

Research article

ADVANCED QUALITY CHARACTERIZATION OF COMMERCIAL THAI ARABICA GREEN COFFEE BEANS USING SYNCHROTRON FTIR MICROSCPECTROSCOPY AND X-RAY TOMOGRAPHY

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<https://doi.org/10.34302/crpjfst/UGBA4598>

Article history:

Received:

November 25th, 2025

Accepted:

August 25th, 2026

Published

September 20th, 2026

Keywords:

Thai Arabica coffee beans;
Synchrotron-based FTIR
microspectroscopy,
Synchrotron X-ray
tomographic microscopy,
Microstructure;
Biochemical fingerprint.

ABSTRACT

Thai Arabica coffee has gained increasing recognition in the specialty coffee market due to its distinctive quality attributes and continuing development in post-harvest handling. This study applied synchrotron-based techniques for advanced quality characterization of commercially obtained Thai Arabica green coffee beans representing four post-harvest processing types: dry, washed, honey, and low-temperature/low-humidity (LTLH). Moisture content was determined in triplicate for each commercial sample. Synchrotron Fourier transform infrared (SR-FTIR) microspectroscopy, combined with second-derivative spectral preprocessing and principal component analysis (PCA), was applied to evaluate biochemical fingerprints associated with lipid-, protein-, and carbohydrate-related constituents, which are important quality-related components and potential contributors to aroma and flavor development during roasting. Approximately 50 spectra were initially acquired across three separately prepared subsamples for each processing type. Moisture contents differed significantly ($p < 0.05$) among the commercial samples, with LTLH beans showing the lowest value ($10.48 \pm 0.37\%$) and honey-processed beans showing the highest value ($12.64 \pm 0.09\%$). PCA of the SR-FTIR spectra showed clustering trends among the four commercial sample groups, with PC1 and PC2 explaining 15% and 12% of the total spectral variance, respectively. Dry-processed beans exhibited relatively stronger lipid- and ester-associated spectral features, whereas the LTLH sample showed more pronounced carbohydrate/polysaccharide-related features. Complementary synchrotron X-ray tomographic microscopy (XTM), performed on three representative beans per processing type, provided non-destructive three-dimensional visualization of representative internal air-channel organization and dense bean matrix structure. The LTLH sample showed a more continuous and well-defined air-channel pattern in the representative XTM images. Since

the coffee beans were commercially obtained and were not experimentally processed under controlled conditions by the authors, the observed differences should be interpreted as comparative quality-related characteristics rather than direct causal effects of specific processing parameters. Overall, the integration of SR-FTIR microspectroscopy and XTM provides complementary biochemical and structural information that may support advanced quality assessment of commercial Thai Arabica green coffee beans.

1. Introduction

Green coffee bean quality is determined by a complex combination of biochemical composition and internal physical structure. Major constituents such as lipids, polysaccharides, proteins, chlorogenic acids, caffeine, trigonelline, and other cell-wall-associated compounds contribute to the formation of aroma precursors, roasting behavior, extraction characteristics, and overall beverage quality (Wang & Lim, 2012; Aung Moon et al., 2024). In green coffee beans, lipids are associated with aroma retention and mouthfeel, while polysaccharides and cell-wall materials influence bean hardness, porosity development, heat transfer, and the release of volatile compounds during roasting (Schenker et al., 2000; Li et al., 2021; Al-Shemmeri et al., 2024). Therefore, understanding both the chemical composition and internal microstructure of green coffee beans is essential for evaluating coffee quality beyond conventional grading and sensory assessment.

Post-harvest processing is one of the key factors influencing the biochemical and structural characteristics of coffee beans. Processing types such as dry, washed, honey, and controlled drying differ in the degree of mucilage retention, microbial activity, drying rate, moisture removal, and exposure of the bean to fruit-derived compounds (Zhang et al., 2019; Jakkaew et al., 2024; Coelho et al., 2024; Aung Moon et al., 2024). These differences can modify the chemical matrix of green coffee beans, particularly lipid-associated, protein-associated, phenolic-associated, and carbohydrate-related components (Aung Moon et al., 2024). They may also influence internal structural organization by affecting

dehydration stress, cell-wall integrity, and air-channel formation within the bean (Schenker et al., 2000; Dong et al., 2018). Such chemical and structural differences are especially relevant for specialty coffee, where consistency in roasting performance and quality attributes is highly valued.

Thailand's Arabica coffee sector has developed rapidly in recent years, particularly in highland areas such as Chiang Rai and Chiang Mai, where agro-climatic conditions are suitable for specialty Arabica production (Noppakoonwong et al., 2015; Aung Moon et al., 2024). Commercial Thai Arabica coffee is increasingly available in several post-harvest processing types, including washed, dry, honey, and controlled low-temperature drying. However, integrated studies combining SR-FTIR microspectroscopy and synchrotron XTM to jointly evaluate the biochemical fingerprints and internal microstructure of commercially processed Thai Arabica green coffee beans remain scarce. Most routine quality evaluations rely on moisture content, physical grading, and sensory assessment, which are useful but provide incomplete information on the molecular and structural basis of bean quality (Castillejos-Mijangos et al., 2022; Aung Moon et al., 2024).

Fourier transform infrared (FTIR) spectroscopy has been widely applied as a rapid vibrational spectroscopic technique for characterizing coffee composition, including lipid-associated bands, ester carbonyl groups, protein-related amide bands, and carbohydrate fingerprint regions (Wang & Lim, 2012; Weldegebreal et al., 2017; Castillejos-Mijangos et al., 2022). When combined with multivariate analysis such as principal component analysis (PCA), FTIR can

differentiate coffee samples according to origin, processing, storage condition, and chemical composition (Castillejos-Mijangos et al., 2022; Aung Moon et al., 2024). Synchrotron-based FTIR microspectroscopy offers additional advantages because the high brightness of synchrotron radiation enables spectra to be collected from small sampling areas with improved signal-to-noise characteristics. This is particularly useful for studying heterogeneous biological materials such as coffee beans, in which biochemical composition may vary at the microscale.

In addition to chemical fingerprinting, internal microstructural information is important for understanding coffee quality. X-ray tomographic microscopy (XTM) provides non-destructive three-dimensional visualization of internal features such as air channels, dense bean matrix, and structural continuity (Schoeman et al., 2016). These microstructural characteristics may affect heat and mass transfer during roasting and may therefore contribute to differences in roasting uniformity and quality consistency (Schenker et al., 2000; Al-Shemmeri et al., 2024). The integration of SR-FTIR and XTM can provide complementary biochemical and structural observation.

In the present study, commercially obtained Thai Arabica green coffee beans representing four post-harvest processing types—dry, washed, honey, and low-temperature/low-humidity (LTLH)—were characterized using synchrotron FTIR microspectroscopy and synchrotron X-ray tomographic microscopy. The samples were not experimentally processed by the authors; rather, they were analyzed as commercial green coffee beans representing different processing types. The objectives of this study were to (i) compare the biochemical fingerprints of commercial Thai Arabica green coffee beans using SR-FTIR microspectroscopy and PCA, (ii) visualize representative internal microstructural features using XTM, and (iii) evaluate how combined chemical and structural information may

support advanced quality assessment of Thai specialty coffee.

2. Materials and Methods

2.1. Sample collection

Commercial Thai Arabica green coffee beans (*Coffea arabica* L.) representing four post-harvest processing types, namely dry, washed, honey and low-temperature/low-humidity (LTLH), were used in this study. The dry-, washed-, and honey-processed green coffee beans were obtained from a local commercial coffee producer in Doi Chang, Chiang Rai Province, northern Thailand. The LTLH green coffee bean samples were obtained from Preda Roasting House, Lampang Province, Thailand. All samples were purchased as finished green coffee beans after commercial post-harvest processing. Therefore, the authors did not experimentally perform, control, or modify the post-harvest processing conditions. The processing types used in this study were based on information provided by the producer and the commercial classification of the samples.

The dry-processed beans represented naturally processed coffee, in which whole coffee cherries were dried before removing the outer fruit layers. The washed beans represented coffee processed by pulp removal and mucilage removal prior to drying. The honey-processed beans represented coffee in which partial mucilage was retained during drying. The LTLH beans represented coffee dried under a controlled low-temperature and low-humidity condition, as described by the producer. Since all samples were commercially obtained, detailed commercial processing parameters, including exact drying duration, airflow rate, drying-layer thickness, turning frequency, and batch-to-batch environmental variation, were not controlled by the authors. This limitation was considered when interpreting the results. After purchase, the green coffee bean samples were kept in sealed plastic bags and stored in a refrigerator at 4 °C. This storage condition was used to minimize moisture uptake and reduce potential

compositional changes before analysis. Prior to analysis, beans with visible physical defects were removed. Representative beans from each commercial processing category were used for moisture content determination, synchrotron FTIR microspectroscopy, and synchrotron X-ray tomographic microscopy.

2.2. Moisture Content Determination

Moisture content of green coffee beans was determined using the oven-drying method based on the gravimetric loss in mass at 105 °C, following the principle described in ISO 6673:2003 (International Organization for Standardization, 2003) for green coffee moisture analysis. Approximately 10 g of whole coffee beans were placed in pre-weighed aluminum moisture cans and dried in a hot-air oven at 105 °C until constant weight was achieved. Moisture content (%) was calculated from the difference between the initial and final sample mass using the following equation:

Moisture content (%)

$$= \frac{(\text{Initial weight} - \text{Dried weight})}{\text{Initial weight}} \times 100$$

(1)

Moisture content was determined in triplicate for each commercial sample ($n = 3$). The results were expressed as mean $\pm$ standard deviation. Statistical differences among the commercial samples were evaluated using one-way analysis of variance (ANOVA), followed by Duncan's Multiple Range Test (DMRT) at the 95% confidence level ($p < 0.05$), using SPSS software version 26.0 (IBM Corp., Armonk, NY, USA).

2.3. Synchrotron FTIR Microspectroscopy (SR-FTIR)

Synchrotron-based Fourier transform infrared (SR-FTIR) microspectroscopy was performed at the BL4.1 beamline of the Synchrotron Light Research Institute (SLRI), Nakhon Ratchasima, Thailand. For SR-FTIR

analysis, three separate subsamples, each weighing approximately 50 g, were randomly collected from each commercial processing type. Each subsample was ground separately and thoroughly homogenized. A small amount of each ground sample was compressed between diamond windows of a diamond anvil cell to form a thin film suitable for the transmission-mode FTIR measurement. FTIR spectra were collected in transmission mode over the mid-infrared range of 4000-800 cm^{-1} using synchrotron radiation as the infrared source. Spectra were acquired at a spectral resolution of 6 cm^{-1} , with 32 scans accumulated per spectrum. The aperture size was $30 \times 30 \mu\text{m}^2$. Background spectra were collected under the same instrumental conditions before sample measurement and were used for spectral correction. Approximately 50 spectra in total were initially acquired from multiple representative positions across the three prepared subsamples for each processing type. Following spectral quality screening, spectra with poor signal quality, excessive scattering, or strong atmospheric interference were excluded, and the remaining valid spectra were used for spectral preprocessing. Second-derivative transformation was applied to enhance overlapping bands and resolve subtle spectral differences. Extended multiplicative signal correction (EMSC) was used to reduce baseline variation and scattering effects. Principal component analysis (PCA) was subsequently performed using The Unscrambler X software (version 10.1) to explore biochemical variation among green coffee bean samples representing different commercial processing types. Major absorption regions used for interpretation included lipid-associated CH_2 stretching vibrations around 2924 and 2854 cm^{-1} , ester carbonyl absorption around 1745 cm^{-1} , protein-associated amide bands at approximately 1642, 1548, and 1531 cm^{-1} and carbohydrate/polysaccharide fingerprint regions around 1200-1000 cm^{-1} . Band assignments were interpreted based on

previous FTIR studies of coffee and food matrices.

2.4. Synchrotron X-ray Tomographic Microscopy (XTM)

Synchrotron X-ray tomographic microscopy (XTM) was performed at Beamline 1.2W of the Synchrotron Light Research Institute (SLRI), Thailand. For XTM analysis, three representative green coffee beans from each commercial processing type were selected (based on available synchrotron beamtime) for internal microstructural visualization. Each bean was secured on a metal rod using adhesive and mounted on the rotation stage for tomographic scanning. The synchrotron storage ring operated at 1.2 GeV and 150 mA. A 350- μm alumina foil was used as an attenuator to reduce imaging artifacts and adjust the X-ray intensity to a suitable level for coffee bean imaging. The mean X-ray energy was approximately 11.5 keV. The detection system consisted of a 100- μm -thick YAG:Ce scintillator (Crytur, Czech Republic), a lens-coupled X-ray microscope (Optique Peter, France), and an sCMOS camera (Andor NEO 5.5; 2560×2160 pixels, 16-bit), providing an effective optical pixel size of 3.61 μm . Due to the limited field of view, each bean was scanned at three consecutive sample positions to cover the entire bean. Therefore, nine tomographic scans were acquired for each commercial processing type (three scans per bean across three representative beans). For each tomographic scan, X-ray projection images were collected over 180° rotation with an angular step of 0.3° . Projection images were corrected using background normalization before reconstruction. Tomographic reconstruction was performed using Octopus Reconstruction software (TESCAN, Gent, Belgium). For each bean, the three reconstructed volumes corresponding to the three scan positions were subsequently stitched to generate a complete three-

dimensional dataset. The reconstructed image volumes were further analyzed using Octopus Analysis software to visualize internal air-channel structures and dense bean matrix. Three-dimensional volume renderings were generated with Drishti software.

The reconstructed XTM images were used for qualitative visualization and descriptive comparison of internal microstructural features among the commercial green coffee bean samples. Since three representative beans from each processing category were analyzed based on the available synchrotron beamtime, the XTM results were interpreted as representative microstructural observations rather than as a fully replicated quantitative pore-network analysis.

3. Results and Discussion

3.1. Moisture content of green coffee beans

The moisture content of commercial Thai Arabica green coffee beans differed among the four post-harvest processing types (Table 1). The honey-processed beans showed the highest moisture content ($12.64 \pm 0.09\%$), followed by washed beans ($11.30 \pm 0.13\%$) and dry-processed beans ($11.19 \pm 0.25\%$). In contrast, the LTLH beans exhibited the lowest moisture content ($10.48 \pm 0.37\%$). These differences indicate that the commercial coffee samples varied in their residual moisture levels at the time of analysis.

Although the beans were commercially obtained and post-harvest processing conditions were not controlled by the authors, the moisture results provide useful supporting information for interpretation of the subsequent spectroscopic and microstructural observations. The relatively lower moisture content of the LTLH beans may be associated with more controlled dehydration, whereas the higher moisture content of the honey-processed beans may reflect the influence of mucilage retention and drying process.

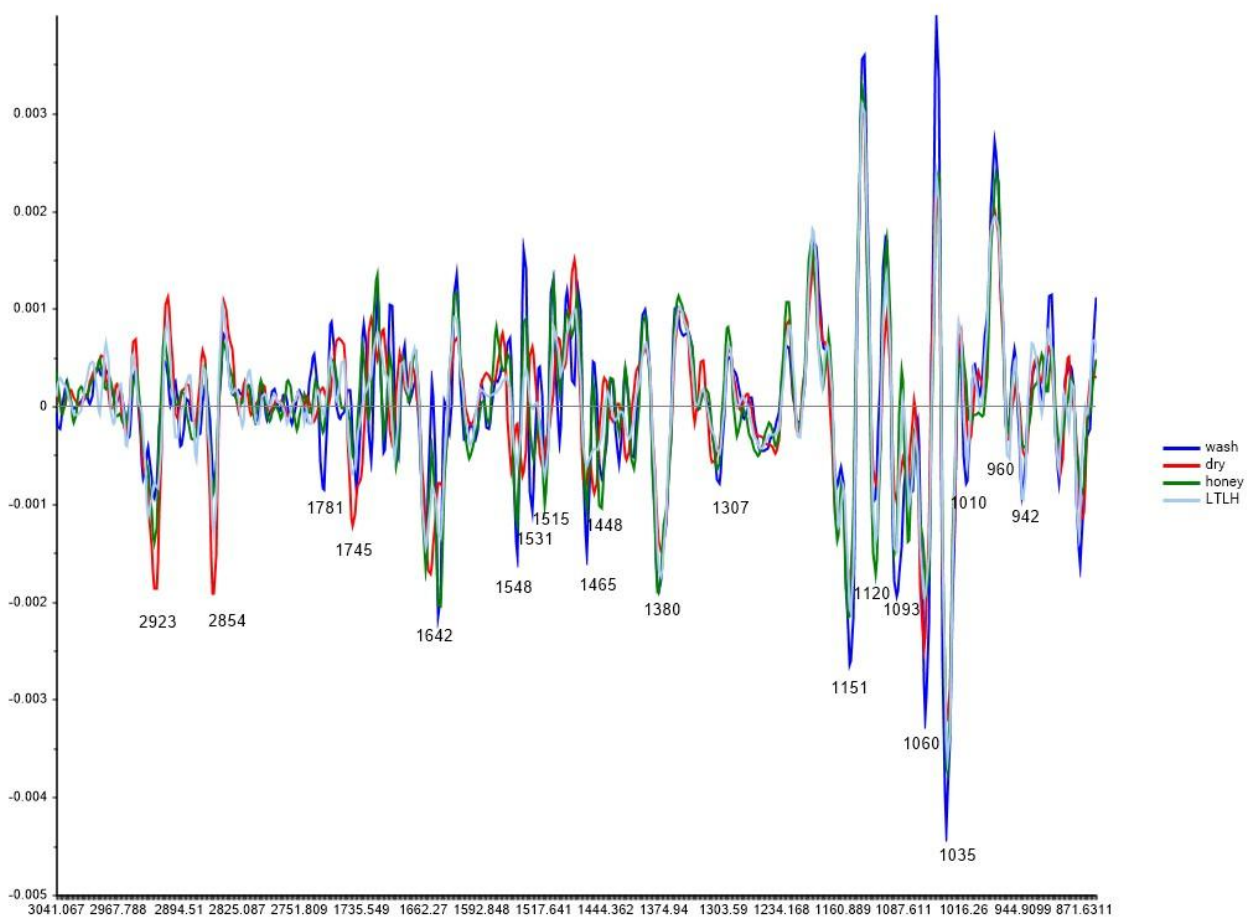
Table 1. Moisture content (%MC) of Thai Arabica green coffee beans classified by post- harvest processing type

Post-harvest preprocessing type	% MC
Washed	11.30±0.13 ^b
Dry	11.19±0.25 ^b
Honey	12.64±0.09 ^c
LTLH	10.48±0.37 ^a

Previous studies have shown that drying methods can affect the final moisture and physicochemical characteristics of Arabica coffee beans (Coelho et al., 2024; Aung Moon et al., 2024). However, these interpretations should be considered comparative observations among commercial samples

rather than direct causal effects of controlled processing parameters.

Data are presented as Mean ± Standard Deviation. Values followed by different lowercase letters in the same column are significantly different at the 95% confidence level ($p < 0.05$).

**Figure 1.** Average second-derivative FTIR spectra of commercial Thai Arabica green coffee beans. Differences were observed in lipid-, protein-, and polysaccharide-related spectral regions, indicating biochemical variation among the commercial processing types.

3.2. Synchrotron FTIR spectral characteristics

Average second-derivative SR-FTIR spectra of the green coffee bean samples are shown in Figure 1. The spectra revealed characteristic absorption bands associated with major biochemical constituents of coffee beans. Prominent differences were observed in lipid-associated CH_2 stretching bands at approximately 2924 and 2854 cm^{-1} , ester carbonyl absorption band around 1745 cm^{-1} , amide/protein-associated bands at approximately 1642 , 1548 , and 1531 cm^{-1} , and carbohydrate/polysaccharide-related fingerprint regions between 1200 and 1000 cm^{-1} . These spectral regions are commonly associated with lipids, proteins, polysaccharides, and other compounds associated with the cell wall in coffee matrices (Wang & Lim, 2012; Castillejos-Mijangos et al., 2022).

Dry-processed beans showed relatively stronger lipid-associated spectral features, particularly in the CH_2 stretching region at 2924 and 2854 cm^{-1} and ester carbonyl region around 1745 cm^{-1} . This suggests a relatively higher contribution of lipid-related molecular

features in the analyzed micro-regions of the dry-processed beans. In contrast, the LTLH beans exhibited more pronounced spectral features in the carbohydrate/polysaccharide fingerprint region, suggesting a stronger contribution of cell-wall-associated polysaccharide structures. Meanwhile, washed and honey-processed beans showed intermediate spectral patterns. The major FTIR bands used for interpretation are summarized in Table 2.

The amide-related region also exhibited differences among the sample groups, particularly around bands 1642 , 1548 , and 1531 cm^{-1} . These bands are mainly associated with protein-related amide I and amide II vibrations, although overlapping contributions from aromatic or phenolic compounds may also be present. Previous studies have shown that post-harvest processing can affect protein modification and phenolic-associated changes in green coffee beans (Figuerola Campos et al., 2022). Therefore, the observed spectral variation suggests differences in the relative contributions of lipid-, protein-, and carbohydrate-associated biochemical features among the commercial samples.

Table 2. Major FTIR band assignments and observed spectral trend among commercial processing types.

Wavenumber region (cm^{-1})	Band assignment	Observed trend in this study
2924 and 2854	Lipid-related CH_2 asymmetric and symmetric stretching vibrations	Relatively more pronounced in dry-processed beans
1745	Ester $\text{C}=\text{O}$ stretching associated with lipid ester/carbonyl containing compounds	Relatively more pronounced in dry-processed beans
1642, 1548, and 1531	Protein-associated amide I and II bands, with possible overlapping contributions from aromatic/phenolic compounds	Minor spectral differences observed among commercial processing types
1200-1000	Carbohydrate/polysaccharide fingerprint region, mainly $\text{C}-\text{O}$ and $\text{C}-\text{O}-\text{C}$ vibrations of cell-wall-associated compounds	Relatively more pronounced in LTLH beans

3.3. PCA analysis of SR-FTIR spectra

Principal component analysis (PCA) was applied to the second-derivative FTIR spectra to explore biochemical variation among the washed, dry, honey, and LTLH commercial coffee samples. As shown in Figure 2, the PCA score plot revealed clustering trends among the four commercial sample groups, indicating variation in their biochemical fingerprints. FTIR spectroscopy combined with multivariate analysis has been widely reported as a useful tool for coffee quality evaluation, authentication, and discrimination based on chemical fingerprints (Wang & Lim, 2012; Castillejos-Mijangos et al., 2022).

PC1 explained 15% of the total spectral variance. Along this component, the dry and LTLH samples were located mainly on the negative side, whereas the washed and honey-processed samples were located on the positive side. PC2 explained a further 12% of the spectral variance and described additional variation in the sample positioning, particularly between the LTLH and dry-processed samples. Together, PC1 and PC2 accounted for 27% of the total spectral variance. The honey-processed sample group showed an intermediate clustering pattern.

Because the coffee beans were commercially obtained and were not

experimentally processed under controlled conditions by the authors, PCA was used as an exploratory multivariate analysis. Accordingly, the clustering trends should be interpreted as comparative biochemical variation among the commercial sample groups rather than as inferential statistical evidence or direct evidence of processing effects. Nevertheless, these trends may be considered in the context of previous reports showing that post-harvest processing and drying conditions can influence the physicochemical properties and metabolite profiles of Arabica coffee beans (Zhang et al., 2019; Aung Moon et al., 2024).

To aid interpretation of the biochemical variation observed in the PCA score plot, the average second-derivative spectra (Figure 1) and FTIR band assignments (Table 2) were considered together. Descriptive comparison of the average spectra showed apparent variation in lipid-related bands, ester carbonyl absorption, amide/protein-associated bands, and carbohydrate/polysaccharide fingerprint regions. Taken together, the results demonstrate the potential of SR-FTIR microspectroscopy combined with PCA as a rapid biochemical fingerprinting approach for the quality characterization of commercial Thai Arabica green coffee beans.

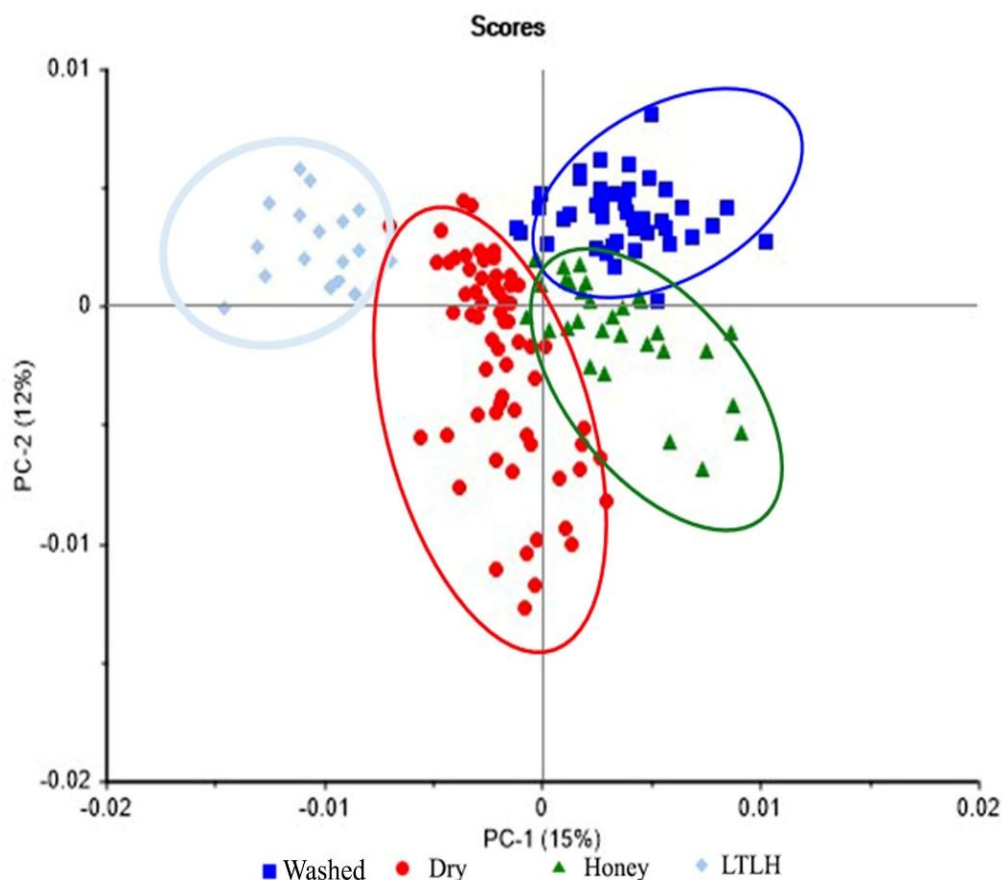


Figure 2. PCA score plot of second-derivative FTIR spectra of commercial Thai Arabica green coffee beans. The score plot shows clustering trends among the washed, dry, honey, and LTLH commercial sample groups, indicating variation in their biochemical fingerprints. The ellipses are included as visual guides to illustrate clustering patterns and do not represent statistical confidence regions.

3.4. Microstructural Characterization by XTM

Synchrotron X-ray tomographic microscopy (XTM) was applied to visualize the internal microstructural features of representative green coffee beans from each commercial processing type (Figure 3). XTM provides non-destructive three-dimensional visualization of internal structures in food materials, allowing observation of internal air spaces and matrix organization without physical sectioning (Schoeman et al., 2016). In the present study, the reconstructed

tomographic images visualized the internal air-channel network and dense bean matrix of the Arabica green coffee beans. Visual comparison of the representative XTM images indicated apparent differences in air-channel distribution, continuity, and structural organization among the commercial samples.

The representative washed and honey-processed beans appeared to exhibit relatively uniform air-channel distributions, whereas the dry-processed beans appeared to have more heterogeneous internal air-channel arrangements. The representative LTLH

sample showed a more continuous and well-defined air-channel pattern than the other commercial samples. One possible explanation is that differences in dehydration rate and moisture-removal history may influence the internal structural organization of green coffee beans. However, because the samples were commercially obtained and were not processed under controlled conditions by the authors, these interpretations should be considered possible mechanisms rather than confirmed causal relationships. In addition, because the LTLH sample was obtained from a different commercial source, potential source- and lot-related variation could not be separated from variation associated with the commercial processing classifications. Nevertheless, these observations suggest that XTM can provide

useful complementary information on the internal structure of green coffee beans, particularly in relation to air-channel organization and matrix continuity.

Previous studies have reported that drying or thermal processing conditions can influence the microstructure and pore characteristics of coffee beans and other food materials. Dong et al. (2018) showed that microwave-vacuum drying affected the drying characteristics, color, microstructure, and antioxidant activity of green coffee beans. Schenker et al. (2000) also demonstrated that roasting conditions affected coffee bean pore structure, which is relevant to heat and mass transfer during roasting. These studies provide useful context for interpreting the apparent structural variation observed in the present XTM images.

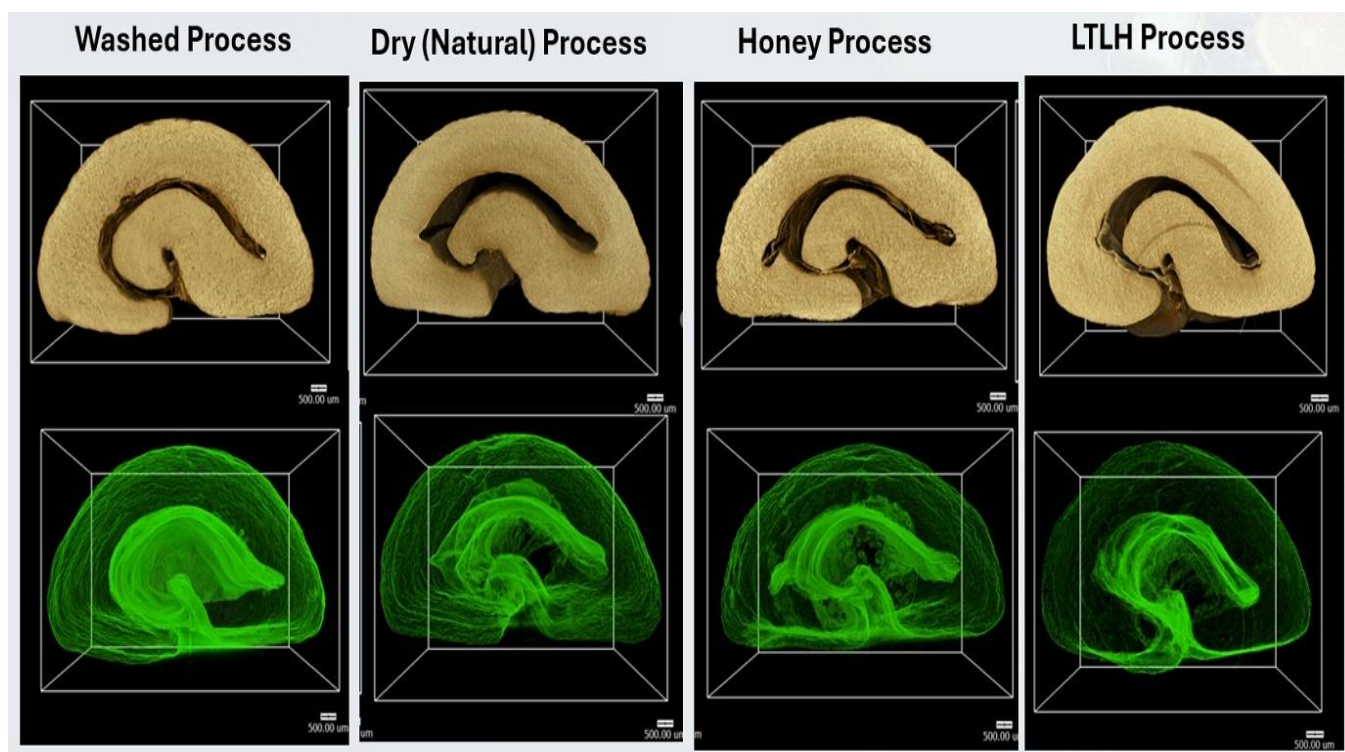


Figure 3. Representative X-ray tomographic microscopy (XTM) images of commercial Thai Arabica green coffee beans representing washed, dry, honey, and LTLH processing types. Green regions represent internal air channels, whereas black regions correspond to dense coffee bean matrix. Apparent differences in air-channel continuity and structural organization were observed among the commercial samples. The XTM images are representative and were used for qualitative visualization and descriptive comparison rather than quantitative pore-network analysis.

In this study, the XTM analysis was intended for qualitative visualization and descriptive comparison of representative internal structures. Due to the limited synchrotron beamtime, three representative beans from each commercial processing type were analyzed. Quantitative image segmentation and morphometric analysis were not performed; consequently, no statistical comparison of pore-network parameters was conducted. Further studies using larger sample numbers and validated quantitative morphometric analysis, including porosity, pore-size distribution, connectivity, and tortuosity, are required to confirm these structural trends.

3.5. Combined Interpretation of Biochemical and Microstructural Features

The integration of SR-FTIR and XTM observations provided complementary information on the biochemical and structural characteristics of the commercial Thai Arabica green coffee bean samples. SR-FTIR microspectroscopy showed variation in lipid-, protein and carbohydrate-associated spectral features, whereas XTM provided representative visualization of internal air-channel organization and dense bean matrix structure.

Dry-processed beans revealed relatively stronger lipid- and ester-associated spectral features, while their representative XTM images appeared to show more heterogeneous internal air-channel arrangements. In contrast, the LTLH sample exhibited more pronounced carbohydrate/polysaccharide-related spectral features, while its representative XTM images appeared to show a more continuous and well-defined internal air-channel network.

The combined SR-FTIR and XTM observations suggest that variation in biochemical fingerprints occurred alongside apparent variation in internal structural organization among the commercial coffee samples. Cell wall polysaccharides,

particularly galactomannans and arabinogalactans, are major structural components of coffee beans and contribute to their physical and quality-related properties (Li et al., 2021). However, the present study did not perform correlative chemical and structural mapping or statistical correlation between the SR-FTIR and XTM results. Therefore, the more pronounced carbohydrate-associated spectral features and the more continuous air-channel pattern observed in the LTLH sample should be interpreted as parallel observations rather than as evidence of a direct relationship.

Previous studies have shown that drying and thermal processing can affect the microstructure, pore characteristics, and heat and mass transfer behavior of coffee beans (Schenker et al., 2000; Dong et al., 2018; Al-Shemmeri et al., 2024). In the present study, however, the coffee beans were commercially obtained and were not experimentally processed under controlled conditions. In addition, because the LTLH sample was obtained from a different commercial source, potential source- and lot-related variation could not be separated from variation associated with the commercial processing classifications. Therefore, the relationship between SR-FTIR spectral variation and XTM structural features should be interpreted as a comparative association among the commercial samples rather than a confirmed causal relationship.

Overall, the combined SR-FTIR and XTM results indicate that synchrotron-based chemical fingerprinting and three-dimensional microstructural visualization can provide complementary information for the advanced quality characterization of commercial Thai Arabica green coffee beans. This integrated approach may support a deeper understanding of quality-related variation among commercial coffee samples. Future studies using controlled processing conditions, larger sample numbers, quantitative pore-network analysis, roasting trials, and sensory evaluation are required to

confirm the relationships among biochemical fingerprints, microstructural features, roasting performance, and sensory quality.

4. Conclusion

This study demonstrated the potential of synchrotron-based techniques for advanced quality characterization of commercial Thai Arabica green coffee beans. SR-FTIR microspectroscopy combined with PCA revealed clustering trends among commercial green coffee bean samples representing washed, dry, honey, and LTLH processing types, based on biochemical fingerprints associated with lipid-, protein-, and carbohydrate-related spectral features. Complementary XTM analysis provided non-destructive, representative qualitative visualization of internal air-channel organization and dense bean matrix structure.

Among the commercial samples, dry-processed beans showed relatively stronger lipid- and ester-associated spectral features, whereas the LTLH sample exhibited more pronounced carbohydrate/polysaccharide-related spectral characteristics. The representative XTM images of the LTLH sample appeared to show a more continuous air-channel pattern. These observations indicate that the commercial samples varied in both biochemical fingerprints and representative microstructural appearance. However, because the coffee beans were commercially obtained and were not experimentally processed under controlled conditions by the authors, the observed variation should be interpreted as comparative quality-related characteristics rather than as direct causal effects of specific processing parameters. Potential source- and lot-related variation should also be considered because the LTLH sample was obtained from a different commercial source.

Overall, the combined use of SR-FTIR microspectroscopy and XTM provides complementary biochemical and structural information that is not readily obtained from conventional visual grading alone. This

integrated synchrotron-based approach may provide a foundation for further investigation of potential quality indicators for commercial Thai specialty coffee. Future studies should include controlled post-harvest processing conditions, larger sample numbers, quantitative pore-network analysis, roasting trials, and sensory evaluation to validate the relationships among biochemical fingerprints, internal microstructure, roasting performance, and final cup quality.

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Acknowledgements

The authors gratefully acknowledge the Synchrotron Light Research Institute (SLRI), Nakhon Ratchasima, Thailand, for providing access to beamlines BL4.1 and BL1.2W. This research project was financially supported by the Science, Research, and Innovation Fund (SRI Fund), Fiscal Year 2025.

Declaration of Interest Statement

The authors declare that they have no conflict of interests.