quality. The juice and the flesh of the immature fruit are sour and over-soft (jelly-like) while the over-mature fruit is considered by consumers to be too sweet and hard. However, the properly mature fruit is characterized by juice that is sweet and slightly sour, and has a moderately

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Nomenclature

SG	Specific gravity
f_n	Resonant frequency, kHz
HF _R	Husk rupture force, N
SF _R	Shell rupture force, N
HSL	Husk firmness, N mm ⁻¹
SSL	Shell firmness, N mm ⁻¹
TSS	Total soluble solid, °Brix
TA	Titrate acidity, %
TSS/TA	Total soluble solid and titrate acidity ratio, °Brix % ⁻¹

FT	Flesh thickness, mm
F _w	Wet flesh weight, g
D _w	Dry flesh weight, g
t	Days after pollination, day
R	Correlation coefficient
R ²	Coefficient of multiple determination
SEP	Standard error of prediction
RMSEP	Root Mean Square Error of Prediction
RMSECV	Root Mean Square Error of Cross Validation
N	Number of equivalents of solute per litre of solution, Normality

soft flesh. Competent fruit growers are able to detect changes in physical characteristics, mechanical strength, acoustic and physiological properties as the young coconut matures and changes which are usually imperceptible to the layperson (Jarimopas and Kusol, 2007).

Several researchers have described the physical, mechanical, physiological and acoustic properties characterizing the maturity of other types of fruit. For example, Kato (1997) described the relationship between the density and maturity of Japanese watermelon. Pleasantly sweet watermelon that does not include cavities has a density that is equal to or greater than 0.934. Specific gravity is a physical and physiological property that is recognized by horticulturists and postharvest technologists. Researchers have used the specific gravity to determine the maturity of mango (Jarimopas and Kittawee, 2007), mangosteen (Sornsrivichai et al., 1999), and dragon fruit (Wanichang and Jarimopas, 2008). However, in practice, specific gravity is rarely applied to sorting in the modern packing line, although it can serve as an alternative monitoring indicator.

The slope of the force-deformation curve is another measure that has been used to determine fruit maturity. Jarimopas and Kittawee (2007) subjected mango to slow compression to determine the relationship between firmness and maturity. They found that the slope remained constant from immaturity to maturity but decreased as the fruit became over-mature. Alternatively, maturity of a fruit can be found from the force response of the fruit at constant compression deformation. Takao and Ohmori (1994) successfully developed a hardness immaturity tester (HIT) based on experiments with kiwi fruit.

The relationship between acoustic properties and maturity has also been investigated (Kouno et al., 1993; Terdwongworakul et al., 1998; Gatchalian et al., 1994). Kouno et al. (1993) investigated the sound properties of watermelon and plotted natural frequency against the height of watermelon. Grouping together co-ordinate points was proposed to identify the immature, mature and over-mature fruit. Terdwongworakul et al. (1998) observed a correlation between the maturity of Mhonthong durian and the function $2/3f_n^2 \ln(m)$, where f_n is the natural frequency of the durian and m is its mass. The function decreases in value when durian approaches the onset of over-maturity. Gatchalian et al. (1994) investigated the acoustic properties of young Philippine coconut after observing that farmers and traders in that country differentiate fruit

maturity by tapping the fruit. They recorded the tapping sounds and analyzed the sound signal through an analogue-to-digital converter and Fast Fourier Transformation. The average power spectrum of the sound produced by immature fruit was lower and more “solid” than the “hollow” sound produced by mature and over-mature fruit. However, natural frequency of young coconut fruit was not quantitatively discussed, and thus the hollow and the solid sounds did not quantitatively characterize the maturity of the young coconut. Nevertheless, it was established that flesh thickness was also a significant physical characteristic separating young coconut of various maturities.

Recently, Boonmung et al. (2006) attempted to classify pineapple quality (unripe, ripe, overripe) using resonant frequency and level of soluble solids in the fruit as guides. The acoustic property tester developed by Jarimopas et al. (2004) was used to measure the frequency spectrum of the pineapple subjected to a single hit. An artificial neural network for classification was most efficient with the maximum amplitude of the resonant frequency and the soluble solids included in the model.

A common method of determining the maturity of fruit is to analyze its dry matter, soluble solids and acidity. Sangwanakul and Siripanich (2000) followed the growth and development of “Mhonthong” durian, and recommended from their observations that the dry matter of the pulp was the best indicator for determining durian maturity. Furthermore Subhadrabandhu and Ketsa (2001) suggested that the soluble solids content of durian changes inversely with aril firmness in relation to maturity development and the decrease in firmness coincides with an increase in water-soluble pectin. A more mature durian aril has greater water-soluble pectin and its water-soluble pectin increases more rapidly than that of a less mature durian aril (Ketsa and Daengkanit, 1999). Dry matter can be used as a harvesting indicator for hard green mango fruit as it has a strong relationship with the ripe-stage eating quality (soluble solids content) (Saranwong et al., 2004). Acidity is also a parameter describing fruit growth (Mercado-Silva et al., 1998; Saranwong et al., 2004).

However, apart from the acoustic properties of coconut, no physical or physiological properties (including acidity) have ever been shown to reliably correlate with the maturity of young coconut. Nevertheless, even when it is understood that human beings are at present the most reliable sensing

instrument for coconut maturity, the fact that on-line packing lines are an established part of the coconut processing industry means that it is necessary to develop quantitative information to sort fruit of different maturity. This research therefore aims to (a) investigate the physical, mechanical, physiological and acoustic properties of young coconut in relation to maturity, and (b) develop a multivariate model for predicting a young coconut maturity index using a partial least squares technique.

2. Materials and methods

2.1. Determination of physical characteristics

A well-known export-orientated orchard in Samut Sakhon province, Thailand, was chosen as the source for the young coconuts which provided data for this experiment. Newly harvested young “Nahm Wahn” coconuts of uniform size were purchased every four days beginning on the 170th day after pollination and continuing until the 206th day after pollination. They were transported on the same day to a laboratory at the Department of Agricultural Engineering at Kasetsart University, Kamphaengsaen. While the young coconuts were harvested 170 days after pollination, they require 170–195 days to reach the desirable level of maturity. Those that were harvested between 170 and 180 days after pollination were considered immature. The fruit becomes over-mature after 195 days (Siripanich, 1995). Twenty coconuts were randomly selected in accordance with ASAE Standard (ASAE Standard, 1994). The diameter and height of each fruit sample were measured with a vernier caliper, and the weight was measured on an electronic balance (Sartorius PT 6000V2). The specific gravity of each sample was determined by using the water displacement method described by Mohsenin (1996).

2.2. Determination of acoustic properties

Each sample was put in an acoustic property tester of the type described by Boonmung et al. (2006) (Fig. 1). The young coconut was placed on a support at the centre of the tester. The impact force was applied to the equator of the sample and the sound signal was recorded by a microphone mounted a few millimetres above the sample surface opposite the strike point. Each sample was struck at six positions around its equator, one at the middle of each ridge, and one in the middle of each face (a young coconut has three ridges and three faces) (Fig. 2).

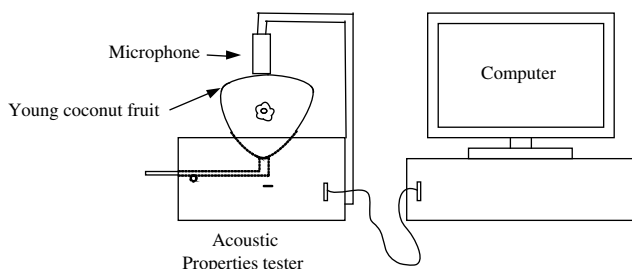


Fig. 1 – Acoustic property tester.

Three repetitions were made at each ridge and face. Fast Fourier transformation of the sound signal gave the frequency spectrum of the young coconut. The tests were repeated every four days for all 20 samples until the 206th day after pollination.

2.3. Determination of mechanical properties

Each sample was put in a moist sand container under the 4 mm diameter spherical plunger of the Universal Testing Machine (UTM) Instron 5569 in such a way that its stem axis was parallel to the horizontal plane. The UTM slowly pressed the plunger into the young coconut surface at its equator at a loading rate of 25 mm min^{-1} (ASAE Standard, 1994) until rupture of the husk. The point of application of the slow compression was at the middle of the ridge and face of the fruit. Six application points were used for each sample. Husk rupture force, deformation at rupture and the slope of the force-deformation curve were analyzed. The same process was repeated with 20 samples every four days until the 206th day after pollination.

2.4. Determination of physiological properties

The physiological properties of interest are soluble solids content, acidity, flesh wet weight F_w , flesh dry weight D_w and thickness of the flesh FT. To determine these each coconut was cut open. The fruit juice of each was sampled with a digital refractometer (PR-32, Palette Series, Atago Co. Ltd, Tokyo) to find the soluble solids content. Aliquots of 10 ml of the fruit juice were titrated against standard NaOH 0.1 N with phenolphthalein indicator until a pink colour was perceptible for 30 s. The titratable acidity of the juice is reported as percentages in terms of the malic acid equivalent.

After the young coconut fruit was emptied, the wet flesh was scooped out and weighed with an electronic balance. Ten grams of the wet flesh were dried based on the ASAE Standard (1998) and weighed. The corresponding total dry flesh weight was given by multiplying the total wet weight by the dried sample weight divided by 10.

Fig. 3(a) shows the carpel of young coconut comprising two small eyes and one big, soft eye. The carpel was cut out of the fruit sample. Fig. 3(b) shows the big eye of the overturned carpel. The flesh located 1 cm from the rim of the big eye was removed and the flesh thickness measured (Fig. 3(c)). This procedure was performed on all 20 samples. The same testing procedure was repeated with 20 samples every four days until the 206th day after pollination.

2.5. Partial least squares analysis

A total of 300 new intact, uniformly sized young coconuts at three stages of maturity (immature, mature and over-mature) were used in determining the physical, mechanical, acoustic and physiological properties using the methods described above. Random sampling was based on the expertise of competent growers to get the available young coconuts of different stages of maturity but not necessarily of equal number for each stage. The specific gravity, resonant frequency, husk rupture force, husk firmness, shell rupture

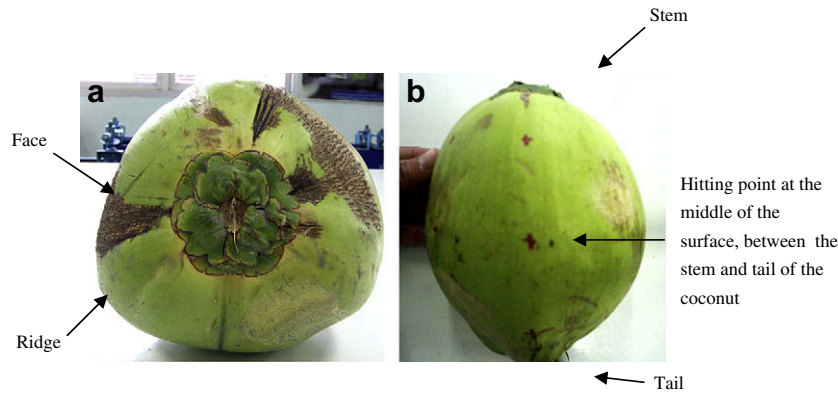


Fig. 2 – (a) Fruit orientation and (b) Hitting point.

force, shell firmness, total soluble solids, acidity, wet flesh weight, dry flesh weight, and flesh thickness for each coconut were recorded.

The property that exhibited maximum correlation with the maturity (days after pollination) was used as maturity index or predicted property. The samples were sorted based on that property and alternately picked so as to set aside about one third to a validation set (100 samples) and the remainder to a calibration set (200 samples). Both sets thus contained samples having a range of similarly distributed maturity with a wider range in the calibration set than the validation set.

The calibration set was used to create a calibration model using the partial least squares regression (PLSR) in the Unscrambler V9.8 program (Camo, Oslo, Norway). Full cross validation using samples in the calibration set was performed for determining the optimal number of PLS factors for each calibration model. The number of factors giving the lowest standard error of cross validation (SECV) determined the optimal number of terms to be used for the calibration. The performance of the calibration model was evaluated using the coefficient of determination (R^2) and SECV. Finally, the predicting performance of the model was determined by comparing measured values and model predictions for the data in the independent validation set. The statistics for the performance assessment were R^2 , standard error of prediction (SEP) and bias.

3. Results and discussion

3.1. Physical characteristics

Fig. 4 shows the distribution of specific gravity (SG) of young coconut with regard to days after pollination. SG slowly reduced from 1.105 to 0.890 at the end of the immature period. Furthermore, SG continued to decrease linearly to 0.854 by the end of the mature period, and kept on reducing linearly but at a faster rate to an SG of 0.695 at the end of the over-mature stage. This matches the declining SG of durian (cv “Chanee”) which was 0.913, 0.908 and 0.863 at 20, 10 and 0 days before full maturity, respectively (Jarimopas *et al.*, 1986).

3.2. Acoustic properties

Fig. 4 shows the distribution of the strongest resonant frequency f_n of young coconut with time. At the immature stage, f_n is increased from 0.591 kHz to 0.883 kHz, continued to increase linearly to 1.106 kHz at the end of the mature stage, and then rose linearly at a higher rate to 1.391 kHz at the end of the over-mature stage. These results are in agreement with those reported by Gatchalian *et al.* (1994) on young Philippine coconut fruit, where the coconut fruit which was developing from immature to mature was observed to produce sounds which progressed from “solid” to “hollow”. They found an

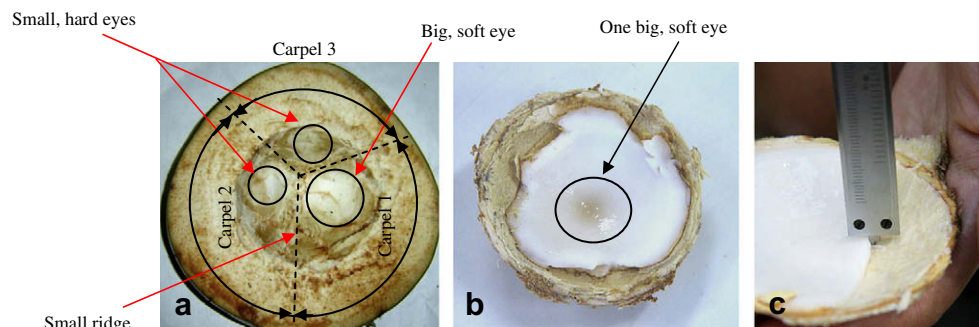


Fig. 3 – The eyes of young coconut. (a) Uncut shell. (b) The cut and overturned shell. (c) Measurement of flesh thickness.

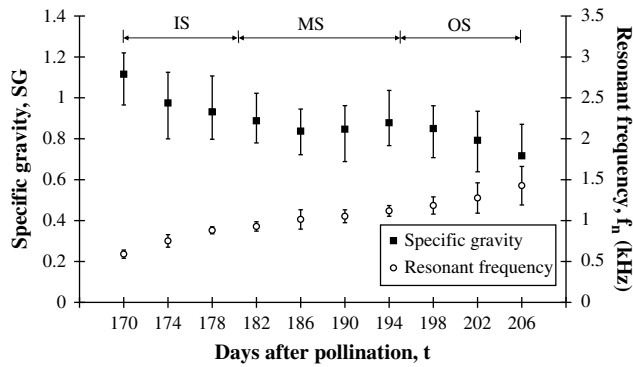


Fig. 4 – Specific gravity and resonant frequency with respect to days after pollination (IS, immature stage; MS, mature stage; OS, over-mature stage).

increase in resonant frequency, which corresponds with the behaviour of Thai young coconut. A possible explanation for this is that the immature fruit is full of juice, which makes the fruit sound “solid”. In other words, the resonance or natural frequency of young coconut is at the low end of the spectrum. However, when the fruit is mature, gaps develop in the fruit, the sound becomes “hollow”, and the resonance frequency increases.

3.3. Mechanical properties

The mechanical properties investigated were the rupture force of husk (SF_R) and that of shell (SF_R), and the slope of force-deformation curve of husk (HSL) and that of shell (SSL).

Fig. 5 shows that HF_R quickly decreases from 75.7 N to 53.3 N during the immature stage. After that, HF_R reduces slowly and linearly to 46.5 N at the end of the mature stage, then continues to decrease to 36.6 N at the end of the over-mature stage. While the young coconut fruit is developing towards over-maturity, husk consisting of spongy tissue and embedded fibres (Jarimopas and Ruttanadat, 2007) gradually loses moisture (Jarimopas and Kusol, 2007) leaving empty spaces in the tissue. Accordingly, when more mature and drier husk is compressed it deforms more easily and needs less force to rupture.

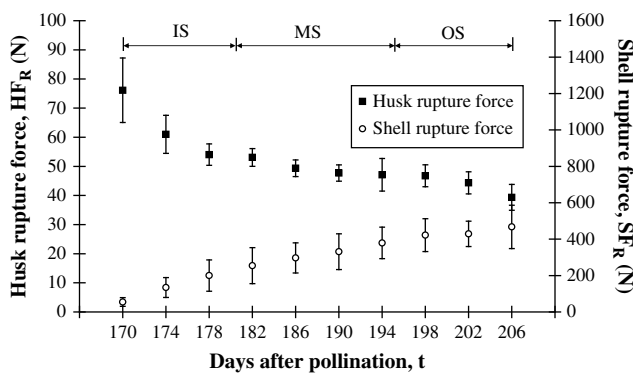


Fig. 5 – Husk rupture force and shell rupture force with respect to days after pollination.

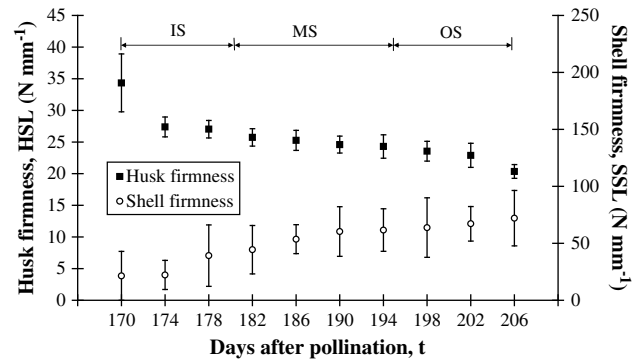


Fig. 6 – Husk firmness and shell firmness with respect to days after pollination.

Fig. 5 also shows the distribution of changes in SF_R . SF_R uniformly and linearly increases in the days after pollination. SF_R increases from 58.6 N to 222.3 N for the first stage, continues to increase to 381.8 N at the end of the second stage, and reaches 443.2 N at the final stage of over-maturity. This distribution agrees with that found by Jarimopas and Kusol (2007). The slope of the SF_R -t curve reduces sequentially when maturity progresses from immaturity to over-maturity. This appears to be because young coconut produces a shield which protects the endosperm and embryo. As a coconut tree is tall, the fruit is subjected to heavy drops and adverse environmental conditions before germinating. Therefore, the fruit shell acquires strength through accumulation of internal components during the maturing process.

Fig. 6 shows that HSL quickly drops from 34.2 N mm^{-1} to 26.3 N mm^{-1} during the first stage, decreases slowly and linearly to 23.8 N mm^{-1} at the end of the second stage, and then decreases faster to 19.6 N mm^{-1} at the end of the third stage. Husk firmness is an alternative description of husk strength when change of force and deformation are considered together. Husk firmness shows a reduction in strength of the husk with maturity, which is similar to the trend seen for HF_R . Husk was deformed and exhibited less firmness when it was pressed (Jarimopas and Ruttanadat, 2007). While HF_R requires less measurement and calculation, the HSL is favoured as a non-destructive technique.

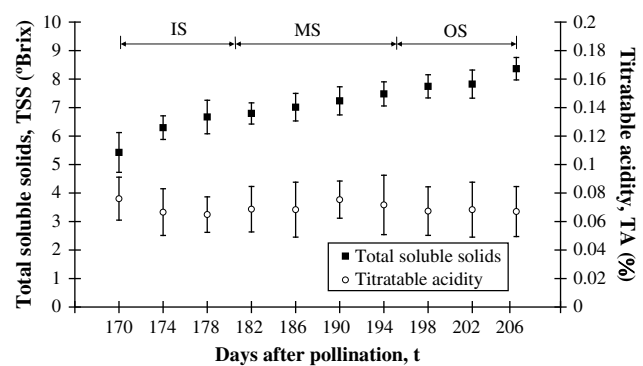


Fig. 7 – Total soluble solids and titratable acidity of young coconut juice with respect to days after pollination.

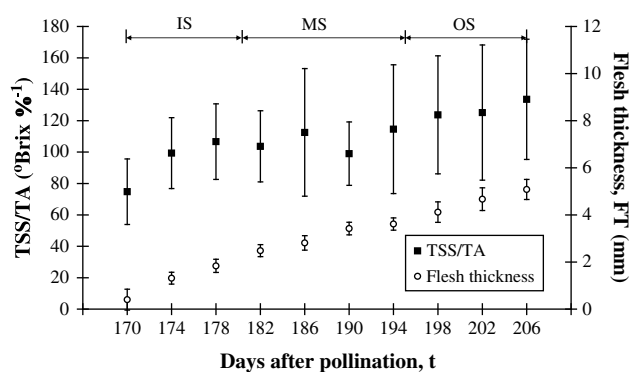


Fig. 8 – TSS/TA and flesh thickness of young coconut fruit with respect to days after pollination.

Fig. 6 displays the SSL graph which is somewhat sigmoid in appearance. SSL seems to increase parabolically from 21.9 N mm^{-1} to 40.8 N mm^{-1} during the first stage, continues to increase to 60.1 N mm^{-1} at the end of the second stage, and linearly increases to 68.7 N mm^{-1} at the end of the third stage. The shell is similar to wood whose mechanical behaviour is characterized by increasing strength with increasing age (Chou, 1998). Taiwania wood, for example, increases in density from 350 to 400 kg m^{-3} , rupture stress from 0.233 to 0.252 N m^{-2} and modulus of elasticity from 54.94 to 58.37 N m^{-2} with an increase in age from 11 to 15 years. Determination of density (Mohsenin, 1996) of young coconut shell at the immature, mature, over-mature stage (five fruit for each maturity and three replications for each fruit) revealed that the shell density increased with maturity age (immature = 1087 kg m^{-3} , mature = 1138 kg m^{-3} ; over-mature = 1174 kg m^{-3}). As previously shown, the shell rupture force and the shell slope (which is a kind of firmness measurement apart from modulus of elasticity) also increased with maturity age. This agrees with the mechanical response of wood. The slope of the SSL curve reduces during the progression of the fruit from immaturity to over-maturity.

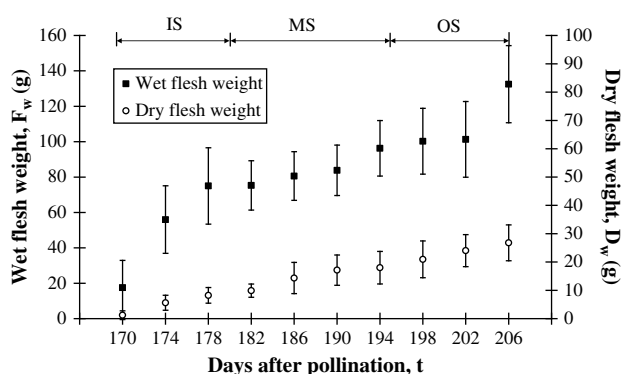


Fig. 9 – Wet flesh weight and dry flesh weight of young coconut with respect to days after pollination.

Table 1 – Correlations between properties of young coconut

	FT	SG	f_n	HF _R	SF _R	HSL	SSL	TSS	TA	TSS/TA	F _w	D _w
FT	1.000											
SG	0.614**	1.000										
f_n	0.970**	0.614**	1.000									
HF _R	-0.994**	-0.583**	-0.967**	1.000								
SF _R	0.984**	0.653**	0.957**	-0.982**	1.000							
HSL	-0.956**	-0.574**	-0.944**	0.953**	-0.920**	1.000						
SSL	0.989**	0.613**	0.974**	-0.993**	0.991**	-0.935**	1.000					
TSS	0.380**	-0.150**	0.393**	-0.406**	0.291**	-0.483**	0.355**	1.000				
TA	0.075	0.061	0.064	-0.085	0.074	-0.063	0.072	0.071	1.000			
TSS/TA	0.133*	-0.126*	0.135*	-0.134*	0.092	-0.178**	0.120*	0.385**	-0.830**	1.000		
F _w	0.983**	0.657**	0.958**	-0.968**	0.973**	-0.959**	0.968**	0.337**	0.047	0.133*	1.000	
D _w	0.883**	0.722*	0.884**	-0.871**	0.938**	-0.797**	0.910**	0.076	0.027	0.024	0.897**	1.000

*Correlation is significant at the 0.05 level (two-tailed); **Correlation is significant at the 0.01 level (two-tailed).

Table 2 – Statistics of calibration and validation of FT and the lower and upper limits of a 95% confidence interval for the ratio of the true standard deviations

Properties	R_{cal}^2	RMSECV	No. of PLS factors	R_{pre}^2	RMSEP	SEP	BIAS	$SEP_1 / (SEP_2 \times L)^b$	$SEP_1 \times L / SEP_2$
SSL, HF _r , f _n , SF _r , F _w , HSL, D _w , SG, TSS, TSS/TA, TA	0.986	0.168	1	0.980	0.203	0.204	0.009		
HF _r , SSL, SF _r , F _w , HSL	0.991	0.133	1	0.991	0.133	0.133	0.004		
HF _r , SSL, SF _r , F _w	0.991	0.135	1	0.990	0.141	0.142	0.001	0.886	1.113
HF _r , SSL, SF _r	0.986	0.171	1	0.985	0.172	0.173	-0.001	0.697	0.952
HF _r , SSL	0.994	0.155	1	0.986	0.167	0.168	0.004	0.709	0.987
HF _r ^a	0.988	0.155		0.988	0.157	0.158	0.001	0.728	0.998
SSL ^a	0.977	0.218		0.980	0.200	0.201	-0.002	0.594	0.824
SF _r ^a	0.968	0.257		0.967	0.257	0.259	-0.001	0.460	0.645
F _w ^a	0.966	0.264		0.967	0.260	0.261	0.006	0.456	0.637
HF _r , HSL, f _n , SG	0.978	0.212	2	0.980	0.199	0.200	0.005	0.603	0.820
f _n , SG	0.889	0.466	1	0.856	0.541	0.544	0.000	0.214	0.314
f _n ^a	0.937	0.359		0.927	0.385	0.386	0.034	0.300	0.440
SG ^a	0.351	1.149		0.406	1.099	1.104	-0.016	0.105	0.155

R_{cal}^2 , coefficient of determination of calibration; R_{pre}^2 , coefficient of determination of prediction; RMSECV, Root Mean Square of Standard Error of Cross Validation; RMSEP, Root Mean Square of Error of Prediction; SEP, Standard of Error of Prediction.

a Multiple linear regression model.

b $k = 1 + 2(1 - r^2)t_{(N_p - 2), 0.025}^2 / N_p - 2$ where $t_{(N_p - 2), 0.025}^2$ is the upper 2.5% percentile of a t-distribution with $N_p - 2$ degrees of freedom

$L = \sqrt{[k + \sqrt{(k^2 - 1)}]}$ (Snedecor and Cochran, 1989).

3.4. Physiological properties

The physiological properties include total soluble solids (TSS) and titratable acidity (TA) of young coconut juice, flesh thickness (FT), wet weight (F_w) and dry weight (D_w) of the fruit flesh. Fig. 7 shows TSS increases from 5.39 to 6.76 °Brix in the immature stage, continues to increase linearly to 7.45 °Brix at the end of the mature stage, and linearly rises at a slightly higher rate to 8.24 °Brix at the end of the over-mature stage.

Fig. 7 shows that, while fluctuating, TA tends to reduce from 0.076% to 0.067%. Small changes in TA probably cause TSS to sweeten the juice as suggested by its Thai name “Nham Whan” (“sweet juice”). Fig. 8 shows that TSS/TA tended to increase with t from 74.8 to 133.6 °Brix %⁻¹, with fluctuations throughout the three stages because of the fluctuating effect of TA. Fig. 8 shows that flesh thickness FT uniformly increases from 0.41 mm to 2.12 mm during the immature stage. It then increases to 3.71 mm by the end of the mature stage, and continues to increase linearly to 4.88 mm at the end of the over-mature stage. The linear change in FT corresponds well with the significant relationship between flesh thickness and maturity of Philippine coconut reported previously (Gatchalian et al., 1994).

Fig. 9 shows the distribution of F_w with respect to t . The F_w - t curve displays a sigmoid shape, starting from 20 g and rising quickly to 74.4 g in the first stage. F_w increases rather linearly to 96.9 g by the end of the second stage and rather parabolically to 131.5 g at the end of the third stage. Fig. 9 also presents the dry flesh weight D_w with respect to t . D_w increases as a convex curve with respect to t from 1.33 to 9 g in the first stage, continues to increase in a convex fashion to 18.7 g at the end of the second stage, and linearly rises to 26.7 g at the end of the third stage. The D_w - t relationship with the linear increase is similar to that exhibited by durian (Sangwanakul and Siripanich, 2000).

3.5. Partial least squares regression

The 12 properties presented so far to describe fruit maturity could be combined by means of multivariate data analyses to create powerful predictive models for the maturity in a quantitative sense.

First of all, a maturity index was sought to replace days after pollination. This was because days after pollination varied at 10 levels only and thus samples harvested on the same day had the same value of maturity. The property which varied among individual samples and was best related to days after pollination would be preferred as maturity index for quantitative analysis.

The best linear correlation was found between flesh thickness FT and days after pollination t ($FT = 0.1227t - 20.095$, $R^2 = 0.986$). Also, FT was found to be significantly affected by young coconut maturity (Gatchalian et al., 1994). Additionally, FT is the coconut characteristic in which consumers are interested and perceived as a quality indicator. Therefore FT was used as the maturity index for this study. Based on FT, the set of 300 new young coconut samples were sorted into the calibration and validation sets as previously stated.

Table 1 shows correlations among young coconut properties. HF_r had the best correlation with FT ($R = 0.994$). Other properties such as SSL, SF_r, F_w and HSL also showed high correlations with FT.

Initially, the model for predicting FT was built based on multiple linear regressions of the other properties. Collinearity between properties in multiple linear regression models for FT was assessed by calculating the tolerance for each of them in the full models. All properties except SG and TSS exhibited tolerance values <0.20 (Kleinbaum, 1998), which indicated excessive collinearity. As a result, the multiple linear regression model was deemed unreliable for the prediction. To overcome the multicollinearity, partial least

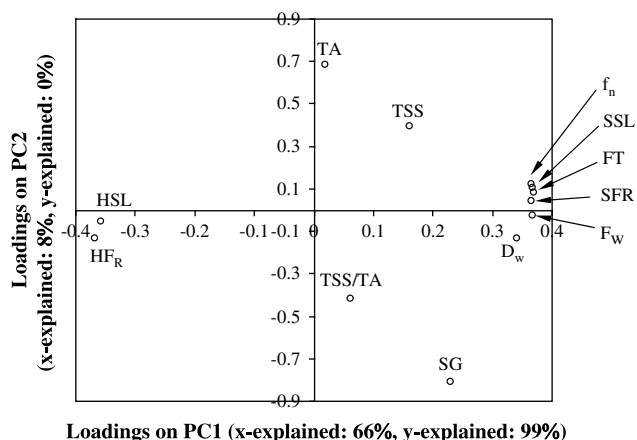


Fig. 10 – Loadings plot (PC1 × PC2) showing relationship between predicting properties and FT.

squares regression was performed. The calibration set was used to develop a PLS calibration model for FT prediction using the remaining 11 properties. The values of the properties were weighted by dividing by their corresponding standard deviations prior to analysis.

The first PLS model to predict FT was created based on the remaining 11 properties which gave $R^2_{pred} = 0.980$, (Table 2) $SEP = 0.204$ and $Bias = 0.009$. The performance of prediction could be improved and simplified by removing the properties contributing least to the model. The loadings (Fig. 10) and weighted regression coefficients (Fig. 11) of each property on the first factor were used as tools to select properties to omit. They were analyzed to determine which properties are important to maturity prediction. The SSL and the HF_R were the most responsive properties for predicting the FT, and TA was the least. HF_R and HSL were the only properties that showed negative correlations with the FT. The other procedure for removing properties was to rank the significance of each property based on the correlation coefficients of each property to FT from Table 1.

The best model was based on HF_r , SSL, SF_r , F_w and HSL (Table 2), in ascending order according to the correlation coefficients, having the highest accuracy in predicting the FT

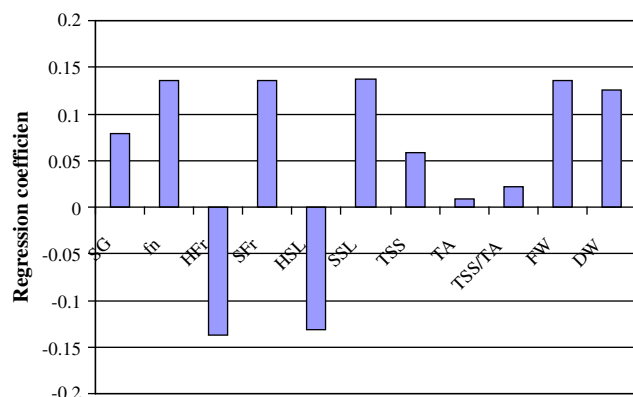


Fig. 11 – Regression coefficients for the PLS model using 11 predicting properties.

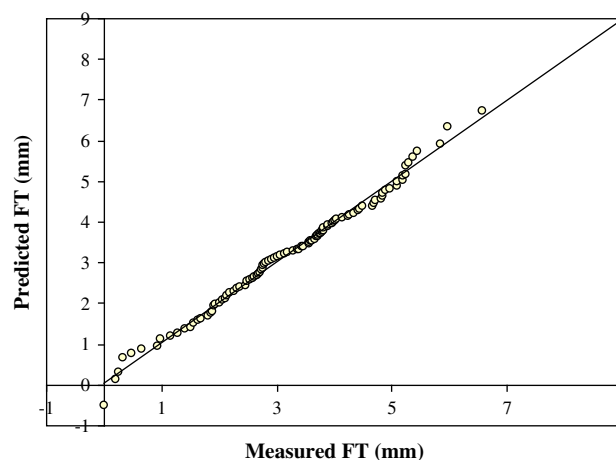


Fig. 12 – Measured versus predicted values of flesh thickness of the validation samples for the best PLS model using HF_r , SSL, SF_r , F_w and HSL with $R^2 = 0.991$ and $RMSEP = 0.133$.

with $R^2_{pred} = 0.991$, $SEP = 0.133$ and $Bias = 0.004$ (Table 2). The corresponding scatter plot between the measured and the predicted values of FT for the data in the independent validation set is given in Fig. 12. The optimal number of factors for the model was one, which explained 99.0% of the variation.

The next PLS models were generated by removing, one at a time, the properties having either low values for regression coefficients or low values of correlation coefficients. With reference to the best PLS model based on five properties, the differences between the SEP of the new models and the original SEP were tested using the methodology described by Snedecor and Cochran (1989). In this methodology, the correlation coefficient (R) between the two sets of prediction errors was determined, and k value and L value as defined under Table 2 were calculated. Calculating $SEP_1/(SEP_2 \times L)$ and $(SEP_1 \times L)/SEP_2$ gave the lower and upper limits of a 95% confidence interval for the ratio of the true standard deviations. Unless the interval includes one, the SEPs are significantly different. Removal of predicting properties resulted in better models than the model of all properties as exemplified in Table 2.

The simpler PLS model is the one combining HF_r , SSL, SF_r and F_w which was as accurate in prediction ($R^2_{pred} = 0.990$, $SEP = 0.142$ and $Bias = 0.001$) as the best PLS model. The lower and upper limits of the intervals from both models included one. This could be justified by high correlation coefficients of each property (Table 1). The best simple linear regression model of HF_r also showed high accuracy in prediction ($R^2_{pred} = 0.988$, $SEP = 0.158$ and $Bias = 0.001$) but with significantly lower SEP than that of the best model. The results suggested that selection of the properties based on the correlation coefficients with the predicted property was better than that based on the regression coefficients of all property PLS model.

Since the best model included destructive measurements it was of no practical use in sorting. Therefore models based on non-destructive (f_n and SG) and partially non-destructive (HF_r

and HSL) properties were also analyzed. The PLS model of non-destructive and partially non-destructive properties (HF_r , HSL, f_n and SG) offered the accuracy with $R^2_{pred} = 0.980$, $SEP = 0.200$ and $Bias = 0.005$. Among non-destructive models, the simple linear regression of f_n presented the best performance with $R^2_{pred} = 0.927$, $SEP = 0.386$ and $Bias = 0.034$. Although the prediction ability of the non-destructive model was acceptable, it could possibly be improved by using more non-destructive measurements such as electronic nose or colour spectroscopy.

4. Conclusion

The distribution of specific gravity, rupture force and slope of the force-deformation curve of husk and shell, total soluble solids, titratable acidity, flesh thickness, wet and dry weight of the flesh, and resonant frequency of young coconut with regard to days after pollination was determined. Flesh thickness was significantly affected by maturity at $p < 0.05$. The maturity index of young coconut fruit based on flesh thickness was best predicted by the PLS regression model using five predicting parameters (HF_r , SSL, SF_r , F_w and HSL). The FT was well characterized by the SSL in a positive manner and HF_r in a negative manner. The simpler model was found to be based on HF_r , SSL, SF_r and F_w with comparable predicting ability. The best non-destructive model was a simple linear regression model of resonant frequency.

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