

EFFECT OF PLANTATION CLIMATE ON AQUAPHOTOMIC CHARACTERISTICS OF DURIAN FRUIT (*DURIO ZIBETHINUS* MERR. CV. MONGTHONG)

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Abstract

This study investigated the effect of plantation climate on the aquaphotomic characteristics of durians. Near-infrared spectra were collected using an FT-NIR spectrometer (12500-4000 cm⁻¹; 800-2500 nm) to explore the water molecular structures within the peel. Spectral data were pretreated with the standard normal variate, and specific water matrix coordinate aquagrams were constructed and analyzed in both the first (1300-1600 nm) and the second (900-1100 nm) overtone regions. Climate factors, including temperature, precipitation, humidity, sunshine hours, rainy days, wind speed, and wind direction, were examined for their influence on aquagram patterns. Differences among provinces appeared mainly in the absorption of C1-C4 bands in the second overtone range. Aquaphotomic analysis revealed that C1 (896 nm) and C2 (910 nm) are associated with environmental interactions, C3 (916 nm) represents joint vibrational modes related to water molecule arrangement and dehydration processes such as durian ripening, and C4 (923 nm) corresponds to water shell structure linked to ion binding, indicating tightly bound structural water that reduces water loss. These spectral variations suggest that precipitation at the harvesting stage affects the osmotic potential of water within the peel, while temperature, humidity, rainy days, sunshine hours influence transpiration driven by the vapor pressure deficit between the fruit interior and the surrounding environment. Overall, these findings establish a novel basis for integrating aquaphotomics with geographical and climatic data to discriminate durian geographical origins.

Keywords: Durian; Aquaphotomics; Near infrared spectroscopy; Plantation climate; Geographical origin; Identification

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Introduction

The key durian producers are Thailand, Malaysia, and Indonesia. The ASEAN Standard for Durian recognizes three commercial cultivars of Thai durian (*Durio zibethinus* Murr.): Monthong, Channee, and Kan-yao. This standard applies to commercial varieties of durian grown from *Durio* spp. of the *Bombacaceae* family and supplied fresh to consumers supplied fresh to the consumer (Siriphanich, 2011). These cultivars represent the most widely cultivated species, especially for export.

Exporters must consider several factors, particularly fruit maturity and ripeness. The percentage of pulp dry matter (DM) is the key parameter, with Monthong requiring $DM \geq 32\%$ (Wiangsamut and Wiangsamut 2023). Commercial harvesting typically occurs 120 days after anthesis (DAA). “Durian 120 DAA” refers to fruits harvested at this stage, where anthesis marks the flowering stage when the buds first appear. Counting begins from the day the flower is pollinated and blooms, making DAA a standard measure of maturity.

Studies have also examined pulp color and carotenoid content. Increased yellowness, caused by carotenoid accumulation, is positively associated with maturity (Youryon and Supapvanich, 2022). These standards specify both the internal and external properties of durian.

Fertilizer management tailored to durian growth stages is essential for supporting plant growth and yield, as each stage requires different nutrient inputs. Durian cultivation can be divided into four stages (Phanomsophon *et al.*, 2023): the unproductive stage, covering the first 1-4 years of tree growth (Stage 0: S0); the flowering stage (Stage 1: S1); the fruiting stage (Stage 2: S2); and the harvesting stage (Stage 3: S3).

During the unproductive stage (S0), when trees are still establishing growth, additional nitrogen (N) is required to support development. In the flowering stage (S1), phosphorus (P) is essential to stimulate flower initiation. At the fruiting stage (S2), potassium (K) plays a key role in enhancing fruit quality. During the harvesting stage (S3), a balanced supply of all nutrients is necessary to restore the tree and prepare it for the next production cycle (Menesatti *et al.*, 2010; Mohd Asaari *et al.*, 2018; Rébufa *et al.*, 2018; Ng *et al.*, 2019; Shi *et al.*, 2021).

These standards serve as guidelines for diagnosing nutritional problems and provide a basis for fertilizer recommendations (Zornoza *et al.*, 2018). In this study, we focused primarily on the growth of durians at stage 3 and 120 DAA.

However, S0 is also critical, as early plant growth and photosynthesis influence the final yield. Maintaining healthy trees is essential for producing high-quality durian fruits.

Among the factors affecting tree health, precipitation plays a major role, with distinct impacts during wet and dry seasons. In the wet season, increased compost moisture and slower aerobic degradation can lead to nitrogen loss (Wong *et al.*, 2017). Thus, farmers can adjust fertilizer formulations and application rates based on the nutrient status of the leaves (Zubairi *et al.*, 2021).

During the dry season, cellulose may play an important role in maintaining plant hydration and supporting photosynthetic activity (Zubairi *et al.*, 2021). In this context, leaf health and efficiency, reflected in chlorophyll content, can influence the overall quality and biochemical composition of the peel (Ahmad *et al.*, 2024).

Although chlorophyll is not a major component of mature durian peel, its presence in the leaves is fundamentally important for peel formation and biochemical properties (Ahmad *et al.*, 2024). During the unproductive stage, trees need to accumulate high levels of chlorophyll in the leaves to support growth. A strong positive correlation between leaf chlorophyll content and leaf humidity has been reported by Tan *et al.* (2024). Leaf humidity, defined as the moisture content inside the leaf, is critical for photosynthesis, as it directly influences the leaf's efficiency to functional capacity (Lin *et al.*, 2023). The rate of water loss from leaves through transpiration is strongly influenced by climatic factors, including temperature, relative humidity, wind speed (the ambient air velocity), or precipitation (Zhu *et al.*, 2022).

The flowering stage occurs approximately 40 days after the first DAA, with an optimal temperature of around 26°C (Thongkaew *et al.*, 2021). This stage has a direct impact on yield, and precipitation patterns must be well-timed to synchronize flowering (Thongkaew *et al.*, 2021). Comparisons between flat and terrace cultivation areas indicate that higher terraces require greater precipitation during the flowering stage (Tan *et al.*, 2024).

The fruiting stage, occurring between 40-80 DAA, requires higher temperatures than the flowering stage to achieve optimal yield. Elevated soil temperatures are also necessary for root activity, which contributes to increased fruit size (Masaru *et al.*, 2016).

A study indicated that chlorophyll content in durian leaves can be influenced by light (Susila *et al.*, 2021). During this stage, the amount of sunlight directly affects peel growth and development. Similarly, adequate precipitation is essential for optimal carbohydrate accumulation in developing fruits (Thongkaew *et al.*, 2021).

The harvest stage at 120 DAA represents the optimal maturity for Monthong durians, ensuring superior eating quality, sweetness, and texture. Warmer climates accelerate ethylene synthesis and respiration, thereby hastening ripening (Tan *et al.*, 2024). Additionally, longer sunshine hours and warm temperatures (24-32°C) promote starch-to-sugar conversion and increase soluble solids content (25-30%) in tree-ripened durians (Youryon and Supapvanich, 2022). These findings highlight the strong relationship between sunshine, temperature, and durian pulp quality during this stage.

Precipitation is also an important factor. During the harvest stage, rainfall is usually limited, which reduces the incidence of physiological disorders related to excess moisture, such as uneven ripening, wet core, tip burn, hardened flesh, and chilling injury (Virkar *et al.*, 2019).

Another factor influencing durian growth from the flowering stage through to the harvesting stage is its geographical origin. Previous research indicated that leaf humidity was highest during the mature fruiting stage in flat areas, whereas in terrace areas it peaked from the mature flower bud to the flowering stage, as higher terraces provide better water and nutrient management (Tan *et al.*, 2024). The physicochemical characteristics of fruits depend on multiple factors including geographic, climatic, and agronomic conditions, which are also used to define product authenticity (Tzouros and Arvanitoyannis, 2021).

Several studies have examined durian using both qualitative and quantitative approaches with non-destructive techniques such as near-infrared spectroscopy (NIRS). NIRS is effective for evaluating fruit maturity directly from the peel of intact durians, making it crucial for quality control in the industry. One study combined peel and stem spectra with machine learning algorithms, including Linear Discriminant Analysis (LDA), Support Vector Machine (SVM), and K-Nearest Neighbors (K-NN), using short and long-wave near-infrared (SWNIR/LWNIR) data, achieving 97-100% accuracy in maturity classification (Ditcharoen *et al.*, 2023).

Another study evaluated the physicochemical properties of durian pulp by scanning intact fruit, stem, and pulp using the NIRS technique. The results showed that NIRS can identify water molecules through distinct electromagnetic

absorption bands. For durian peel, the critical water-specific absorption wavelengths are 970 nm, 1198 nm, 1452 nm, and 1938 nm (Onsawai *et al.*, 2021). During durian maturation, the water content of the peel decreases, while the proportion of DM (starch and sugars) in the pulp increases (Onsawai *et al.*, 2021).

An interesting study on the geographical origin of durian using NIR diffuse reflectance spectroscopy reported that intact durian spectra collected with an FT-NIR spectrometer showed distinct absorption bands at 10314 (970), 8598 (1162), 6827 (1465), and 5122 (1952) cm^{-1} (nm), corresponding to H_2O vibrations. When coupled with chemometric analysis, these spectra enabled the identification and classification of durians by geographical origin. However, the specific factors influencing origin classification were not clearly identified (Chanachot *et al.*, 2023).

The NIR spectrum of fruit is influenced by temperature, particularly in the water absorption bands. As a result, calibration equations developed at a fixed temperature cannot reliably predict samples measured under different conditions, indicating that geographic origin verification using NIR technology must be conducted in a controlled-temperature environment.

A key limitation of NIRS in agricultural analysis is spectral interference, especially within the broad water band, which overlaps with signals from organic compounds (e.g., oils and proteins) and complicates the quantification of nutrients or contaminants (Blanco and Villarroya, 2002). Nevertheless, this challenge provided the motivation for our study.

Many studies on the aquaphotomics of agricultural products have been conducted in the longer-wavelength region, especially the first overtone (1300-1600 nm), where products exhibit higher water absorbability. Examples include strawberry (Muncan *et al.*, 2022), apple (Vanoli *et al.*, 2018; Kaur, 2019), and kiwi juice (Kaur *et al.*, 2022). Strawberries were analyzed in the second overtone region (800-1100 nm) to monitor changes during storage. Kiwifruit juice was studied in the 800-1100 nm range to assess water structure changes with temperature and quality parameters, specifically comparing the first and second overtones under temperature variation and noting distinct responses in each region.

Using the framework of aquaphotomics to link water molecular dynamics with climate change and geographical variation provides new insights into aquaphotomic signatures and enables visualization of changes in water molecular structures in the peel of intact durians. However, no published aquaphotomic studies have specifically examined

the durian peel. Changes in the molecular structure of water within cellulose nanofibers can be analyzed using NIR spectroscopy to assess hydration, hydrogen bonding, and water mobility (Xing *et al.*, 2022). This forms the foundation for the present study, which aims to investigate the effects of plantation climate on the aquaphotomic characteristics of durian (*Durio zibethinus* Merr. cv. Monthong) fruit. The insights are valuable for determining the geographic origin of durian fruits.

Materials and Methods

Durian fruit samples and geographic origins

To verify the geographical origin of the samples, durians were sourced directly from orchards across multiple provinces in Thailand, including Prachuap Khiri Khan (PraCh), Chomphon (Chom), Surat Thani (Su), Chanthaburi (Chan), Prachin Buri (PraJ), Rayong (Ra), Trat (T) and Sisaket (Sri), as shown in Figure 1.

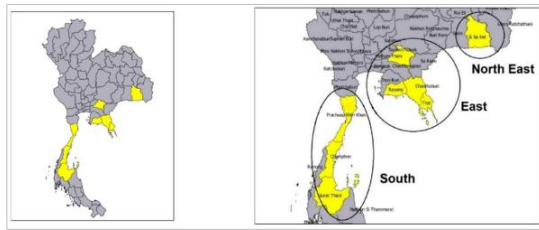


Figure 1. Map of the geographical origin of the samples included Prachuap Khiri Khan, Chomphon, Surat Thani, Chanthaburi, Prachin Buri, Rayong, Trat and Srisaket

The number of samples and detailed information regarding the collection of 100 durian fruits are presented in Table 1. Durian samples were randomly selected from 5-10-year-old durian trees in three orchards per province, each managed by different owners.

The conditions for durian sample collection were established by the National Bureau of Agricultural Commodity and Food Standards (Bureau of Commercial Provincial Office of the Permanent Secretary Ministry of Commerce, 2020). According to these standards, fruits were harvested at 120 DAA with a weight range of 2.5-3.5 kg.

The experiment was designed according to the specific harvest times of each orchard, determined by tagging ten trees on the first day of flower blooming. From these, one in five tags was randomly selected per tree across the orchard, resulting in one fruit sample per tree. The samples were carefully transported to the NIRS Research Center for Agricultural Product and Food, Department of Agricultural Engineering, School of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand. Upon arrival, the samples were stored overnight at approximately 23-27°C (room temperature) prior to analysis. All measurements were conducted at room temperature ($25 \pm 2^\circ\text{C}$).

Geographic origin and its climate data of durian plantation

Durian plantation climate data (Source 1) were collected from the European Center for Medium-Range Weather Forecasts (ECMWF), a leading international organization specializing in weather forecasting and climate research that produces

Table 1. Geographical origin

Harvesting time	Province (Abbreviations)	Abbreviations of orchard	Number of samples	Latitude	Longitude
Jun-2019 and Jun-2020	Prachuap Khiri Khan (PraCh)	PraChA	5	12°34'20.97"N	99°32'10.38"E
		PraChB	5	12°35'7.69"N	99°32'12.04"E
		PraChC	5	12°30'17.37"N	99°31'24.25"E
Aug-2019	Chomphon (Chom)	ChomA	5	8°53'24.04"N	99°14'44.99"E
Jul-2019	Surat Thani (Su)	SuA	5	10°47'47.20"N	99°13'9.60"E
		SuB	5	8°56'33.71"N	99° 1'14.37"E
May-2019	Chanthaburi (Chan)	ChanA	5	12°51'44.20"N	102° 2'47.20"E
		ChanB	5	12°52'6.99"N	102° 3'0.76"E
		ChanC	5	12°34'9.60"N	102°16'8.22"E
May-2019	Prachin Buri (PraJ)	PraJA	5	14° 6'33.33"N	101°25'19.85"E
		PraJB	5	14° 7'30.92"N	101°18'49.12"E
May-2019	Rayong (Ra)	RaA	5	12°45'20.37"N	101°33'4.09"E
		RaB	5	12°46'7.14"N	101°44'31.08"E
		RaC	5	12°47'6.39"N	101°37'47.04"E
May-2019	Trat (T)	TA	5	12°34'6.16"N	102°26'48.35"E
		TB	5	12°35'12.51"N	102°26'16.83"E
		TC	5	12°34'52.60"N	102°26'45.85"E
Jun-2019 and Jun-2020	Srisakat (Sri)	SriA	5	14°40'49.56"N	104°38'37.71"E
		SriC	5	14°35'15.93"N	104°29'49.94"E
		SriB	5	14°33'33.97"N	104°26'43.52"E
Total			100		

climate reanalysis datasets. Climate data from eight provinces in Thailand were compiled, including the monthly average temperature ($^{\circ}\text{C}$), precipitation (mm), humidity (%), number of rainy days (days), and average sunshine hours (hr), covering the period from 1991 to 2021. All data were retrieved from <https://en.climate-data.org/> on April 22, 2025 (see Supplementary Information, S1).

For durian plantation climate data (Source 2), measurements of temperature ($^{\circ}\text{C}$), precipitation (mm), wind direction (deg), and wind speed (kt) were obtained from the Thai Meteorological Department. The data were retrieved on May 5, 2019 (see Supplementary, S2) and were taken into consideration for the analysis.

Climate data from Source 1 provide temporal consistency by capturing long-term regional climate trends, while Source 2 provides local accuracy through site-specific observations. Both sources were considered in relation to the key cultivation stages of durian: the unproductive stage, the flowering stage (S1), the fruiting stage (S2), and the harvesting stage (S3).

Near infrared spectra acquisition

Off-line scanning was conducted using an FT-NIR spectrometer (Multi-Purpose Analyzer, MPA, Bruker Optik, Ettlingen, Germany) with a wavenumber range of $12500\text{--}4000\text{ cm}^{-1}$ (800–2500 nm), a resolution of 16 cm^{-1} , and 32 scans per spectrum.

Each durian fruit was scanned three times at the same point in the middle of each locule. A black polyurethane foam sponge was placed between the sample and the NIR beam window of the spectrometer to prevent radiation leakage, as the material itself has minimal NIR absorption. The leakage-avoidance method was adapted from Włodarska *et al.* (2021), who analyzed apples using an FT-NIR spectrometer equipped with a microsphere sample accessory.

The most relevant research includes a study that analyzed the total and specular reflectance of various black materials over the 250–2500 nm range. Marshall *et al.* (2014) reported that such analyses can help identify the most effective materials for reducing stray light. Additionally, Coyle *et al.* (2005) investigated the use of black polyvinyl chloride (PVC) foam in functional NIRS systems to prevent crosstalk between the source and detector by absorbing NIR light.

Therefore, black polyurethane foam was used to prevent leakage of NIR light during the experiment. Before scanning each sample, a gold plate was internally scanned to obtain the maximum NIR radiation intensity from the light source and to provide background compensation. Spectral data

were collected and analyzed using OPUS 7.5 (Bruker Optik, Ettlingen, Germany). Actual and simulated images of the measurement instruments used for sample scanning are presented in Figure 2.

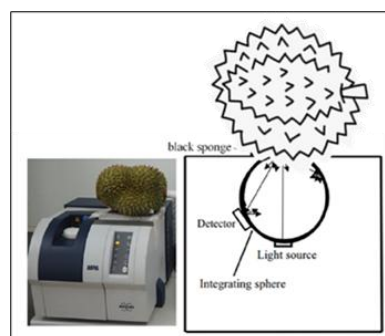


Figure 2. Actual and simulated images of the FT-NIR spectrometer (multi-purpose analyzer, MPA) used for sample scanning

Aquaphotomic characteristic determination

Aquagrams development

In the aquaphotomics method, an aquagram is constructed from spectral data that have been normalized and averaged. Prior to aquagram construction, all raw spectra were pretreated using the Standard Normal Variate (SNV) method to correct spectral variations arising from physical differences such as particle size, surface scattering, and baseline shifts, which can obscure true chemical information. SNV standardizes each spectrum by centering and scaling, thereby removing additive and multiplicative effects caused by light scattering (Barnes *et al.*, 1989; Rinnan *et al.*, 2009).

This pretreatment enhances the comparability of spectra and ensures that subsequent analyses reflect genuine chemical absorbance features rather than physical artifacts. Without SNV correction, interpretation of raw spectra may be misleading. Following SNV pretreatment, aquagram is constructed using normalized absorbance values at selected wavelengths (Tsenkova *et al.*, 2015; Appaw *et al.*, 2025). Aquagrams are effective tools for determining the dynamics of water structural changes under various perturbations (Tsenkova *et al.*, 2018; Appaw *et al.*, 2025; Shrestha *et al.*, 2025).

In this study, perturbation analysis was applied to evaluate changes in water structure in the durian peel of intact fruits at the commercial harvesting stage, influenced by climatic variation across different geographic locations. Aquagrams were constructed from spectral data obtained through FT-NIR measurements of intact durian samples harvested from plantations in multiple provinces of Thailand.

The selected WAMACs in this study were derived from SNV-normalized spectral data across two key regions: 1300-1600 nm, corresponding to the first overtone vibration band of water, and 900-1020 nm, corresponding to the second overtone vibration band of water, where water absorbance patterns are most distinct (Tsenkova *et al.*, 2018; Appaw *et al.*, 2025). These regions were based on previously established water absorbance bands reported in aquaphotomics literature and verified by the consistent appearance of characteristic peaks across samples and treatments within the specific spectral regions (Kaur., 1994; Muncan *et al.*, 2016; Muncan *et al.*, 2019).

Each wavelength region corresponds to specific water molecular vibration modes and hydrogen-bonding structures, confirming that the selected WAMACs effectively capture dynamic changes in water spectral patterns related to sample composition and state. Characteristic peaks in the radar diagram were identified by comparing normalized, averaged absorbance differences among samples from different provinces, and the climate difference effects corresponding thereby linking climate variation to changes in water molecular configurations. Therefore, aquagrams, which visualize these absorbance changes at selected WAMACs, can clearly reveal structural differences.

Dry matter content

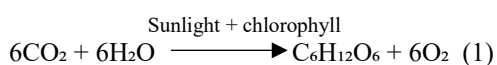
One of the factors that exporters need to consider is fruit maturity and ripeness, expressed as pulp dry matter (DM). The methodology for analyzing DM in durian pulp was described by (Onsawai and Sirisomboon, 2015), who employed gravimetric analysis at $60 \pm 2^\circ\text{C}$ until constant weight was achieved.

Factors

Definition of factor A to I

This section provides an overview of the factors affecting water content in the peel, as detected by NIR light absorption. The relationships between these factors, the peel, and external climate conditions are explained in detail under factors A through I.

A: Photosynthesis. The photosynthesis equation is described by Equation (1) (Farquhar *et al.*, 1981)



where CO_2 is molecules of carbon dioxide, H_2O is molecules of water, $\text{C}_6\text{H}_{12}\text{O}_6$ is molecule of glucose, O_2 is molecules of oxygen.

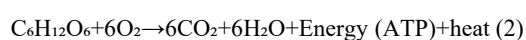
During this process, peel-related factors such as sunshine exposure and chlorophyll content were considered. Sunshine hours, documented in Climate Source 1, influence the timing of stomatal opening and closing in leaves, which in turn regulates transpiration.

Chlorophyll is not a major component of the mature durian peel; however, its presence in the leaves is fundamentally important for peel formation and biochemical properties (Ahmad *et al.*, 2024). Chlorophyll supports the growth and development of all plant tissues, including the peel. Consequently, leaf health and efficient photosynthesis, reflected in chlorophyll content, can influence the overall quality and biochemical composition of the peel (Kondo *et al.*, 2017).

A study on plant growth under varying humidity conditions reported a strong positive correlation between leaf chlorophyll content and leaf humidity. Therefore, the relationship between the leaf and the peel is indirect. It should be noted that the rate of water loss from the leaf (transpiration) is strongly influenced by external climatic conditions such as temperature, relative humidity, wind speed, and precipitation.

B: Transpiration at the leaf. A study on plant response to air temperature indicated that warm conditions combined with low relative humidity increased transpiration rates (Islam *et al.*, 2021). The study also explained the relationship between leaf stomata and precipitation: in climates with more precipitation, plants tend to keep their stomata open longer, thereby maintaining internal moisture and promoting growth. In contrast, in drier climates, stomata close more frequently to conserve water, resulting in lower internal moisture levels (Buckley and Sack, 2019). Wind speed further influences transpiration by removing the humid boundary layer around leaves, which accelerates water loss and reduces internal leaf moisture (Lin *et al.*, 2023). Therefore, leaf transpiration is strongly influenced by the combined effects of temperature, relative humidity, wind speed, and precipitation.

B1: Transpiration at the peel. The durian peel is porous (Lufu *et al.*, 2021). Once the fruit is detached from the tree, it no longer receives water from the roots; however, cellular respiration continues within the peel (Sriyook *et al.*, 1994). The process, represented by the general equation of cellular respiration (Equation (2)), produces water and releases heat (Skulachev *et al.*, 2023).



where ATP is adenosine triphosphate.

The heat generated during respiration accelerates water evaporation through the porous peel structure. Consequently, durian fruit experiences progressive weight loss during storage due to increased respiration and ethylene production, leading to peel shrinkage and fruit dehiscence (Booncherm and Siriphanich, 1991; Wiangsamut *et al.*, 2021).

The peel becomes increasingly permeable to water loss postharvest, as cell wall weakening and lenticel activity facilitate transpiration (Lindh *et al.*, 2021). When internal water pressure exceeds that of the external environment, water moves outward via osmotic pressure, a phenomenon referred to as transpiration from the peel. Although this physiological process begins while the fruit is still attached to the tree, it occurs at a relatively low and stable rate under those conditions (Gariglio *et al.*, 2024).

Postharvest, the intensity of both respiration and water loss increases significantly (Paull & Ketsa, 2014). Accordingly, transpiration in the peel is closely linked to ethylene production, the porous structure of the peel, and external environment (Ullah *et al.*, 2024).

C: Planting methods. These factors are directly related to growers' water management and fertilization practices (both soil and leaf) (Siriphanich, 2011; Wiangsamut and Wiangsamut 2023). Such practices depend on growers' experience and must take into account geographical characteristics, climatic conditions, and soil properties (Cheychom *et al.*, 2019).

D: Geographical origin. This study analyzed each province separately (see Table 1).

D1: Elevation. It uses the same principles as those of geographical origin.

D2: Flat/Terrace area. The study reported that terracing often facilitates better water management and nutrient distribution, promoting healthier root systems and overall tree vigor (Tan *et al.*, 2024). The distinction between flat and terraced areas in this study was based on how topography influenced soil conditions, leaf traits, and durian fruit development across different phenological stages. Terraced areas exhibited better drainage and higher soil temperature, pH, and N (nitrogen), phosphorus (P), and potassium (K) levels, whereas flatlands retained greater accumulated moisture (Tan *et al.*, 2024).

Therefore, topography should be considered an important factor, operating under the same principles as geographical origin.

E: Soil. Soil properties and soil conditions are partly influenced by geographic origin; however, optimized planting techniques, fertilization strategies, and water management, adjustments can

be tailored to climatic conditions and developmental stage of the crop. For example, the unproductive stage (S0) requires additional N, whereas the flowering stage (S1) demands increased P (Phanomsophon *et al.*, 2023). Water management is directly related to precipitation and depends on soil properties and conditions at each stage. During the fruiting stage (S2), greater precipitation is needed to support fruit development and ensure optimal carbohydrate accumulation in developing fruits (Thongkaew *et al.*, 2021). Conversely, S1 requires less water, with dry spells helping to synchronize flowering and related processes.

F: Climate data (Sources 1 and 2). The explanation is in Section 2.2.

F1: Climate data during transportation. The samples were transported by different courier agencies depending on the province. During transport, the ethylene process, respiration, and transpiration at the peel interact with external climatic conditions. These conditions vary according to the transportation methods employed by each courier company, making this factor specific to, and constant within, each province's transport route to the laboratory.

F2: Climate data in storage conditions. Climate data are assumed to be uniform across all provinces owing to controlled conditions.

G: Ethylene process. The process occurs throughout durian growth, both preharvest (90–120 DAA) and postharvest. This finding is supported by a study reporting that immature durians were harvested at 90 DAA (Sriyook *et al.*, 1994). The onset of dehiscence advanced by approximately one day, and the rate of dehiscence was higher in ethylene-treated fruit than in control fruit. Ethylene production became more pronounced as the fruit matured.

Another study reported that durian fruit weight loss increased during storage due to elevated respiration and ethylene production (Booncherm and Siriphanich, 1991). Therefore, it can be concluded that the ethylene process is linked to both respiration and transpiration in durian fruit (Sriyook *et al.*, 1991).

H: Respiration of the peel. This process is related to transpiration at the peel, as described in B1 (*Transpiration at the peel*), and is also associated with the ethylene process from preharvest (90-120 DAA) through postharvest, as described in G (*Ethylene process*).

I: Durian peel structure. The durian peel structure is formed preharvest through fruit growth and development, involving leaf respiration as described in Section A (*Photosynthesis*). This

process produces cell wall components rich in pectin, cellulose, and hemicellulose, which contribute to peel density and its capacity to absorb water (Onsawai *et al.*, 2021).

Leaf chlorophyll content, which reflects photosynthetic efficiency, influences the biochemical composition and development of the durian peel (Kondo *et al.*, 2017). Consequently, peel structure and biochemical properties vary across cultivation regions depending on climatic conditions, which affect cellular metabolism and the accumulation of pectin, cellulose, and hemicellulose, key components that contribute to peel density and water absorption capacity (Onsawai *et al.*, 2021).

At the cellular level, osmotic potential is determined by solute concentration within the cell (Jia *et al.*, 2020). In this study, the relationship between durian peel and pulp was examined. Ha *et al.* (2024) reported that fresh mesocarp layers adjacent to the peel contain higher water content. As the percentage of DM increases, water moves out of peel cells, leading to dehydration. This dehydration causes the mesocarp cell wall to become more rigid and reduces its water-holding capacity, thereby decreasing peel water content during ripening. A similar phenomenon has been observed in strawberries, where increased solute concentration elevates osmotic potential (Jia *et al.*, 2020). Thus, peel structure, DM percentage, and water content are interrelated.

Effect of plantation climate on durian

This study applied deductive reasoning to interpret the causes of observed phenomena, as illustrated in Figure 3. Two categories of factors

were considered: those occurring before harvest and those occurring after harvest. The postharvest period includes transportation and laboratory conditions, whereas the preharvest period encompasses Stage 0 (the unproductive stage, covering the first 1-4 years), Stage 1 (the flowering stage), Stage 2 (the fruiting stage), Stage 3 (the harvesting stage), and the stage at 120 DAA.

Measurements were initiated at the laboratory postharvest. The factors considered included B1, F, G, H and I (*I*: Durian peel structure), which emphasized on percentage of Dry matter (DM)). F2 was set to identical values across all provinces. Therefore, B1, G, H, and I are interrelated and should be considered. However, these factors were not measured quantitatively in this study, which led us to focus on the earlier stage. B1, G, H, and I were observed during transpiration postharvest, while G, H, and I were observed preharvest at 120 DAA, Stage 3, and Stage 2, respectively.

B1, G, H, and I were related to the water content in the durian peel, as detected by NIR absorption. Additionally, I appeared at 120 DAA, Stage 3, and Stage 2, and during postharvest (transportation and laboratory analysis), making it an essential indicator in this context. Focusing on I, its relevance to A and B reflects the preharvest formation of the peel structure at 120 DAA, Stage 3, and Stage 2, driven by fruit growth and development. Moreover, I was related to F, which itself is linked to A and/or B. Since I was consistently observed at 120 DAA, Stage 3, and Stage 2, D and E, originally determined by geographical origin, were also considered relevant at this stage.

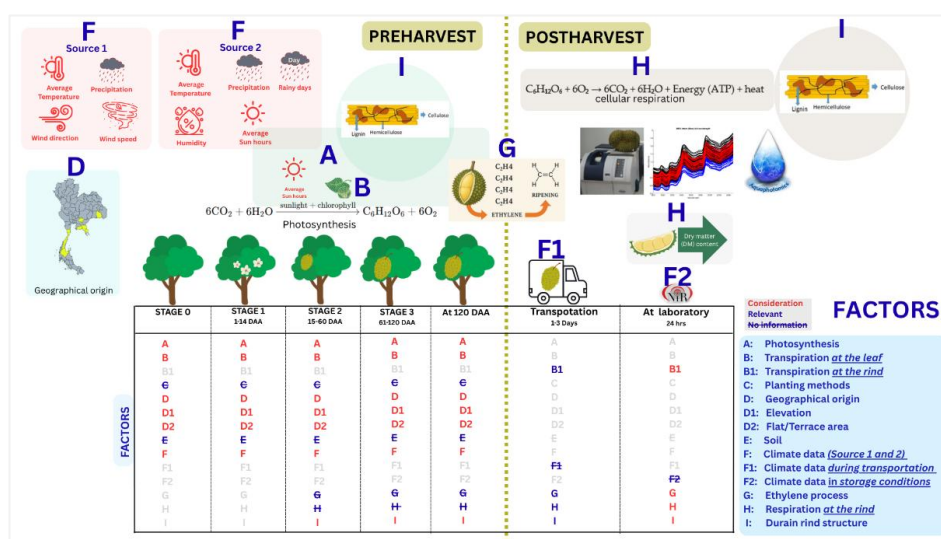


Figure 3. Factors affect water in the durian peel, which is detected by NIR absorption light

Table 2. Description of focusing factor data available based on provinces

Factors	Description	Provinces							
		Ra	Sri	Chom	PraJ	Su	T	PraCh	Chan
<i>B1: Transpiration at the peel</i>	It related to osmotic potential of water in the cells	No data and discussion is case by case							
<i>G: Ethylene process</i>	It is linked to both respiration and transpiration processes in durian fruit	No data and discussion is case by case							
<i>H: Respiration of the peel</i>	Related to transpiration at the peel	No data and discussion is case by case							
<i>I: Durian peel structure</i>	The durian peel structure is formed preharvest related to A (<i>A: Photosynthesis</i>)	No data and discussion is case by case							
<i>D: Geographical origin</i>	It is indicated origin by Geography, Latitude and Longitude	Province-specific differences (see Table 1)							
<i>D1: Elevation</i>	Elevation above sea level (m)	32	211	62	13	90	44	172	43
<i>D2: Flat/Terrace area*</i>	Flat or terrace areas significantly affect water and nutrient management efficiency	F	T	F	F	T	T	T	T
<i>F: Climate data (Source 1 and 2)</i>	Climate data (Source 1): the monthly average temperature (°C), precipitation (mm), humidity (%), number of rainy days (days), and average sunshine hours (hr)	Province-specific differences (see supplementary information, S1)							
	Climate data (Source 2): temperature (°C), precipitation (mm), wind direction (deg), and wind speed (kt)	Province-specific differences (see supplementary information, S2)							

*F:Flat, T:Terrace

Factor E can be adjusted according to climatic conditions and crop developmental stages; therefore, it was excluded from consideration. The analysis instead focused on the factors related to I. The available data included D, D1, D2, and F, as summarized in Table 2. These factors, which influence the water content in the durian peel, were evaluated in combination with aquaphotomic characteristics to examine the effect of plantation climate on the aquaphotomic properties of durian fruit.

Results and Discussion

Near infrared spectra characteristics

Figure 4 (a) presents the NIR spectra of intact durian samples from three regions: east (E), northeast (NE), and south (S). Figure 4(b) shows the average spectra of durian samples from eight provinces: Prachuap Khiri Khan (GI, (PraCh)), Chomphon (Chom), Surat Thani (Su), Chanthaburi (Chan), Prachin Buri (PraJ), Rayong (Ra), Trat (T), and Sisaket (Sri). In Figure 4 (a), the spectra of the NE region overlap with those of the E and S regions.

Figure 4 (b) shows that the average spectra exhibit similar patterns across all provinces. Although some separation among provinces and regions can be observed, this is primarily due to a baseline shift. Therefore, Standard Normal Variate (SNV) correction must be applied to the data to remove this artifact.

Figure 4 (c) compares the spectra of pure water with the average SNV spectra. Five absorption peaks were observed at 970, 1190, 1195, 1450, 1900, and 1940 nm. The peaks at 970, 1190, 1450, and 1940 nm correspond to characteristic water absorption bands (Omar *et al.*, 2012). The peak at 1195 nm is attributed to the second overtone of C-H stretching vibrations, specifically associated with CH₃ groups (Onsawai *et al.*, 2015). Additionally, a minor peak at 1780 nm was attributed to the first overtone of the C-H stretching vibrations, indicative of cellulose (Phanomsophon *et al.*, 2022).

Figure 5 (a) shows the SNV-pretreated spectra in the first overtone region of water vibrations (1300-1600 nm). The most prominent peak was observed at 1450 nm. The absorbance values ranged from -0.2 to 1.2. Considerable overlap of the spectra was evident among provinces or regions.

Figure 5(b) shows the SNV-pretreated spectra in the second overtone vibration bands of water (900-1020 nm), with absorption values ranging from -1 to -0.65. A fundamental principle of molecular vibrational spectroscopy in the NIR region is that the second overtone exhibits lower intensity than the first overtone. This occurs because vibrational overtone transitions become progressively less probable and weaker as the vibrational quantum number increases, due to anharmonicity and reduced transition dipole moments (Weyer *et al.*, 2022).

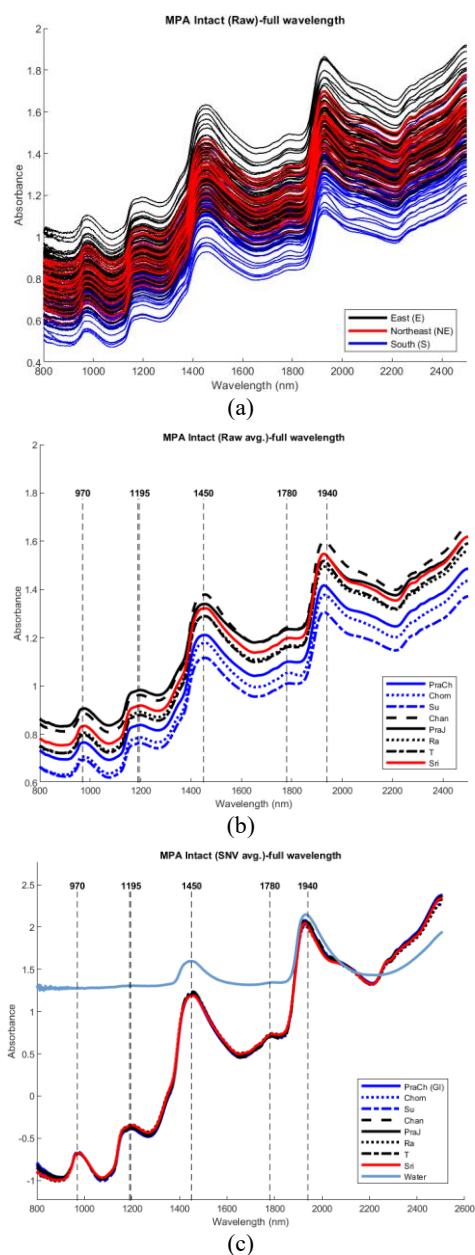


Figure 4. Spectral data of eight provinces (sorted by color in three different regions): every raw spectrum of durian samples (a), average raw spectrum of each province (b), SNV-pretreated of average spectrum of each province with, and spectrum of pure water (c)

This finding is consistent with previous reports, which indicated that the first and second overtones of C-H, O-H, and N-H stretching vibrations occur at 1660-1730/1200-1350 nm, 1360-1460/930-980 nm, and 1480-1560/1000-1100 nm, respectively (Weyer *et al.*, 2022). The most prominent peak was observed at 970 nm, where Su (South region) exhibited the highest absorption

value compared to the other provinces. Absorption values in the remaining provinces were relatively similar.

Additionally, significant differences were observed in the 900-940 nm range. The order of absorption values from lowest to highest was Ra > Sri > Chom > PraJ/Su > T > PraCh/Chan; however, this pattern did not correspond to regional groupings. Figure 5 (c) shows the average spectrum of each province alongside SNV-pretreated spectra and the spectra of pure water.

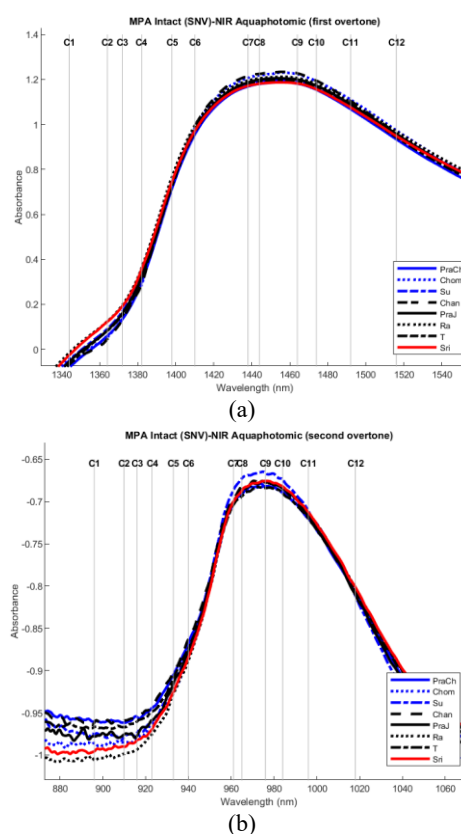


Figure 5. SNV pretreated spectra in the first overtone of water vibrations (1300-1600 nm) (a) and SNV pretreated spectra in the second overtone of water vibrations (900-1020 nm) (b)

Dry matter content

According to essential indicator I (*Durian peel structure*), the dry matter (DM) of durian pulp, which is closely related to its water content, is influenced by factors associated with osmotic pressure from both internal and external sources (see Section 2.6.1, definition of factors A to I). These include B1 (*Transpiration at the peel*), G (*Ethylene process*) cellular respiration, Equation (2) and H (*Respiration of the peel*).

Figure 6 presents the variation in the percentage of DM in durian pulp among provinces. ANOVA (Type II) revealed a significant provincial effect ($F = 6.96$, $p < 0.001$; data not shown). Tukey's HSD test indicated that PraCh and Su (group b) had significantly higher mean values than other provinces (group a). The complete measurement dataset, including all provincial values, is provided in Supplementary S3. These findings suggest that provincial differences may be influenced by environmental conditions. Although all samples were collected during the same harvesting period (120 DAA), the observed variations could be attributed to several interacting factors. These combined influences may have affected fruit development and physiological processes, thereby resulting in the differences in DM percentage among provinces.

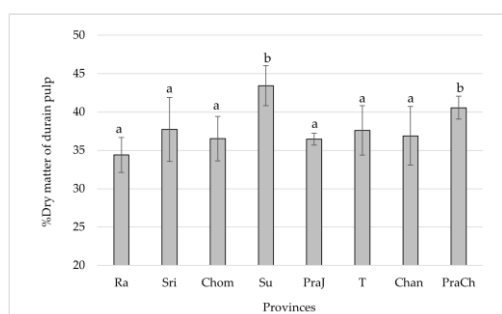


Figure 6. Mean comparison of the Dry matter (DM) of durian pulp among provinces

Aquaphotomic characteristic of peel of intact durian fruit

Table 3 summarizes and assigns characteristic water absorbance bands for selected first and second-overtone vibrations (Kaur, 1994; Muncan *et al.*, 2016; Muncan *et al.*, 2019). Figure 7 presents the aquagram in the first overtone region of water vibrations (1300-1600 nm), showing the NIR absorption of the peel of intact durian fruit obtained from SNV-pretreated spectra using the FT-NIR spectrometer.

The overall shape of the aquagram expands more strongly towards C7-C12, reflecting that the water structure in these samples is dominated by structured (bound) water rather than free water (Table 3). Bound water species are associated with water tightly linked to biological structures in the durian peel, such as cell walls, pectin, cellulose, and hemi-cellulose (Tsenkova *et al.*, 2018). In contrast, absorbance values at C1-C4 were relatively low, suggesting that free water species were present in smaller amounts than bound water (Tsenkova *et al.*, 2018).

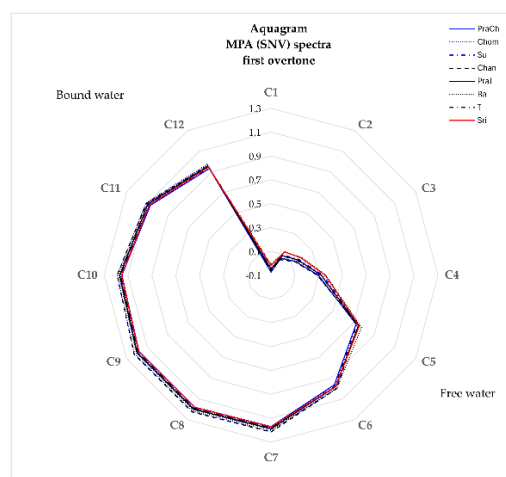


Figure 7. The aquagram in first overtone vibration of water molecule (1300-1600 nm) of NIR absorption retrieved from the SNV-pretreated spectrum of intact durian fruit

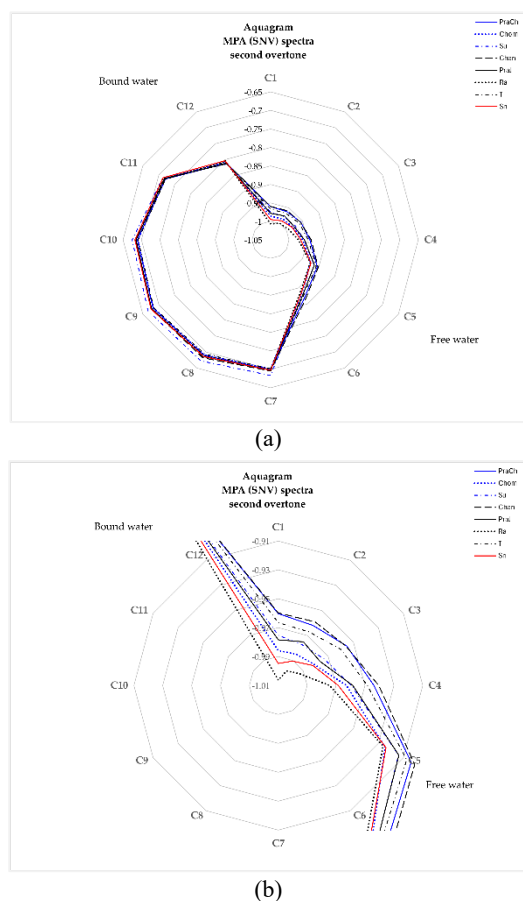
The durian peel across all provinces exhibited similar water spectral patterns, suggesting that the tissue contained a comparable water structure. However, differences in water quantity were reflected in variations in NIR absorption. Bound water predominated over free water, emphasizing the strong interaction of water molecules with biological structures in the durian peel (Bázár *et al.*, 2016).

Figure 8 (a) presents the aquagram of SNV-pretreated spectra of the second overtone region of vibrations (900-1100 nm), while Figure 8 (b) provides an enlarged view of absorption across coordinates C1-C6, corresponding to free water or water structures with weak or no hydrogen bonding (Kaur *et al.*, 2022).

This indicates the presence of loose structures with higher water mobility, however, NIR absorption of durian peel samples differed substantially among provinces than between C7-C12. Vibrations at C7-C12 are associated with bound water, or water structures stabilized by hydrogen bonds, ranging from ion-hydrated water to strongly bonded species (Green *et al.*, 2014). Such vibrations suggest a tight association of water with biomolecules in the durian peel, including cell walls, pectin, cellulose, and lignin. Observable differences among provinces were detected within C1-C4, reflecting distinct spectral variations likely influenced by geographic or environmental factors. Similar to the findings reported in Kaur's doctoral thesis on apple and kiwifruit (Kaur *et al.*, 2022), significant variations were associated with changes in temperature and environmental conditions (Kaur, 1994).

Table 3. Description of focusing factor data available based on provinces

WAMACs	Assignment	Related vibrations	First overtone region	Activated wavelengths	Second overtone region	Activated wavelengths
			1300–1600 (nm)		900–1100 (nm)	
C1	ν_3	Bulk water (H ₂ O asymmetric stretch)	1336–1348	1344	891–899	896
C2	OH stretch (water shell)	Weakly H-bonded, perturbed shell	1360–1366	1364	907–911	910
C3	$\nu_1 + \nu_3$	Symmetric + asymmetric H ₂ O vibrations	1370–1376	1372	913–917	916
C4	OH stretch (water shell)	Hydrated ions, structured shell	1380–1388	1382	920–925	923
C5	S_0	Free water (least bonded)	1398–1418	1398	932–945	933
C6	Water hydration, H ₂ O ₂	Hydration band (H ₂ O ₂)	1421–1430	1410	947–953	940
C7	S_1	1 H-bonded water molecule	1432–1444	1438	955–963	961
C8	$\nu_2 + \nu_3$	Bending + asymmetric stretching	1448–1454	1444	965–969	965
C9	S_2	2 H-bonded water molecule	1458–1468	1464	972–979	976
C10	S_3	3 H-bonded water molecule	1472–1482	1474	981–988	984
C11	S_4	4 H-bonded water molecule	1482–1495	1492	988–997	996
C12	Strongly bonded water or ν_1, ν_2	Symmetric stretch, highly structured	1506–1516	1516	1004–1011	1018

**Figure 8. Aquagrams of NIR absorption after raw spectra pretreated by SNV in second overtone vibration of water molecule (900–1100 nm) (a) and enlargement of the C1 to C6 (b)**

By ordering the values in ascending order, the following sequence was obtained: Ra > Sri > Chom > Su/PraJ > T > PraCh/Chan. WAMACs have been described with the following assignments: C1 (896 nm), corresponding to bulk water or the basic water structure; C2 (910 nm), indicating the solvation shell structure altered by external stimuli; C3 (916 nm), representing the joint vibration mode related to the state of water arrangement; C4 (923 nm), associated with water structures in the hydration shell and ion binding; and C5 (933 nm), corresponding to free water molecules (least H-bonded), which are sensitive to high temperatures (Kaur, 1994). At C5, ordering the values in ascending order yielded the following sequence:

Ra/Sri/Chom > Su/PraJ > T > PraCh > Chan.

Durian plantation climate data

Durian plantation climate data (Source 1)

Climate data of Source 1 represent daily averages compiled for each month from 1991 to 2021 across durian-producing provinces. The variables include: (a) average temperature (°C), (b) precipitation (mm), (c) number of rainy days (d), (d) relative humidity (%), and (e) average sunshine hours (hr). Data were collected for Prachuap Khiri Khan (PraCh), Chomphon (Chom), Surat Thani (Su), Chanthaburi (Chan), Prachin Buri (PraJ), Rayong (Ra), Trat (T), and Sisaket (Sri).

According to the essential factors, the DM of durian pulp, which is closely associated with its water content and with factors influencing osmotic potential from both internal and external sources,

plays a key role in clarifying the aquaphotomic characteristics of the peel in intact durian fruits. Table 4 presents the climate conditions of durian plantations across different provinces during Stage 3 (harvesting stage).

The aquagram of NIR absorption, obtained from SNV-pretreated raw spectra in second overtone region of water vibrations (900-1100 nm) with enlargement of coordinates C1-C6 (Figure 8 (b)), highlights the C1-C4 water matrix coordinates (WAMACs). The lowest absorption was observed in Ra, corresponding to the province's highest precipitation (Table 4) and the lowest percentage of DM content (Figure 6).

Precipitation events are typically associated with a drop in ambient temperature and an increase in relative humidity (Acero *et al.*, 2024). Transpiration is driven by the vapor pressure deficit (VPD), defined as the difference between the saturated vapor pressure inside the fruit and that of the surrounding air (Slabbert *et al.*, 2017). Under low VPD conditions, water transpiration slows, whereas changes in the percentage of DM can be explained in terms of osmotic potential. Postharvest, the peel becomes increasingly permeable to water loss as cell wall weakening and lenticel activity facilitate transpiration. Lenticels are associated with the porous structure of the peel (Zerbini *et al.*, 2020).

At the cellular level, osmotic potential refers to the water potential determined by the concentration of solutes inside the cell (Jia *et al.*, 2020). Water movement into or out of the cell reflects an equilibrium of water potential forces, maintaining balancing of water potential forces, where a decrease in osmotic potential draws water

into the cell (Jia *et al.*, 2020). In strawberries, solute concentration increases, resulting in higher osmotic potential (Jia *et al.*, 2020). In the case of Ra durian peel, water is transferred from the peel to the pulp to balance water potential, leading to lower water content in the peel. This was reflected by the lowest aquagram intensity among the studied provinces.

Conversely, the climate conditions in Chan were characterized by the lowest average temperature and the highest humidity. Such conditions reduce VPD, thereby slowing water loss (Ullah *et al.*, 2024). In other words, orchard temperature and humidity influence fruit physiology through a transpiration-driven water movement mechanism (Montanaro *et al.*, 2012). Accordingly, the aquagram in Figure 8 (b) shows that Chan durian peel contained higher water content, reflected by stronger water absorption at C1-C4.

The overlapping aquagram patterns observed for Su and PraJ may be attributed to their similar numbers of rainy days and sunshine hours. Likewise, the similarity in average temperature and sunshine hours between PraCh and Chan contributed to comparable spectral responses. The interrelationship among rainy days, sunshine hours, and average temperature is linked to the internal temperature of the growing fruit, reflecting energy exchange associated with fruit metabolic activity, energy conductance, and evapotranspiration (Ferguson and Triggs, 1990). Therefore, rainy days, sunshine hours, and average temperature collectively influence the amount of free water in the durian peel, resulting in comparable aquaphotomic responses among those provinces.

Table 4. Climate data of durian plantations in different provinces in stage 3 (harvesting stage) from source 1

Stage 3	Ra	Sri	Chom	Su	PraJ	T	Chan	PraCh
Avg. Temperature (°C)	28.1	29.2	27.8	27.2	28.3	27.1	27.1	27.2
Humidity (%)	81%	66%	81%	81%	73%	84%	84%	81%
Precipitation (mm)	226	146	108	113	116	188	113	186
Rainy day (days)	16	12	14	12	12	18	16	19
Avg. Sun hours (hr)	9	10	10	10	9	8	9	9

Table 5. Climate data of durian plantations in different provinces at 120 DAA and stage 3 (harvesting stage) from source 2

At 120 DAA	Ra	Sri	Chom	Su	PraJ	T	Chan	PraCh
Avg. Temperature (°C)	29.5	29.1	27.4	27.6	31.5	29.2	30.1	29.5
Precipitation (mm)	2	4	3	0	0	27	0	0
Wind direction (deg)	230.0	245.0	300.0	110.0	90.0	50.0	195.0	205.0
Wind speed (kt)	12.0	7.5	13.0	5.0	8.0	19.0	10.5	12.5
Stage 3	Ra	Sri	Chom	Su	PraJ	T	Chan	PraCh
Avg. Temperature (°C)	30.3	30.3	28.9	28.4	31.4	28.9	29.4	29.7
Precipitation (mm)	14	17	14	10	11	13	13	16
Wind direction (deg)	212.8	171.8	144.5	203.8	197.6	145.7	153.1	203.4
Wind speed (kt)	9.6	5.9	13.4	14.7	7.6	11.4	12.7	14.5

Durian plantation climate data (Source 2)

Climate data from Source 2 (2019-2020), including measurements of temperature (°C), precipitation (mm), wind direction (deg), and wind speed (kt), were taken into consideration for durian plantations in Prachuap Khiri Khan (PraCh), Chomphon (Chom), Surat Thani (Su), Chanthaburi (Chan), Prachin Buri (PraJ), Rayong (Ra), Trat (T), and Sisaket (Sri).

Table 5 presents the climate conditions of durian plantations across different provinces at 120 DAA and during the harvesting stage (S3). The distinct differences in C1-C4 water matrix coordinates (WAMACs) of durian peel among provinces are shown in Figure 8 (b). At 120 DAA, precipitation of 0 mm was recorded in Su and PraJ as well as in PraCh and Chan (Table 5), which exhibited similar aquagram intensity, indicating closely comparable free water signals.

The aquagram in Figure 8 (b) shows greater water loss was in Su durian peel, which may be due to differences in climate condition between Su and PraJ, including temperature (12%), wind direction (17%), and wind speed (37%). These differences are reflected in the gap at C3 (916 nm), representing the joint vibrational modes of O-H stretching that have been associated with the reorganization of water molecular structures under environmental perturbations (Tsenkova, 2018).

Changes may occur during biological processes involving dehydration (Munéan & Tsenkova, 2019). In durian peel, dehydration progresses as the fruit loses water during ripening (Booncherm and Siriphanich, 1991), which was evident in the Su and PraJ samples. In contrast, PraCh and Chan showed greater overlap in aquagram intensity, reflecting minimal differences in climate conditions, with closely similar values for temperature, wind direction, wind speed, and precipitation. From the perspective of DM content in pulp, Su (DM=43.42%) and PraJ (DM=36.45%) exhibited a larger difference compared to PraCh (DM= 40.55%) and Chan (DM=36.89%), indicating that climatic effects were more pronounced in Su and PraJ.

Conclusions

The objective of this study was to investigate the effect of plantation climate on the aquaphotomic characteristics of durian (*Durio zibethinus* Merr. cv. Monthong) fruit. Two categories of influencing factors were considered: preharvest and postharvest. The postharvest stage encompassed transportation and laboratory measurement conditions, whereas the preharvest stage comprised:

stage 0 (S0), the unproductive stage covering the first 1-4 years; stage 1 (S1), the flowering stage; stage 2 (S2), the fruiting stage; stage 3 (S3), the harvesting stage and 120 DAA. The S3 and 120 DAA durian samples exhibited characteristics closely aligned with those measured by FT-NIR spectrometer in the laboratory.

The conclusion emphasized the major outcomes and their implications, highlighting both scientific significance and practical importance. Specifically, the main effects of climate differences on the transpiration and respiration of the durian peel, as well as the osmotic potential of water in the pulp, were discussed. These effects influenced peel water content through factors such as precipitation, average temperature, humidity, number of rainy days, sunshine hours at stage 3, as well as precipitation at 120 DAA.

These aquaphotomic patterns observed support the potential of NIR-based water spectral profiling as a tool for distinguishing the geographical origin of durian and for understanding the relationship between environmental conditions and peel water content. This discovery contributes novelty to the scientific community by expanding the application of NIRS and aquaphotomics in fruit physiology and geographical origin identification.

However, this conclusion is based on retrospectively collected climate data and their observed effects on the aquagram. Future research should therefore incorporate real-time field measurements of fruit transpiration, respiration, and ethylene emission to validate these climate-induced aquaphotomic variations. The integration would strengthen their application in durian quality monitoring during postharvest handling and storage, as well as in climate-adaptive cultivation strategies.

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