

Longitudinal characterization of the fluorescence properties of wax on avocado (*Persea americana* Mill.) skin during maturation using excitation-emission matrix

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Abstract

Avocado oil content varies significantly during maturation, complicating harvest timing due to the lack of external indicators. Current oil content measurements rely on destructive methods that are time-consuming, costly, and require toxic solvents. This study explores fluorescence properties of avocado skin wax as a non-destructive maturity indicator. Using excitation-emission matrix (EEM) analysis, two fluorescence peaks associated with phenolic compounds were identified, both decreasing in intensity as the fruit matured. A strong negative correlation ($r = -0.86$) was observed between fluorescence intensity and oil content. These findings suggest that UV-excited surface fluorescence could enable rapid, non-invasive oil content estimation, paving the way for fluorescence-based imaging systems to enhance harvest management in avocado production.

[Keywords] avocado, excitation-emission matrix, fluorescence property, oil content

1. Introduction

Avocado (*Persea americana* Mill.) has gained attention due to their unique nutritional profile, particularly for their rich oil content and associated health benefits (Stephen et al., 2022). Studies in the past decade have collectively highlighted the multifaceted importance of avocado oil, from its role in food science and technology (Neves et al., 2024) to its promising potential applications in the pharmaceutical (Ramos-Aguilar et al., 2019) and cosmetic industries (Cervantes-Paz et al., 2021; Ramos-Aguilar et al., 2019).

Oil content, especially flesh oil content, is one of the important commercial indices of avocado maturity and quality (Ncama et al., 2018). In the avocado industry, harvesting fruit at optimum maturity is of utmost importance because it provides market flexibility and ensures attainment of acceptable quality for the consumer (Magwaza et al., 2015). A long-existing challenge is the significant variability in maturity level when avocado is assessed on the tree (Wedding, 2018). Specifically, the oil content can range from 10–30 % depending on the cultivar and growth stage (Qin et al., 2016). However, the visual appearance can only be used to evaluate the external quality of avocado fruit, showing no obvious differences to indicate the internal oil content variations (Arzate-Vázquez et al., 2011; Valiente et al.,

2021). Currently, in harvesting management practices, most avocado producers rely on destructive measurements of representative samples to estimate the maturity of entire orchards (Liu et al., 2023; Lopez-Vega et al., 2021). Measuring oil content is time-consuming, requires the use of toxic solvents, and involves relatively expensive methodologies. Dry matter measurement, on the other hand, is relatively faster, cheaper, safer (as it does not require toxic solvents), and utilizes lower-tech methods, making it better suited for growers and packhouses to monitor maturity. Consequently, dry matter has become the most popular maturity benchmark for avocado producers worldwide, effectively supplanting oil content (Salameh et al., 2022). However, oil content remains a crucial maturity index. Therefore, it is essential to develop novel technologies to monitor oil content and ensure optimal harvest maturity. Researchers have explored the use of near-infrared spectroscopy (NIRS) (Blakey, 2016; Mishra et al., 2022; Olarewaju et al., 2016; Subedi et al., 2020; Wedding et al., 2019) and hyperspectral imaging (Kämper et al., 2020; Vega Díaz et al., 2021) for predicting the dry matter or oil content of avocado. However, NIRS can be affected by internal structural elements like seeds, and the cost for light source and sensor is high. For hyperspectral imaging, while precise, it is costly, and

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the processing of large-sized spectral images becomes hampered by its complexity (Huang et al., 2022). They are not well-suited for harvesting measurements.

Recently, fluorescence technologies have gained traction in agricultural applications due to their speed, accuracy, and non-destructive nature (Abamba Omwange et al., 2021; Al Riza et al., 2023; Huang et al., 2022; Saito et al., 2023). Fluorescent compounds exist in most agricultural products (Khaliduzzaman et al., 2023). The fluorescence signal originating from these compounds can provide insights into the physiological and compositional attributes of agro-products. Based on their fluorescence properties, suitable fluorescence-based devices and algorithms can be developed, such as fluorescence imaging system, offering a non-invasive and rapid approach to monitor fruit quality based on inherent or induced fluorescence signals (Dong et al., 2020; Jiang et al., 2020; Shen et al., 2022; Zhang et al., 2020).

Previous research indicated that front-face EEM measurement of cropped avocado skin proved to contain useful information on the degree of ripeness. Fluorescence peaks attributed to chlorophyll A and phenolic compounds were observed (Kokawa et al., 2020). However, the revealed information about the fluorescence characteristics of avocado skin is still limited, because the cropped size (20 mm diameter) of avocado skin for front-face EEM measurement is relatively small, and the surface condition of avocado skin is rough. Moreover, the measurement can be easily influenced by surface interferences. To our best knowledge, detailed research on the characterization of the fluorescence properties of wax on the outer skin of avocado and its correlation with oil content has not been reported so far.

The objective of this longitudinal study is to delineate the fluorescence characteristics of wax on avocado skin throughout its maturation period and to ascertain its relationship with the internal oil content. First, the wax from the avocado skin and the internal oil were both extracted and quantitatively measured immediately after being harvested from the tree. Second, instead of employing front-face EEM, right-angle EEM was utilized to measure the extracted wax from the skin, aiming to uncover the fundamental fluorescence properties and their changes during the maturation of the avocado. Furthermore, the relationship between these fluorescence characteristics and internal oil content was examined to explore its potential to develop a non-destructive, swift, and precise fluorescence imaging system for assessing avocado maturity in harvesting management.

2. Materials and methods

2.1. Avocado samples

The ‘Bacon’ cultivar of avocado was harvested from Matsuyama, Ehime Prefecture, Japan (Latitude: 33.88°N, Longitude: 132.75°E, Altitude: 40 m above sea level). The avocado samples were collected from healthy trees approximately 12 years old. The

location of the farm is only 5 km from our laboratory. Conducting experiments immediately after harvesting ensures that our results are not influenced by transportation or other factors. This maximizes the preservation of the in-situ state. A longitudinal study was instituted to observe phenological development, with a stratified random sampling method employed to ensure sample diversity. For each sampling event, a total of 6 samples were collected: 2 from the top of the tree, 2 from the middle section, and 2 from the bottom section. Care was taken to ensure that samples were not collected from the same branch. According to the agricultural records from the Agricultural Guidance Center in Matsuyama City, the local maturation period of ‘Bacon’ avocado is from September to December. Moreover, we intentionally avoided wet or fully turgid conditions that could increase the risk of postharvest rots, sensitivity to mechanical abrasion, and lenticel damage, as these factors, along with increased moisture content, could adversely affect our experiments, particularly oil content measurement. As a result, the collection events were scheduled on September 16th, October 18th, November 24th, and December 13th in 2021. An aggregate of 24 samples were used.

2.2. Extraction of wax from skin

Extraction of the wax from skin was carried out each month using the following procedure. The intact avocado was pressed down with a glass rod and immersed in 60 °C chloroform for 20 s. The chloroform solution was then transferred into a 500 mL Erlenmeyer flask using a funnel and concentrated below 50 °C using a rotary evaporator. After concentration, the round-bottom flask was dried using a vacuum pump for 5 min and then weighed as w_{wax} using an electronic balance. Finally, the round-bottom flask containing the concentrated wax was stored in a freezer for further EEM measurement. The procedure is illustrated in Fig. 1.

To compare different avocado, a scaling factor of surface area was introduced. The volume of wax was finally calculated according to Eq. (1).

$$V_{\text{wax}} = \frac{w_{\text{wax}}}{A_{\text{surface}}} \quad (1)$$

Where V_{wax} is the volume of wax (mg/cm^2), and the surface area A_{surface} was estimated using the long diameter (d_{long}) and short diameter (d_{short}) of the avocado sample. In Eq. (2), $a = d_{\text{long}}/2$, $b = d_{\text{short}}/2$, $c = d_{\text{short}}/2$, and $p = 1.6075$.

$$A_{\text{surface}} \approx 4\pi \cdot \left(\frac{a^p b^p + a^p c^p + b^p c^p}{3} \right)^{\frac{1}{p}} \quad (2)$$

2.3. Extraction of internal oil content

Right after the extraction of wax, the green part near the peel and the white part near the seed were removed (Fig. 2 (a)). The flesh of the avocado was cut out, weighed, and finely chopped. Then, approximately 10 g (recorded as w_{wet}^i) of chopped flesh

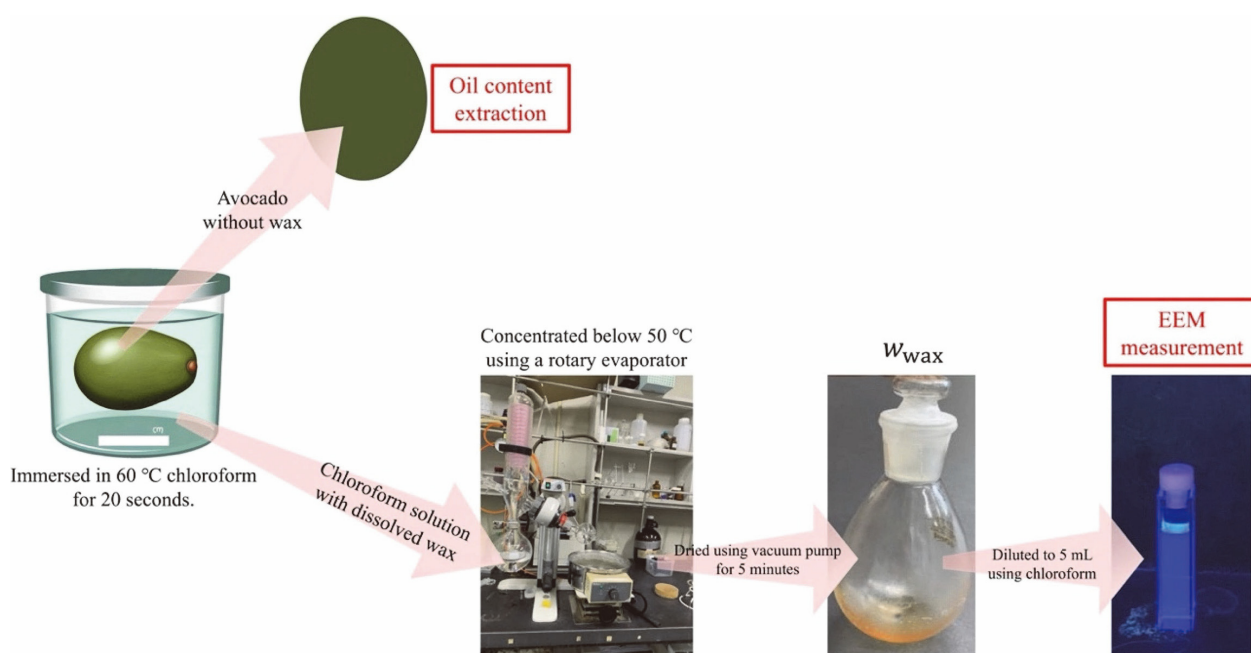


Fig. 1 Diagram of the extraction of wax from skin

was taken and was dried for 24 h in a freeze dryer. The dried avocado flesh (Fig. 2 (b)) was ground into powder using a mill, and the powder was sieved to uniform particle sizes of 150–500 μm (Fig. 2 (c)). The weight of the avocado biomass powder was recorded as w_{dry}^i .

The extraction of internal oil content was performed using the Folch method (Folch et al., 1957) as shown in Fig. 3. For each avocado, we sampled 3 times. For each sampling time, 0.5 g of the fruit powder was collected and placed in a vial bottle. A 10 mL aliquot of a 2:1 chloroform-methanol mixture was added and left for 24 h. Then, the vial bottle was placed in a 40 °C water bath and heated for 30 min. A separatory funnel was used to separate different layers, with the top layer being water-soluble, the middle being the powder layer, and the bottom being the chloroform layer where the oil content of flesh dissolved. The extraction was repeated three times using 10 mL of a 2:1 chloroform-methanol mixture to avoid oil content loss. We collected the chloroform layer and put it into a new tube. Anhydrous sodium sulfate was then added to the extracted liquid to remove water. After precipitation was complete, filtration was performed using a thick pipette with a cotton plug. The extracted liquid was then concentrated, followed by a 5-min vacuum. Finally, the oil content for 0.5 g of fruit powder was measured with an analytical balance and recorded as w_{oil}^i .

To compare different avocado, we recorded the oil content in terms of per 100 g of flesh. We used the mean value of three measurements for each sample. Thus, the oil content of each avocado fruit was calculated using Eq. (3).

$$OC = \frac{1}{3} \cdot \sum_{i=1}^3 \left(\frac{w_{\text{oil}}^i}{0.5} \right) \cdot \left(\frac{w_{\text{dry}}^i}{w_{\text{wet}}^i/100} \right) \cdot 100 \quad (3)$$

Where OC is the oil content (%), i denotes the i -th measurement for one avocado fruit.

2.4. EEM measurement

The EEM was measured using an RF-6000 spectrofluorometer (SHIMADZU Corp., Japan). The excitation and emission wavelength ranges were set to 260–500 nm and 290–750 nm, respectively. The bandwidths for excitation and emission were set to 5 nm and 1 nm, respectively. Saturation issues were avoided by setting the sensitivity of the photomultiplier tubes to low.

Right-angle measurement was conducted after the concentrated wax sample was diluted to 5 mL with chloroform. As the avocado samples vary in size and shape, we rescaled the fluorescence intensity value into the fluorescence intensity per gram of wax for comparison between samples.

For the measurement of phenolics, 0.1 g of caffeic acid (>98.0%, Tokyo Chemical Industry Co., Ltd., Japan) and 0.1 g of chlorogenic acid (>98.0%, Tokyo Chemical Industry Co., Ltd.) were each dissolved in 100 mL of 100% ethanol solution. Then, 5 mL of each solution was taken for right-angle measurement. The fluorescence intensity value was normalized to compare with the parallel factor analysis (PARAFAC) results.

All measured EEMs were calibrated and normalized to a unified scale of Raman units (Lawaetz et al., 2009). This normalization process utilized daily measurements of the water Raman peak were from pure distilled water samples. This approach served as a calibration standard, correcting for daily instrumental variations due to environmental factors such as



(a) Avocado flesh after removal, with green part near the peel and white part near the seed discarded



(b) Freeze-dried avocado flesh



(c) Uniform particles sized 150–500 μm

Fig. 2 Avocado shape

temperature and humidity. Given the extended measurement period of several months, this normalization was crucial for ensuring data comparability across different measurement days. By normalizing each day's EEM data to the corresponding day's water Raman peak area, we accounted for fluctuations in instrument sensitivity.

2.5. PARAFAC analysis

The PARAFAC method (Bro, 1997) was used to deconvolute the fluorescent components and their corresponding spectral

characteristics. PARAFAC decomposed the excitation-emission matrix spectra into individual fluorescence components and a residual matrix. These components are proportional to their concentrations in the sample and can be converted to actual concentrations when their excitation and emission properties are known.

The PARAFAC model can be expressed mathematically as Eq. (4).

$$x_{ijk} = \sum_{n=1}^F a_{in} b_{jn} c_{kn} + \epsilon_{ijk} \quad (4)$$

Where x_{ijk} is the observed value in the excitation-emission matrix, a_{in} , b_{jn} , and c_{kn} are the model parameters corresponding to the sample, excitation, and emission dimensions, respectively, F is the number of components, and ϵ_{ijk} is the residual error.

Since PARAFAC modeling of EEMs is hindered by the presence of diagonal scatter peaks caused by phenomena other than fluorescence (Coble et al., 1990), Rayleigh scattering must be removed as a preprocessing step. First-order Rayleigh scattering occurs at the same wavelength as the excitation wavelength, while second-order Rayleigh scattering occurs at twice the excitation wavelength. In our EEMs, neither first-order nor second-order Rayleigh scattering intersected with fluorescence peaks. Therefore, the scatter-affected regions were defined as $E_x - w \leq E_m \leq E_x + w$ and $2E_x - w \leq E_m \leq 2E_x + w$ for first-order and second-order Rayleigh scattering, respectively. w was the scatter window set to 10 nm. These scatter-affected regions were subsequently set to missing values. Baseline correction and normalization were then applied. Finally, the non-negative PARAFAC analysis was performed.

The accurate interpretation of PARAFAC depends on fitting the correct number of components. After confirming the resolution of under-specification and over-specification issues, the number of components was set to three. This approach enabled the identification of three distinct components, each representative of underlying fluorescent substances within the skin tissue.

2.6. Statistical analysis

Oil content for each sample was repeated 3 times. The mean values were used to represent the oil content, and standard deviations were used to identify outliers. To assess the normality of the oil content data, the Shapiro-Wilk (Shapiro et al., 1965) test was performed. Given the results indicating non-normal distribution, non-parametric methods were employed for further analysis. Specifically, the Wilcoxon Signed-Rank Test (Wilcoxon, 1945) was utilized to compare paired samples, providing a robust analysis in the presence of non-normal data.

3. Results and discussion

3.1. Weight

The weight of all samples ranged from 125.0 to 264.2 g, with a mean value of 194.7 g and a standard deviation of 35.89 g.

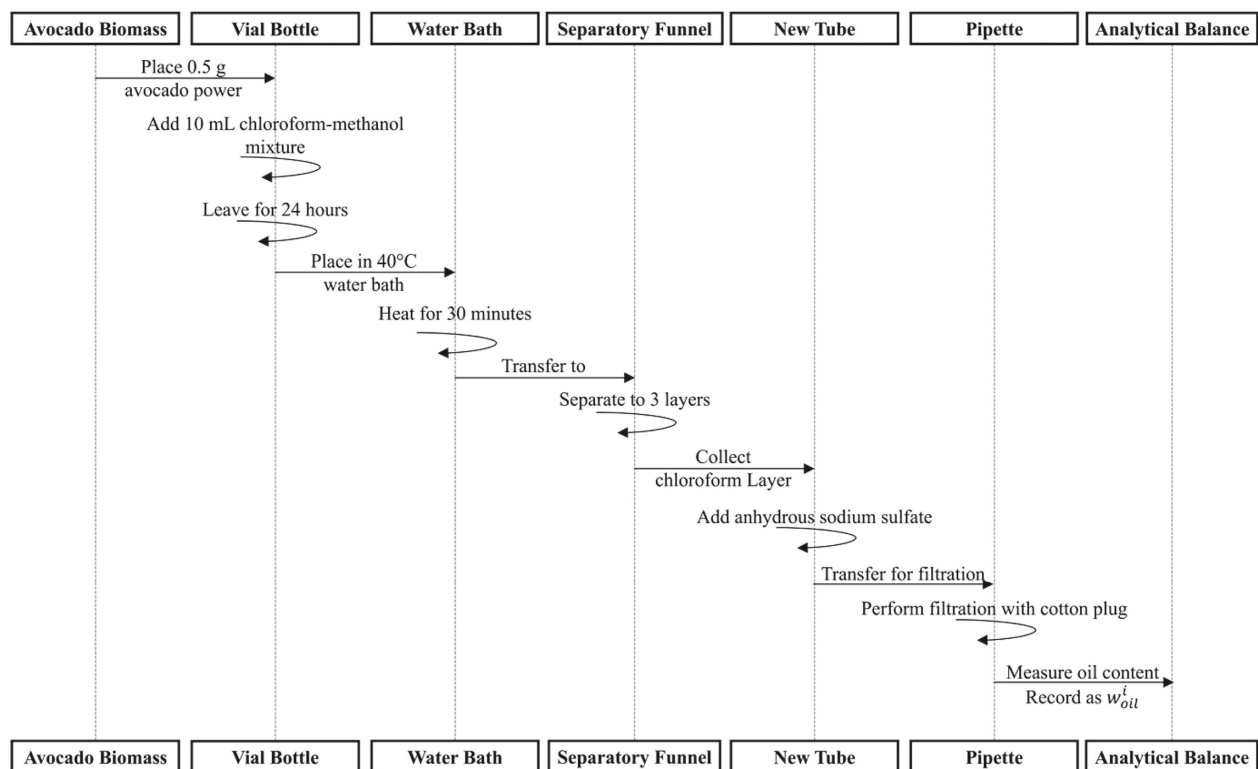


Fig. 3 Flowchart of extraction of internal oil

The mean values and standard deviations for each temporal data point were 157.0 ± 13.8 g, 202.2 ± 11.9 g, 222.2 ± 15.0 g, and 197.4 ± 15.9 g, respectively. This indicates that the samples we collected have a high-level variety on weights independent of collection events and maturation stage.

3.2. Wax and oil content

The volume of wax from the skin ranged from 0.03 mg/cm^2 to 0.20 mg/cm^2 . There is a consistent increase in the weight of wax from September to December, as shown in Fig. 4. This increase could be related to the growth and development of the fruit, possibly as a protective mechanism as the avocado matures (Durand et al., 1984; Verardo et al., 2003).

A clear upward trend in oil content was also confirmed from September to November (Fig. 4). To assess the normality of the oil content data, the Shapiro-Wilk test was performed, yielding a test statistic of 0.91 and a p -value of 0.03, indicating a non-normal distribution. Consequently, non-parametric methods were employed for further analysis. Specifically, the Wilcoxon Signed-Rank Test was utilized to compare paired samples, yielding a test statistic of 0.00 and a p -value less than 0.01, confirming significant differences. The data ranged from 5.7% to 17.4%, which is in agreement with the normal range (Salameh et al., 2022). The slight decrease in December could suggest a maturation process where the oil content peaks in late fall.

3.3. EEM measurement

Figure 5 (a) showed a typical EEM result of the wax sample diluted to 5 mL. Region A and Region B were noises that due to the first-order and second-order Rayleigh scattering, respectively

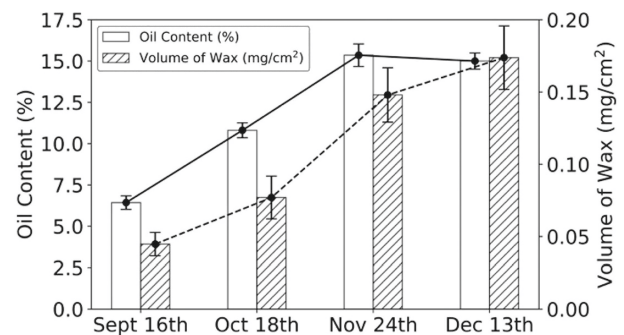


Fig. 4 Progressive changes in oil content and volume of wax over four months

(Rinnan et al., 2005). Two prominent fluorescence peaks were observed from the EEM measurement. The excitation (Ex) and emission (Em) wavelengths were Ex: 375 nm and Em: 410 nm for Peak A, and Ex: 375 nm and Em: 431 nm for Peak B. The intensity of Peak A was stronger than that of Peak B. The fluorescence of the wax sample solution was bluish in color, as shown in Fig. 5 (b) taken under 365 nm UV light. Besides the fluorescence peak attributed to chlorophyll A, previous researchers only observed one fluorescence peak with an excitation and emission wavelength of Ex: 370 nm and Em: 450 nm, using front-face EEM measurement of cropped avocado skin (Kokawa et al., 2020). Our result confirmed this phenomenon. In addition, we confirmed that at least two dominant fluorescent compounds, resulting in Peak A and Peak B, contribute to it. There was another relatively weak fluorescence Peak C observable from

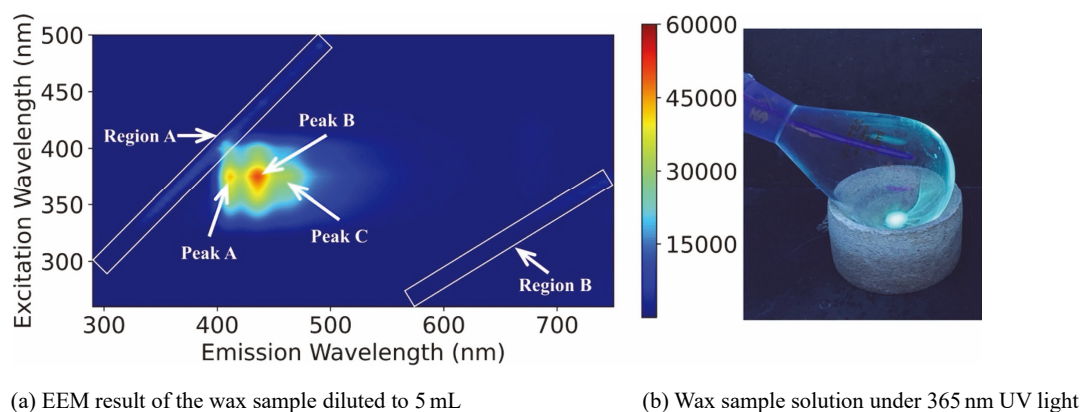


Fig. 5 The representative EEM result of the wax sample and its solution under 365 nm UV light

the EEM. However, it was coupled with other peaks, especially with Peak B. The excitation and emission wavelengths were hard to identify. To compare and evaluate the compound species in the fluorescence spectra, the PARAFAC method was used to deconvolute the fluorescent components and their corresponding spectral characteristics.

3.4. PARAFAC analysis

Component 1 (Ex: 375 nm and Em: 410 nm) was characterized by an excitation peak at 375 nm (Fig. 6 (a)) with an emission peak at 410 nm (Fig. 6 (b)). The small Stokes shift observed for this component may indicate a fluorescent species that returns to the ground state more rapidly, possibly due to a less rigid structure or a different molecular environment. This profile is suggestive of caffeic acid, a structural isomer of chlorogenic acid, which may exhibit such fluorescence behavior when present in a complex biological matrix like avocado skin (Rosero et al., 2019).

Component 2 (Ex: 375 nm and Em: 431 nm) exhibited excitation and emission peaks at 375 nm (Fig. 6 (c)) and 431 nm (Fig. 6 (d)), respectively. The slight redshift in the excitation peak relative to Component 1 (Ex: 375 nm and Em: 410 nm), along with a similar emission range, indicates a compound with a degree of structural similarity, potentially another cinnamic acid derivative. This is suggestive of chlorogenic acid (Navarro-Orcajada et al., 2021).

Component 3 (Ex: 355 nm and Em: 435 nm) demonstrated an excitation peak at 355 nm (Fig. 6 (e)) and an emission peak at 435 nm (Fig. 6 (f)). The spectral properties of this component suggest the presence of a phenolic compound, likely a poly-aromatic hydrocarbon or a related complex organic molecule. These spectral characteristics are reminiscent of chlorogenic acid, a cinnamic acid derivative, which is commonly found in plant tissues and known for its antioxidant properties (García-Plazaola et al., 2015). The proximity of the emission peaks of Components 2 (Ex: 375 nm and Em: 431 nm) and 3 (Ex: 355 nm and Em: 435 nm) suggests that they could represent different environmental or bound states of chlorogenic acid or a

related compound.

The process of extracting, purifying, and isolating fluorescent compounds from wax solution using HPLC filtration is shown in supplementary material Fig. S1. However, the volume of the isolated fluorescent compounds was less than 0.1 mg. We failed to confirm the identities of the fluorescent compounds with nuclear magnetic resonance (NMR). The presence of aromatic, vinylic, and aliphatic protons on the ^1H NMR spectrum (Fig. S2) suggested a complex molecular structure with multiple functional groups. Further analysis would be needed to determine the exact structure of the compounds. Additionally, the EEM of caffeic acid and chlorogenic acid dissolved in 100% ethanol solution was measured. From the normalized EEM results shown in Fig. 7, caffeic acid and chlorogenic acid were confirmed to have peaks at Ex: 385 nm and Em: 430 nm and Ex: 385 nm and Em: 450 nm, respectively. Compared with PARAFAC results (Fig. 7 (a) and (b)), the fluorescence peaks of pure caffeic acid (Fig. 7 (c)) and chlorogenic acid (Fig. 7 (d)) solutions were slightly redshifted but remain within a reasonable range. This redshift is attributed to interactions with other compounds in the wax solution and environmental differences such as pH conditions (Valeur et al., 2012). Although this experiment supports our previous discussion, further investigation is required to achieve definitive identification and quantification of chlorogenic acid, caffeic acid, and other phenolic compounds present in the sample.

The implications of these findings are twofold. Firstly, they offer insight into the qualitative composition of the wax on avocado skin, suggesting a significant presence of phenolic compounds (Velderrain-Rodríguez et al., 2021). Secondly, the unique spectral signatures of the components from avocado skin may serve as a quantitative fingerprint, indicating both the presence and condition of these compounds in the avocado skin. This characteristic has potential applications in quality control and authentication of avocados, similar to methods developed for other agricultural products (Al Riza et al., 2023; Dong et al., 2020; Takemoto et al., 2023).

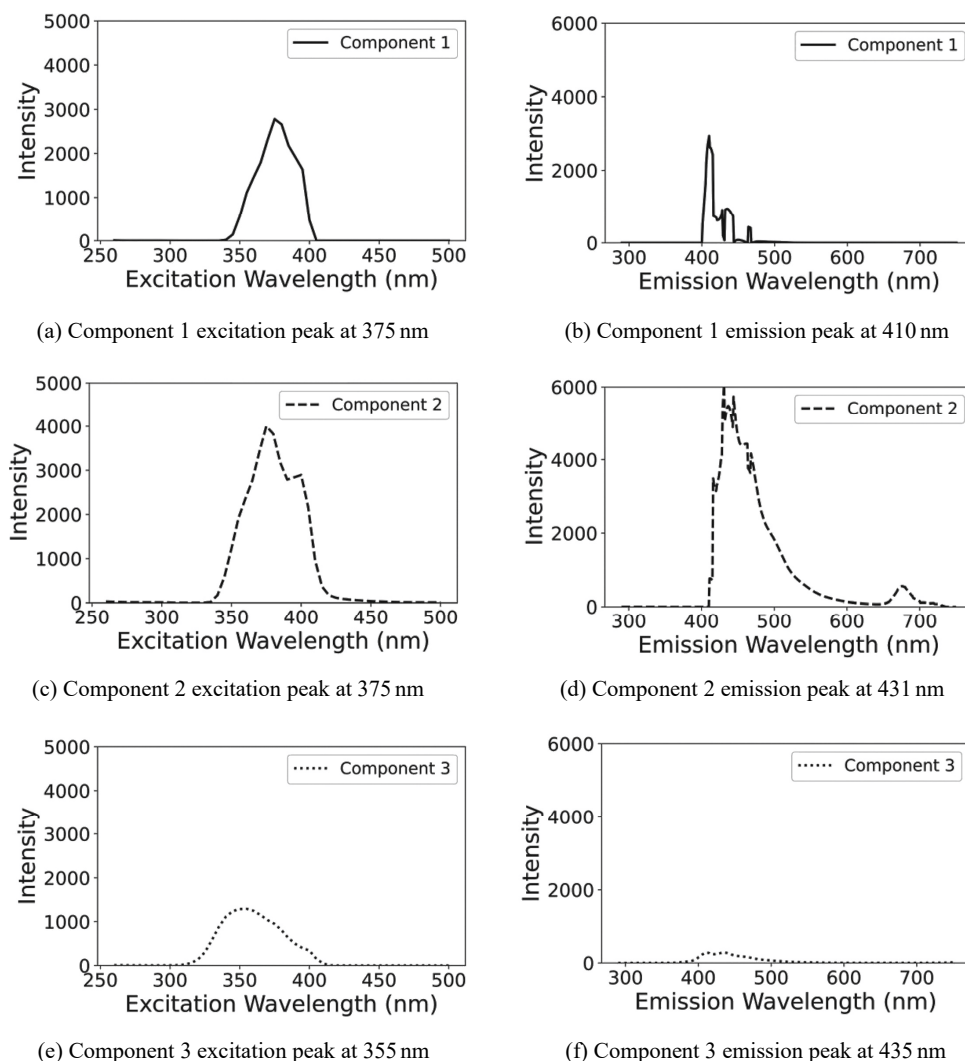


Fig. 6 Characterization of avocado skin fluorescent compounds through PARAFAC-resolved fluorescence spectroscopy

3.5. Relationship between fluorescence properties and oil content

Extracted from the EEM result of the wax sample, the emission spectra excited at a wavelength of 375 nm are shown in Fig. 8 (a) as the fluorescence characteristics of all avocado samples over time. Peak A and Peak B at around 410 nm and 431 nm can be clearly observed. The temporal trend of two specific peaks showed a decrease in intensity over the four-month period, as shown in Fig. 8 (b). This trend could be associated with the degradation of the intensity of fluorescent compounds in the wax, possibly due to oxidation or other metabolic processes as the fruit matures.

As shown in Fig. 9, the fluorescence intensity of both Peak A (Fig. 9 (a)) and Peak B (Fig. 9 (b)) showed a strong negative correlation with oil content, with the correlation coefficient reaching -0.86 for both peaks. As the oil content increased from September to December, a consistent decrease in fluorescence intensity was observed for both peaks across all samples.

The maturation of avocado is accompanied by changes in both physical and chemical properties, including oil accumulation

and variations in fluorescent compounds in the skin (Salameh et al., 2022). Our results showed that the fluorescence characteristics of avocado skin could provide insights into biochemical dynamics during fruit maturation and be utilized as indicators of avocado quality, such as internal oil content.

3.6. Limitations and future perspectives

We attempted to purify, isolate, and identify fluorescent compounds from wax via HPLC filtration and NMR measurement, but the collected volumes of fluorescent compounds were less than 0.1 mg, too small for successful identification. Based on our experiment, a much larger number of avocado samples are necessary to collect sufficient wax for NMR identification of fluorescent compounds after HPLC filtration. This limitation should be further explored.

Our study characterized the fluorescence properties of avocado skin wax during maturation, yet the underlying mechanisms of the observed fluorescence degradation remain to be fully elucidated. The cause of this degradation—whether due to oxidation, molecular breakdown, or other processes—presents a promising avenue for future research. To further investigate

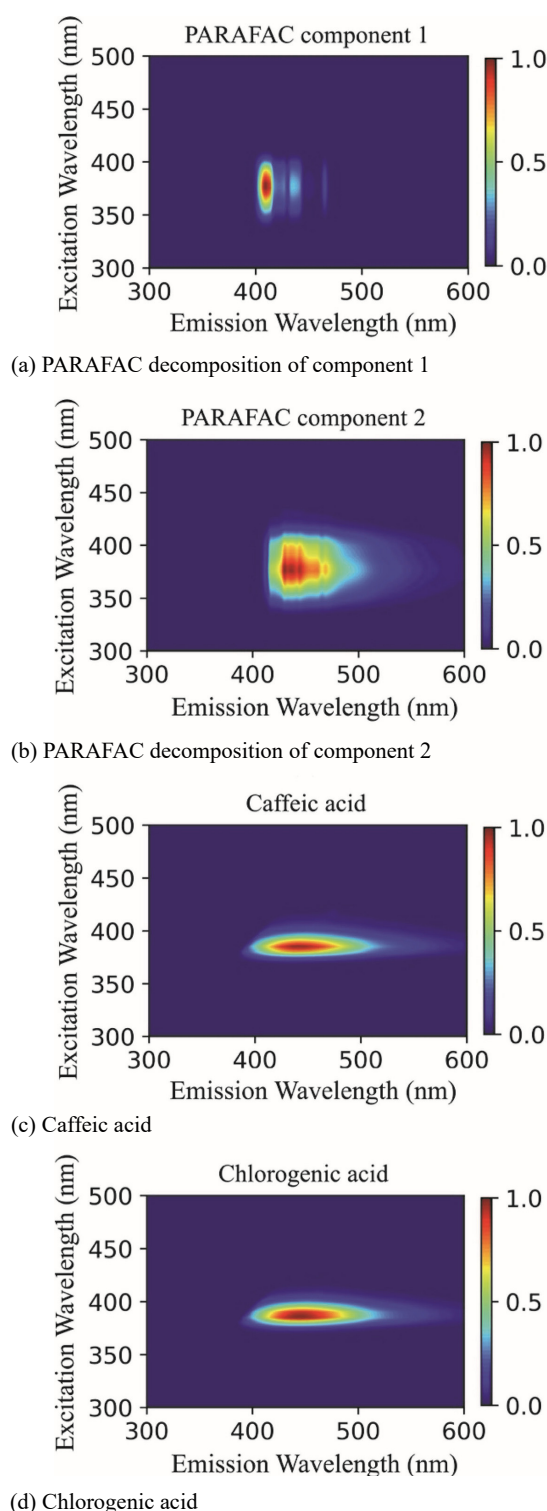
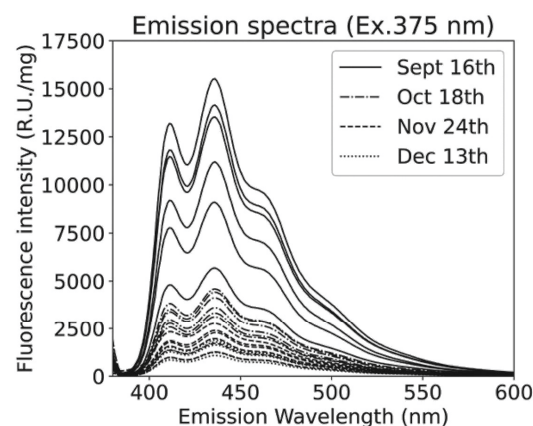
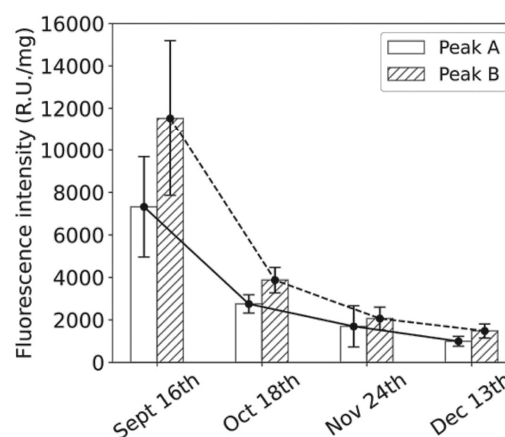


Fig. 7 Normalized EEM results of PARAFAC decomposition, caffeic acid and chlorogenic acid dissolved in 100 % ethanol solution

this phenomenon, subsequent studies should incorporate cross-sectional analysis of the avocado skin. Techniques such as histological staining and microscopic observation could reveal structural changes occurring during maturation. These methods may provide crucial insights into the mechanisms behind the observed trends in fluorescence properties, potentially



(a) The representative emission spectra of 24 avocado samples captured on different dates spanning four months



(b) The temporal trend of two specific peaks at around 410 nm and 431 nm

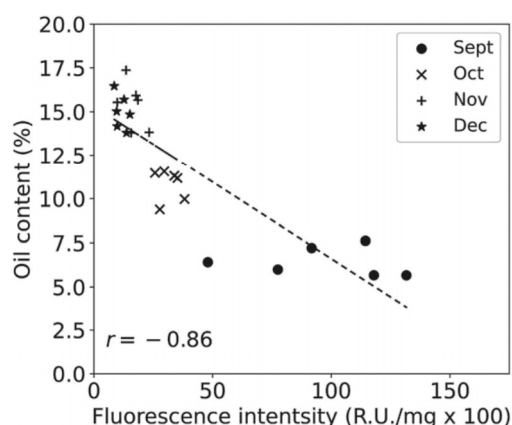
Fig. 8 The representative emission spectra and the temporal trend of two specific peaks

explaining the relationship between physical changes in the fruit's exterior and its internal maturation process.

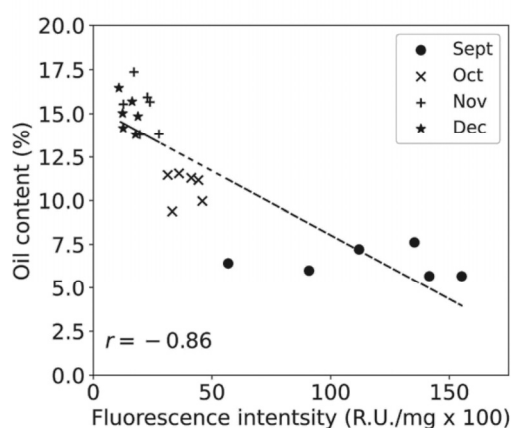
Although our results showed potential for on-site oil content estimation and determining the optimal harvest time for each fruit, our study was limited to the Bacon cultivar, which is locally important in Japan. The generalizability of this method to other cultivars, particularly the commercially important Hass cultivar, should be confirmed.

4. Conclusions

In this longitudinal study, we systematically analyzed the excitation-emission matrix (EEM) of wax extracted from the avocado skin and internal oil content across a four-month maturation process. For the first time, two prominent fluorescence emission peaks were identified and characterized at approximately 410 nm and 431 nm under 375 nm excitation in the wax. These peaks were strongly indicative of the presence of caffeic acid, chlorogenic acid, and other phenolic fluorescent compounds. Furthermore, our study revealed that, though the volume of wax and oil content increases as avocado matures,



(a) Peak A and oil content in avocado skin



(b) Peak B and oil content in avocado skin

Fig. 9 Correlation between fluorescence intensity of two peaks and oil content in avocado skin

there was a strong negative correlation ($r = -0.86$) between the intensity of these fluorescence peaks and the avocado oil content. This correlation underscores the potential of fluorescence-based technologies, such as fluorescence imaging systems, in providing non-destructive, faster, and more cost-effective avocado maturity assessment with accurate oil content estimation. By leveraging the inherent fluorescence properties of wax on avocado skin, a cost-effective handheld fluorescence imaging system equipped with UV LEDs of suitable wavelengths and industrial color cameras can capture fluorescence images of the avocado skin. These images can then be analyzed using algorithms to quickly estimate oil content. As a result, producers can achieve more precise monitoring and control over the harvesting process, thereby improving yield quality and consumer satisfaction.

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Appendix A. Supplementary data

The supplementary data, Figs. S1 and S2 in this article are

published in J-STAGE Data.

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