Antioxidant properties of selected Thai red-fleshed papaya genotypes during the external color break stage

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Abstract Papaya fruit during the external color break stage is a valuable raw material to make food, but its benefits for human health are still limited. Ten selected Thai red-fleshed papaya genotypes during the external color break stage were investigated for morphological, physicochemical, and antioxidant property traits. Most fruit traits evaluated in this study varied significantly among genotypes. The smallest fruit genotype, SNP-KD, had the highest antioxidant activity (4.41 ± 0.62 μmol ascorbic acid equivalents/g fresh weight [FW]), ascorbic acid (838.1 ± 90.2 mg/L), and total phenolic (547.0 ± 52.8 mg gallic acid equivalents/kg FW), and the reddest flesh genotype, KM4-13, contained the highest lycopene (87.5 ± 14.7 mg/kg FW). The correlations between ascorbic acid and total soluble solids and between lycopene and β-carotene were relatively high at \( r = 0.72 \) and 0.69, respectively, which indicates a high correlation was possible for both selections. Antioxidant activity was only strongly positively correlated with total phenolics (\( r = 0.78 \)), which indicates that the total phenolics was an important contributor to antioxidant activity in papaya flesh, and it was feasible to use total phenolics to indirectly estimate antioxidant activity.

Keywords Antioxidant activity · Ascorbic acid · Carotenoids · Phenolics · Physicochemical quality

Introduction

Papaya (Carica papaya L.) is a popular and economically important tropical fruit. The total papaya production from 65 countries in 2014 was over 12.67 million tons [1]. In addition to fresh consumption as a ripened fruit, papaya flesh, particularly during the external color break stage, can be processed into various types of products, such as canned papaya in syrup, dried papaya, cereal flakes, and minimally processed papaya [2]. In addition, unripe fruit in the green fruit stage has been used as a vegetable to make traditional meals, such as papaya salad and sour soup in several countries, including Thailand. Thailand is tenth in the world for papaya production. The annual production of papaya in 2014 was reported to be 157,571 metric tons from a production area of 4320 ha [1]. One-third of this production was for fresh consumption, one-third (during the external color break stage) was used as a valuable raw material in the processing industry, and the rest (at the green fruit stage) was used as a vegetable to make various foods. For processing markets, papaya fruits are typically harvested during the external color break stage (approximately 2-3 yellow stripes at the blossom end).

Besides its economic value, papaya fruit provides valuable amounts of antioxidant compounds, particularly the red-fleshed genotypes. Schweiggert et al. [3] reported that red papaya of Costa Rican genotypes during the ripe

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Ten elongated fruits per genotype were randomly harvested from the hermaphrodite plants during the external color break stage. All the fruit samples were immediately transported to the crop improvement and biotechnology laboratory, Department of Horticulture, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University, Kamphaeng Saen campus, Nakhon Pathom, Thailand, for analysis. The fruit samples were allowed to stand at room temperature (26 ± 1 °C) for about 2 h before investigation. Edible papaya flesh samples at the fruit midpoint were used to determine all physicochemical qualities and antioxidant property traits. For ascorbic acid analysis, all the samples were immediately measured after the physicochemical quality traits were determined. Finally, for the carotenoid, phenolic, and antioxidant activity analyses, about two hundred grams of papaya flesh sample with peel was stored in a freezer at −20 °C until extraction.

**Determination of morphological quality traits**

The fruit weight (kg) was gravimetrically determined using a digital balance (SK-5001, A&D Co., Ltd., Toshima-Ku, Tokyo, Japan). Then, the papaya fruit was cut in half transversally at the equatorial region. The fruit length (cm) was measured from the stem end to the blossom end. The fruit diameter (cm) was then measured at the maximum point of the fruit’s diameter. The flesh color was measured using a color reader (Minolta CR-10, Konica Minolta Sensing Inc., Osaka, Japan), resulting in L, a, and b values. The L value was a luminosity that ranged from 0 = black to 100 = white, the a value ranged from −100 = green to 100 = red, and the b value ranged from −100 = blue to 100 = yellow. The hue angle (h°) was calculated from the a and b values according to the method established by McGuire [12]. The h° value is an angle on a 360° color wheel, which moves counterclockwise from 0° to 90°, 180°, and 270°, representing red–purple, yellow, bluish-green, and blue, respectively. The firmness of the flesh was measured as a penetration force using a fruit hardness tester (Nippon Optical Works Co., Ltd., Tokyo, Japan) with a 0.2-cm-diameter cylinder probe. Next, the data were converted to Newton (N) values by multiplying them by 9.807. The total soluble solids (%Brix) were measured in juice extract from flesh samples using a digital pocket refractometer (PAL-1, Atago Co., Ltd., Minato-Ku, Tokyo, Japan).

**Materials and methods**

**Plant materials and sample preparations**

Ten selected red-fleshed papaya genotypes from the breeding program of the Department of Horticulture, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University, Kamphaeng Saen campus, Nakhon Pathom, Thailand, were used. The genotypes were KD4-1, KD5-8, KD5-10, KM4-13, KM4-20, GPK, PPK, SNP-KD, RNR, and MK-KD. All genotypes are S2 generation breeding lines selected from open pollination populations of commercial cultivars collected from farmers in Thailand. The plants were cultivated in an experimental field at 2.5 × 2.5 m spacing. Based on the Kamphaeng Saen soil series, the soil morphology was non-calcic brown soil type, the pH was 7.0–8.0, and the soil texture was sandy loam [11].
Determination of ascorbic acid content

Two mL of juice extract from the flesh sample was mixed with 5 mL cold solution of 3% oxalic acid (w/v) plus 8% glacial acetic acid (v/v). The mixture was then measured for ascorbic acid using the 2,6-dichlorophenolindophenol titration method as described by AOAC [13]. L-ascorbic acid was used to prepare a fresh standard solution (1 mg/mL). Finally, the ascorbic acid content was calculated by comparing it with the standard and was expressed in mg/L.

Determination of carotenoids content

The lycopene and \( \beta \)-carotene contents of papaya extracts were determined spectrophotometrically according to the method developed by Anthon and Barrett [14]. The frozen papaya samples were thawed at room temperature, peeled, and then chopped into small pieces. Two hundred mg of papaya pulp samples was homogenized in 5 mL of solvent hexane:ethanol:acetone with a proportion of 2:1:1 (v/v/v) until consistency using an Ultra-Turrax homogenizer (Ultra-Turrax T25, IKA-Werke GmbH & Co. KG, Staufen, Germany). Fifteen mL of the solvent was then added. The mixture was allowed to react for 5 min at room temperature. Later, 0.3 mL of 5% NaNO\(_2\) and 0.3 mL of 0.25 N Folin–Ciocalteu reagents in a plastic tube and mixed well using a Vortex (Vortex-Genie 2, Scientific Industries Inc., Bohemia, New York, USA). The mixture was allowed to react for another 6 min at room temperature. Then, 2 mL of 1 M NaOH was added and mixed well using a Vortex. The absorbance was measured at 725 nm using the spectrophotometer. Absolute methanol was used as a blank. Gallic acid was used as the standard curve, and the antioxidant activity was determined using the ferric reducing/antioxidant power (FRAP) method [17] with some modifications. Twenty \( \mu \)L of papaya extract was mixed with 130 \( \mu \)L of absolute methanol. Then, 2850 \( \mu \)L of 0.25 N Folin–Ciocalteu reagents in a plastic tube and mixed well using a Vortex. The mixture was allowed to react for another 6 min at room temperature. Then, 2 mL of 1 M NaOH was added and mixed well using the Vortex. The absorbance was measured at 593 nm using the spectrophotometer. Absolute methanol was used as a blank. Catechin was used as the standard curve, and the total flavonoids content was expressed in mg catechin equivalents (CE)/kg FW.

Determination of total flavonoids content

The total flavonoids content was determined using the Folin–Ciocalteu method [15]. Then, 150 \( \mu \)L of the sample extract was combined with 2400 \( \mu \)L of dH\(_2\)O and 150 \( \mu \)L of 0.25 N Folin–Ciocalteu reagents in a plastic tube and mixed well using a Vortex. The mixture was incubated in dark conditions at room temperature for 2 h. The tube was allowed to Vortex every 30 min, and the absorbance was measured at 725 nm using the spectrophotometer. Absolute methanol was used as a blank. Gallic acid was used as the standard curve, and the total flavonoids content was expressed in mg gallic acid equivalents (GAE)/kg FW.

Determination of antioxidant activity

Antioxidant activity was determined using the ferric reducing/antioxidant power (FRAP) method [17] with some modifications. Twenty \( \mu \)L of papaya extract was mixed with 130 \( \mu \)L of absolute methanol. Then, 2850 \( \mu \)L of the warmed fresh FRAP working solution was added and mixed well using the Vortex. The mixture was then incubated in dark conditions at 37 °C for 1 h in an incubator (Polar 1000C, Contherm Scientific Ltd., Hutt City, New Zealand). The absorbance was measured at 593 nm using the spectrophotometer. L-ascorbic acid was used as the standard curve, and the antioxidant activity was expressed in \( \mu \)mol ascorbic acid equivalents (AAE)/g FW.
Statistical analysis

The data were presented as mean ± standard deviation and were analyzed in a completely randomized design using ANOVA. Duncan’s multiple range test was used to separate the means when the F-values were significant (p < 0.05). Pearson’s correlation coefficient (r) was used to determine the linear relationship between the data.

Results and discussion

Morphological fruit traits

Fruits of all genotypes showed cylindrical shapes (Fig. 1). Most of the morphological fruit traits, except fruit length, varied significantly among the genotypes with MK-KD showing the highest and SNP-KD showing the lowest values for all the significant traits (Table 1). The fruit weight ranged from 0.7 to 2.1 kg, the fruit length ranged from 27.7 to 33.8 cm, the fruit diameter ranged from 6.8 to 12.1 cm, the flesh thickness ranged from 2.0 cm to 3.2 cm, and the cavity diameter ranged from 2.8 to 5.5 cm.

Because food processors in Thailand only accept large papaya fruits (at least 0.8 kg), the cylindrical or oblong fruit shapes and thick flesh (at least 2.0 cm) [18], SNP-KD genotype may not be of interest for food processors. However, it may be of great interest for fresh consumption, especially in Thailand where consumers prefer fruits that are around 0.5 kg because their families are smaller than in the past.

Physicochemical fruit traits

Aside from morphological traits, physicochemical properties, especially flesh color, are also very important for the acceptance of papaya fruits by food processors in Thailand. Both red- and yellow-fleshed papayas, in particular dark red or yellow flesh, with a proportion of 2:1 are required. However, for fresh consumption, flesh color is not as important for the acceptance of papaya fruits by Thai consumers, especially for younger generations. The L values ranged from 42.6 to 50.6, the a values ranged from 33.6 to 42.3, the b values ranged from 28.6 to 34.0, and the h° values ranged from 34.0 to 44.6 (Table 2). In our report, the a values showed a higher range when compared to...
previous reports. During the ripe stage, the \(a\) value was 16.2 in the flesh of the Eksotika papaya [9], 12–17 for the Sunset papaya [19], 7.7 for the Golden papaya [20], and 20 for the Maradol papaya [21], which indicates that our selected papaya genotypes had redder flesh than other genotypes, as previously reported.

Based on the \(a\) value, which represents reddish color, the papaya genotypes were obviously divided into two groups. Genotypes PKK, SNP-KD, and MK-KD were in the same group with lower \(a\) value, compared to the other genotypes, which were also grouped together. In accordance with the \(h^o\) value, PKK, SNP-KD, and MK-KD were also grouped together with higher \(h^o\) values than the other genotypes. PKK, SNP-KD, and MK-KD showed relatively high \(b\) values, which represent the yellowish color, compared to the other genotypes (Table 2). These values indicate that the PKK, SNP-KD, and MK-KD genotypes had less reddish flesh than the other genotypes, which was in agreement with the visual color appearance (Fig. 1). Therefore, the genotypes PKK, SNP-KD, and MK-KD should be not of great interest for food processors.

The firmness of the flesh ranged from 9.8 N in the PPK genotype to 13.3 N in the KD5-8 genotype, and the total soluble solids ranged from 9.8% Brix in the GPK genotype to 13.5% Brix in the SNP-KD genotype (Table 2). A similar range of 8.8–13.5% Brix was reported for ripe Costa Rican papayas [3], and a range of 9.0–13.0% Brix was reported for the ripe Bangladeshi papayas [22]. Although the firmness and total soluble solids of papaya flesh are not important considerations for processing markets in Thailand, these two parameters are important in determining fruit palatability and are considered to be the principal

### Table 1 Morphological fruit traits of the 10 selected red-fleshed papaya genotypes

| Genotype | Fruit weight (kg) | Fruit length (cm) | Fruit diameter (cm) | Flesh thickness (cm) | Cavity diameter (cm) |
|----------|------------------|------------------|---------------------|---------------------|---------------------|
| KD4-1    | 1.2 ± 0.3c       | 29.8 ± 3.0       | 8.8 ± 1.4cd         | 2.4 ± 0.2c          | 4.4 ± 0.9cde        |
| KD5-8    | 1.6 ± 0.3b       | 32.0 ± 3.7       | 10.6 ± 0.7b         | 2.7 ± 0.2b          | 5.1 ± 0.5abc        |
| KM4-20   | 1.0 ± 0.3cd      | 28.9 ± 9.7       | 8.4 ± 0.8d          | 2.2 ± 0.1cd         | 3.9 ± 0.5de         |
| SNP-KD   | 0.7 ± 0.2d       | 27.7 ± 3.3       | 6.8 ± 0.8e          | 2.0 ± 0.2d          | 3.9 ± 0.7e          |
| MK-KD    | 2.1 ± 0.6a       | 30.2 ± 5.5       | 12.1 ± 1.4a         | 3.2 ± 0.2a          | 5.5 ± 1.8a          |
| P value  | <0.01            | 0.11             | <0.01               | <0.01               | <0.01               |

Data are expressed as the mean with standard deviation (\(n = 10\)).

Different letters within each column indicated significant differences (\(p < 0.05\)) by DMRT.

### Table 2 Physicochemical fruit traits of the 10 selected red-fleshed papaya genotypes

| Genotype | Flesh color | Firmness (N) | TSS (%Brix) |
|----------|-------------|--------------|-------------|
|           | L          | a            | b           | \(h^o\)       |             |
| KD4-1    | 46.7 ± 1.9b | 41.2 ± 5.8a  | 33.6 ± 2.6a | 39.4 ± 2.5b   | 10.8 ± 3.8  |
| KD5-10   | 42.6 ± 3.2c | 41.6 ± 4.9a  | 29.7 ± 3.1bc| 35.6 ± 3.1d   | 13.3 ± 2.6  |
| KM4-13   | 43.0 ± 2.4c | 40.1 ± 2.6a  | 29.0 ± 2.3c | 35.9 ± 2.9cd  | 12.1 ± 3.6  |
| KM4-20   | 43.3 ± 1.8c | 42.3 ± 2.3a  | 28.6 ± 1.4c | 34.0 ± 0.8d   | 11.9 ± 2.7  |
| GPK      | 49.8 ± 2.7ab| 40.4 ± 2.0a  | 32.0 ± 1.8ab | 38.4 ± 1.4bc  | 11.9 ± 1.1  |
| PPK      | 50.6 ± 3.3a | 34.9 ± 2.0b  | 33.9 ± 2.6a | 44.2 ± 1.5a   | 9.8 ± 3.6   |
| SNP-KD   | 49.8 ± 2.1a | 34.6 ± 3.4b  | 34.0 ± 1.5a | 44.6 ± 3.7a   | 11.7 ± 4.3  |
| RNR      | 46.4 ± 2.5b | 42.0 ± 4.7a  | 31.0 ± 2.6bc | 36.6 ± 3.4cd  | 12.6 ± 2.2  |
| MK-KD    | 46.6 ± 4.3b | 33.6 ± 3.7b  | 30.7 ± 2.4bc | 42.6 ± 3.4a   | 12.5 ± 1.7  |
| P-value  | <0.01       | <0.01        | <0.01      | <0.01          | 0.35        |

Data were expressed as mean with standard deviation (\(n = 10\)).

Different letters within each column indicated significant differences (\(p < 0.05\)) by DMRT.
Ascorbic acid

Ascorbic acid contents varied significantly among genotypes ranging from 569.9 in MK-KD to 838.1 mg/kg FW in SNP-KD (Table 3). The ascorbic acid contents of our selected papaya genotypes were relatively high compared to Costa Rican papaya genotypes, which ranged from 249–696 mg/kg FW [3], and Bangladeshi papayas, which ranged from 416–424 mg/kg FW [22]. However, they were comparable to Hawaiian papaya genotypes, which ranged from 627–807 mg/kg FW [24], and a Malaysian genotype that was 704 mg/kg FW [25]. Interestingly, the ascorbic acid concentration of papaya fruit increased 20–30% during ripening [7, 8, 10], which indicates that the ranges of ascorbic acid content in our selected papaya genotypes could be from 680 to 1000 mg/kg when ripe. The ascorbic acid contents of our selected red-fleshed papaya genotypes were very high compared to other fruit crops, especially temperate fruits. The ranges of ascorbic acid contents (mg/kg FW) were 25–102 in plums, 36–126 in peaches, 48–132 in nectarines [26], 138 in litchi, 190 in starfruit, 275 in pineapple, and 605 in mango [27].

Due to the variable ascorbic acid contents in our selected red-fleshed papaya genotypes (Table 3), ascorbic acid contents ranged from 570 to 839 mg/kg. Because the recommended dietary allowance of ascorbic acid is 75 and 90 mg/day for adult females and males, ages 15–50 years, respectively [28], the consumption of 150 g/day of any of our selected papaya genotypes would be sufficient to meet these requirements.

Carotenoids

The lycopene contents varied significantly among the genotypes, ranging from 37.8 in SNP-KD to 87.5 mg/kg FW in KM4-13 (Table 3). All of our selected red-fleshed papaya genotypes represented very good nutrition sources of lycopene (>20 mg/kg FW), according to the classification of Britton and Khachik [29]. In addition, the lycopene contents of our selected papaya genotypes showed much higher values than previous reports. Schweiggert et al. [3] reported 22–43 mg/kg FW in red-fleshed Costa Rican papayas, Wall [5] reported 14–37 mg/kg FW in red-fleshed Hawaiian papayas, Nurul and Asmah [25] reported only 7.8 mg/kg FW in a red-fleshed Malaysian papaya, and Charoenriri et al. [30] reported 22 mg/kg FW in a red-fleshed Thai papaya. However, this finding was comparable.
with a report by Setiawan et al. [31], which found that lycopene content in a red-fleshed Indonesian papaya genotype was 43–76 mg/kg FW.

The β-carotene contents also varied significantly among genotypes, ranging from 31.2 in PPK to 55.2 mg/kg FW in KD4-1 (Table 3). The current study offers the interesting information that papaya flesh is a good source of β-carotene. The amount of β-carotene content revealed in this research was much higher than previous reports, including a report from Thailand. Schweiggert et al. [3] reported 2.0–5.5 mg/kg FW in red-fleshed Costa Rican papaya hybrids and lines. Nurul and Asmah [25] reported 7.0 mg/kg FW in a red-fleshed Malaysian papaya, while Charoenri et al. [30] reported only 5.0 mg/kg FW of β-carotene content in red-fleshed papaya in a study on the β-carotene, lycopene, and alpha-tocopherol contents of selected Thai fruits. Moreover, Yano et al. [32] reported 19.8 mg/kg FW in Sunrise papaya, a Hawaiian papaya, grown in Okinawa, Japan.

This finding revealed the very interesting fact that red-fleshed papaya genotypes contain high amounts of both lycopene and β-carotene. This is in agreement with Schweiggert et al. [3] who found that red-fleshed papaya contained much higher lycopene and β-carotene contents than yellow-fleshed papaya, the contents of lycopene and β-carotene in red-fleshed papayas ranged from 22–43 mg/kg FW and 2–6 mg/kg FW, whereas in yellow-fleshed papayas, it only ranged from 0.09–0.12 mg/kg FW and 3–5 mg/kg FW, respectively. Chandrika et al. [33] also reported significantly higher lycopene and β-carotene contents in red-fleshed genotypes (11.5 and 7.0 μg/g dry weight) than yellow-fleshed genotypes (less than 0.08 and 1.4 μg/g dry weight). Other than lycopene and β-carotene, red-fleshed papayas contain another major carotenoid compound, which is cryptoxanthin [3, 31], meaning that papayas, especially those with red-fleshed genotypes, are very good sources of carotenoids.

**Phenolics**

The total phenolic contents varied significantly among the genotypes, ranging from 406.4 in KD5–8 to 547.0 mg GAE/kg FW in SNP-KD (Table 3). The mean values of the total phenolic contents in our selected papaya genotypes were comparable to previous reports. Addai et al. [9] from Malaysia reported 604 mg GAE/kg FW during the ripe stage in Ekotsotika cultivar. Pathamakanokporn et al. [34] from Thailand reported 540 mg GAE/kg FW in a ripe red-fleshed papaya genotype. Ozkan et al. [35] from Turkey reported 410, 510, and 650 mg GAE/kg FW during the ripe stage in the Tainung, Red Lady, and Sunrise Solo cultivars, respectively.

The total flavonoid contents ranged from 91.4 in SNP-KD to 143.6 mg CE/kg FW in PPK (Table 3). The total flavonoid contents of our selected red-fleshed genotypes were lower than those reported by Addai et al. [9] who found 381 mg quercetin equivalents/kg FW in the Eksotikika cultivar. The results obtained from the previous report may be attributed to the different ripening stages. Addai et al. [9] found that the total phenolic contents increased significantly with ripening and ranged from 393 during the external color break stage to 604 during the ripe stage. This indicated that our selected genotypes would contain more phenolic compounds when ripe.

**Antioxidant activity**

Antioxidant activity varied significantly among the genotypes, ranging from 3.1 in KD4-1 and KD5-8 to 4.4 μmol AAE/g FW in SNP-KD (Table 3). The antioxidant activity of our selected red-fleshed genotypes was lower than those reported by Iamjud et al. [36] who found 4.6–8.0 μmol AAE/g FW in ripe red-fleshed papaya breeding lines. Other than the cultivar differences, the different results obtained from Iamjud et al. [36] may be attributed to different maturity stages. This is in agreement with Maisarah et al. [10] who found that ripe papaya contained higher antioxidant activity than unripe papaya. The antioxidant activities in our selected red-fleshed papaya genotypes were medium compared to other fruit crops. Wang et al. [37] reported the antioxidant activity as of 12 fruits (apple, banana, white and pink grapes, pink grapefruit, kiwi, melon, orange, pear, plum, tomato, strawberry), determined by ORAC assay, ranging from less than 1 μmol Trolox equivalents (TE)/g FW for melon up to 15 μmol TE/g FW for strawberry.

**Correlations**

Table 4 shows the correlation coefficients (r) among all fruit traits evaluated. The five morphological traits (fruit weight, fruit length, fruit diameter, flesh thickness, and cavity diameter) were positively correlated (0.44 ≤ r ≤ 0.94) among themselves. The r-value between fruit weight and flesh thickness was relatively strong, as 0.87 indicated that it is possible to concurrently improve fruit size and flesh thickness. However, improving papaya varieties to produce larger fruit may increase the cavity size because the r-value between fruit weight and cavity diameter was fairly strong at 0.83. Moreover, fruit size and fruit weight had negative correlations with several other physicochemical and antioxidant property traits, including total soluble solids (r = –0.32), ascorbic acid content (r = –0.43), total phenolic content (r = –0.54), and antioxidant activity (r = –0.34). This indicated that developing new papaya varieties with large fruit size may
Table 4  Pearson’s correlation coefficients between fruit quality and antioxidant property traits

| Trait | FRW | FRL | FRD | FLT | CD | L  | a   | b   | h  | FLF | TSS | AA | LCP | BCT | TPH | TFL |
|-------|-----|-----|-----|-----|----|----|-----|-----|----|-----|-----|----|-----|-----|-----|-----|
| FRL   | 0.63** |     |     |     |    |    |     |     |    |     |     |    |     |     |     |     |
| FRD   | 0.94** | 0.51** |     |     |    |    |     |     |    |     |     |    |     |     |     |     |
| FLT   | 0.87** | 0.44** | 0.90** |     |    |    |     |     |    |     |     |    |     |     |     |     |
| CD    | 0.83** | 0.46** | 0.88** | 0.71** |    |    |     |     |    |     |     |    |     |     |     |     |
| L     | −0.47** | −0.37** | −0.45** | −0.37** | −0.40** |    |     |     |    |     |     |    |     |     |     |     |
| a     | −0.04 ns | 0.07 ns | −0.09 ns | −0.23* | 0.04 ns | −0.41** |    |     |    |     |     |    |     |     |     |     |
| b     | −0.42** | −0.34** | −0.44** | −0.37** | −0.38** | 0.66** | −0.04 ns |    |     |     |     |    |     |     |     |     |
| h  | −0.23* | −0.27** | −0.20* | −0.05 ns | −0.26** | 0.73** | −0.78** | 0.65** |    |     |     |    |     |     |     |     |
| FLF   | 0.12 ns | 0.01 ns | 0.16 ns | 0.15 ns | 0.12 ns | −0.06 ns | −0.03 ns | −0.11 ns | −0.04 ns |    |     |    |     |     |     |     |
| TSS   | −0.32** | −0.27** | −0.32** | −0.18 ns | −0.34** | 0.17 ns | −0.05 ns | 0.28** | 0.22* | 0.06 ns |     |    |     |     |     |     |
| AA    | −0.43** | −0.24** | −0.43** | −0.36** | −0.39** | 0.10 ns | 0.13 ns | 0.28** | 0.07 ns | −0.02 ns | 0.72** |    |     |     |     |     |
| LCP   | 0.10 ns | 0.20 ns | 0.10 ns | 0.01 ns | 0.15 ns | −0.53** | 0.59** | −0.25* | −0.61** | 0.07 ns | −0.02 ns | 0.08 ns |     |     |     |
| BCT   | 0.05 ns | 0.13 ns | 0.07 ns | 0.04 ns | 0.09 ns | −0.30** | 0.40** | 0.07 ns | −0.27** | −0.03 ns | 0.22* | 0.37** | 0.69** |    |     |
| TPH   | −0.54** | −0.29** | −0.60** | −0.53** | −0.63** | 0.36** | 0.02 ns | 0.40** | 0.22* | −0.08 ns | 0.36** | 0.44** | −0.04 ns | 0.00 ns |     |
| TFL   | 0.19 ns | 0.21** | 0.19 ns | 0.21* | 0.15 ns | −0.05 ns | −0.10 ns | −0.06 ns | 0.03 ns | −0.37** | −0.11 ns | −0.16 ns | −0.03 ns | 0.05 ns | −0.07 ns |     |
| AOA   | −0.34** | −0.27** | −0.41** | −0.33** | −0.44** | 0.32** | −0.06 ns | 0.37** | 0.26** | −0.19 ns | 0.18 ns | 0.21* | −0.15 ns | −0.18 ns | 0.78** | −0.03 ns |     |

a  FRW: fruit weight; FRL: fruit length; FRD: fruit diameter; CD: cavity diameter; FLF: flesh firmness; TSS: total soluble solids; AA: ascorbic acid; LCP: lycopene; BCT: β-carotene; TPH: total phenolics; TFL: total flavonoids; AOA: antioxidant activity

**, *, and ns indicate that values are significant at \( p = 0.01 \), \( p = 0.05 \), and non-significant, respectively.
have an adverse effect on sweetness and antioxidant content and activity. On the other hand, smaller papaya fruit genotypes may be sweeter and contain higher antioxidant compounds than those of the larger fruit genotypes. Schweiggert et al. [3] showed that smaller papaya fruit genotypes had higher total soluble solids and ascorbic acid content than those of larger fruit genotypes; however, the carotenoid contents were not affected by fruit size.

Interestingly, the four flesh color traits (L, a, b, and h°) showed correlations with lycopene, the r-value between L, a, b, and h° value with lycopene was −0.53, 0.59, −0.25, and −0.61, respectively. This is in agreement with Iamjud et al. [36] who reported the r-value between lycopene with L, a, b, and h° value was −0.52, 0.54, −0.47, and −0.67, respectively, in ripe red-fleshed papayas. This indicated that the increase in the intensity of the papaya flesh color was accompanied by an increase in the a values and a decrease in the h°, L, and b values. Therefore, it was possible to use any flesh color value as a quick and simple method to screen for lycopene in papaya, particularly in breeding programs during the early selection generations, which deals with numerous plants. However, the correlation between the b value and lycopene was relatively low (r = −0.25) and was probably not of much practical importance.

The correlation between total soluble solids and ascorbic acid was positive and high (r = 0.72). Schweiggert et al. [3] reported a similar result and found a linear correlation between total soluble solids and ascorbic acid (r = 0.92) in Costa Rican papayas. This is because plant biosynthesis of ascorbic acid via low molecular weight precursors, such as D-glucose and L-galactose, follows the Smirnoff–Wheeler pathway [38]. Lycopene was strongly and positively correlated with β-carotene (r = 0.69). A similar value of r = 0.62 was reported by Iamjud et al. [36] in Thai red-fleshed papaya breeding lines. One objective of this papaya breeding program is to develop new red-fleshed cultivars with high lycopene and β-carotene. This result indicated that selection for high lycopene and high β-carotene was highly feasible.

The antioxidant activity was strongly positively correlated with total phenolic (r = 0.78) and weakly positively correlated with ascorbic acid (r = 0.21), but was not correlated with lycopene, β-carotene, or total flavonoids. Similarly, Iamjud et al. [36] found a high positive correlation (r = 0.77) between antioxidant and total phenolics but found no correlation between antioxidant activity and lycopene in Thai red-fleshed papaya genotypes during the ripe stage. The present finding is also in agreement with Gil et al. [26] who found that phenolic compounds, total phenolics, and flavan-3-ols are the only stone fruit (peach, nectarine, and plum) constituents that are highly correlated with antioxidant activities. Meanwhile, no correlations were found with any of the other antioxidant constituents, including ascorbic acid, carotenoids, flavonols, and anthocyanins. This indicated that total phenolics are the major antioxidant constituent contributing to the antioxidant activity of several fruits, including papaya. The high correlation of antioxidant activity with total phenolics in papaya suggested that it was feasible to use total phenolics to screen for antioxidant activity.

In conclusion, the antioxidant contents, activity, and fruit quality traits of papayas varied greatly among the 10 selected red-fleshed genotypes used in this study. Our results show the potential value of selected papaya genotypes as new cultivars and their possible use in breeding programs to improve new cultivars for both processing and fresh consumption purposes. Smaller fruit genotypes were sweeter and had higher antioxidant properties than larger fruit genotypes, and redder flesh genotypes contained higher carotenoid contents than less red flesh genotypes. Our selected papaya genotypes showed much higher carotenoid contents than other reports and should be very good sources of carotenoids. Fruit size had a negative correlation with total soluble solids and antioxidant compounds, which indicates that developing new papaya varieties with large fruit size may have an adverse effect on sweetness and antioxidant property. Antioxidant activity may also be estimated indirectly using total phenolics since it showed a high correlation with antioxidant activity. Therefore, phenolics are the major contributors to antioxidant activity in papaya fruit during the external color break stage.

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