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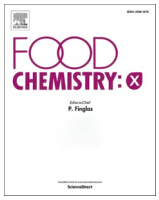

Effects of hot air drying on muscle quality, volatile flavor compounds, and lipid profiles in sword prawn (*Parapenaeopsis hardwickii*) based on physicochemical, GC-IMS, and UHPLC-MS/MS-based lipidomics analysis

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ABSTRACT

The changes in physicochemical index, volatile flavor, and lipid profiles in *Parapenaeopsis hardwickii* during hot air drying were studied. As drying time progressed, the L^*, hardness, chewiness, gumminess, peroxide value (PV), and thiobarbituric acid reactive substances (TBARS) of *P. hardwickii* increased gradually, while the a^* and b^* values first increased and then decreased, and springness decreased progressively. Hot air drying caused the myofibrils to widen and become disordered. Additionally, 5 volatile organic compounds (VOCs) and 30 lipid molecules were identified as key differential markers to the flavor and lipid profiles, respectively. Pearson correlation analysis revealed a strong relationship between shrimp muscle quality and lipid oxidation, with lipid oxidation promoting the development of characteristic flavors and an increase in their levels. Lysophosphatidylethanolamine (LPE), specifically 20:2e, 18:2e, 18:1e, and 16:1e, were identified as primary lipids contributing to the formation of these characteristic flavor differential markers during hot air drying. Glycerophospholipids (GPs) containing LPE as key substrates driving flavor formation in shrimp during hot air drying. This study offers a comprehensive theoretical framework for controlling flavor quality in shrimp muscle during hot air drying.

1. Introduction

The sword prawn (*Parapenaeopsis hardwickii*) is a crucial aquatic species found in sandy seabeds of the Indo-West Pacific coastal waters, ranging from Pakistan to the East China Sea at depths of 5–90 m (Tzeng, 2007). Similar in appearance to *Penaeus orientalis*, the largest species within its genus, *P. hardwickii* is highly valued and widely available in the East China Sea (Ge et al., 2020). Known for its transparent shell and tender, flavorful flesh, *P. hardwickii* is prized for its high protein content and beneficial fatty acids (Ge et al., 2020), making it popular with consumers. Among the various shrimp processing methods, including frying, cooking, salting, and drying, drying stands out for its ability to preserve shrimp safely at room temperature for extended periods while maintaining acceptable quality.

Drying methods are broadly divided into natural drying and artificial drying. Natural drying is heavily influenced by environmental factors, making it difficult to control product quality. Artificial drying methods—including microwave drying, heat pump drying, vacuum drying, and hot air drying—offer better control and improved product quality (Sun et al., 2022). Microwave drying is known for its high selectivity, penetration, and minimal heat loss. Heat pump drying allows precise control of temperature and humidity, which helps maintain shrimp quality. Vacuum drying, with its low-temperature process, is environmentally friendly and helps retain antioxidant properties. However, these three drying methods are relatively complex and require high equipment costs. Therefore, they are unsuitable for large-scale shrimp drying. By contrast, hot air drying is simple to operate, requires low equipment investment, ensures efficient heat transfer, and effectively preserves the

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shrimp's original color, aroma, flavor, and shape. These advantages make hot air drying ideal for large-scale shrimp processing (Huang et al., 2024).

Hot air drying is widely used to improve shrimp storage stability (Li et al., 2020), but it also affects the shrimp's lipids, proteins, and color. Wang et al. (2023) investigated lipid oxidation and enzyme activity in *Penaeus vannamei* during hot air drying, reporting reduced L^* and increased b^*, both linked to lipid oxidation. Similarly, Zhao et al. (2022) found that hot air drying caused lipid oxidation and protein degradation in *P. vannamei*, demonstrated by increased thiobarbituric acid reactive substances (TBARS) value and peroxide value (PV), along with the gradual weakening of the myosin heavy chain (MHC) band (approximately 200 kDa). Furthermore, Li et al. (2020) demonstrated that lipase and lipoxygenase (LOX) were key factors promoting lipid oxidation during hot air drying. Overall, hot air drying can lead to nutrient loss, undesirable flavors, and product darkening (Li et al., 2020), highlighting the significance of optimizing drying parameters. Currently, research specifically addressing quality and flavor changes in *P. hardwickii* during hot air drying remains limited.

Flavor is a critical attribute of aquatic product quality, including both olfactory and gustatory sensations. Aldehydes, alcohols, esters, and ketones are primary volatile flavor compounds in aquatic products, which are derived from lipid oxidation, microbial degradation, and enzymatic reactions. These compounds contribute to flavors reminiscent of grass, mushrooms, and fish (Yarnpakdee et al., 2012). The analysis of volatile organic compounds (VOCs) in aquatic products is heavily reliant on advanced technologies and instrumentation. Among these techniques, gas chromatography-ion mobility spectrometry (GC-IMS) has emerged as an innovative detection method, offering rapid response times, ultra-high sensitivity, and excellent selectivity for detecting and identifying volatile flavor compounds (Jiang et al., 2024). In recent years, GC-IMS has been commonly used to examine the flavor quality of various aquatic products, such as scallops (*Chlamys farreri*), sturgeon fillets, and large yellow croaker (*Larimichthys crocea*). However, to the best of our knowledge, the application of GC-IMS for flavor analysis in dried shrimp products, particularly *P. hardwickii*, remains unexplored.

Lipids play a pivotal role as precursors for flavor compounds, contributing to the development of unique flavors in meat products through thermal oxidation and degradation. In meat, lipids are hydrolyzed to free fatty acids, which are subsequently oxidized to produce hydroperoxides and secondary products such as aldehydes, ketones, and alcohols (Zhang et al., 2011). Lipidomics, a powerful analytical approach, enables comprehensive profiling of lipid species, revealing their biological roles, compositions, dynamics, functions, and structures in tissues, organisms, and/or cells. Lipidomics also identifies and quantifies specific lipid species, including their fatty acyl chain lengths and degrees of unsaturation (Hu & Zhang, 2018). By applying lipidomics, the changes in lipids during the drying process *P. hardwickii* can be systematically examined, providing insights into the mechanisms underlying the formation of characteristic flavors. Furthermore, the relationship between specific lipid profiles and flavor development during drying has garnered little attention to date. To the best of our knowledge, lipidomics technology has not yet been applied for studying dried *P. hardwicki*.

The objective of this study was to investigate the lipid changes occurring in *P. hardwickii* during hot air drying and to elucidate the pathways involved in the formation of its characteristic flavors. A comprehensive analytical approach was employed, including assessments of appearance, sensory properties, color, lipid oxidation indicators, electronic tongue analysis, microstructural changes, VOCs, and lipidomics data. The findings aim to provide a theoretical framework for controlling flavor quality during the hot air drying of *P. hardwickii*.

2. Materials and methods

2.1. Chemical reagents

Methanol-chloroform mixture, chloroform, perchloric acid (PCA), butylated hydroxytoluene (BHT), thiobarbituric acid solution, and sodium chloride (NaCl) were purchased from Sinopharm Chemical Reagent Co., Ltd. (Suzhou, China).

2.2. Shrimp samples and treatments

Fresh *P. hardwickii* specimens (weight: 15 ± 1 g, width: 0.8 ± 0.1 cm, length: 9 ± 1 cm) were purchased in April 2024 from Shenjiamen Fishery Wharf (Zhoushan, China). The shrimp were transported to the laboratory within 0.5 h in a foam box (15 × 25 × 50 cm) filled with crushed ice to maintain freshness.

Upon arrival, the shrimps were thoroughly washed with cold water at 4 °C to remove impurities. They were then boiled in a 3 % (m/v) NaCl solution at 100 °C for 3 min and subsequently placed on a metal mesh to drain excess surface moisture at 20 °C for 10 min. Finally, the shrimps were transferred to a drying oven (BPG-9106 A, Shanghai Yiheng Scientific Instrument Co., Ltd., China) set at 57 °C for 0, 2, 4, 6, 8, 10, 12, 14, and 16 h.

2.3. Appearance, sensory evaluation, and color analyses

The appearance of dried *P. hardwickii* was photographed under uniform lighting conditions. Sensory evaluation was conducted according to the Chinese industry standard Ministry of Agriculture of the People's Republic of China (2016). Ten professionally trained graduate students assessed attributes such as color, volatile odor and taste, morphology and tissue structure, texture, and overall acceptability of the shrimp samples at 20 °C. Specific details of the sensory evaluation criteria are presented in (Table S1).

The color of the dried samples was determined following Zheng et al. (2024)'s methodology. A colorimeter (DS-620, Hangzhou CHNSpec Technology Co., Ltd., China) was used to measure the L^* (+, white; −, black), a^* (+, red; −, green), and b^* (+, yellow; −, blue) values of *P. hardwickii*.

2.4. Lipid extraction

Total lipid extraction was performed according to Folch et al. (1956)'s method. Briefly, 100 g of dried *P. hardwickii* were placed into a conical flask, followed by the addition of 100 mL purified water. Subsequently, 325 mL of a methanol-chloroform mixture (1,2, *v*/v) was added, and the mixture was agitated at 30 °C for 60 min. Afterward, 125 mL chloroform was added. The mixture was stirred for an additional 30 min, followed by the addition of 125 mL deionized water. The mixture was centrifuged for 10 min at 7800 ×*g*, 4 °C by using a high-speed centrifuge (CF-16RN, Hitachi, Japan). The supernatant was filtered, and the solvent was removed using a rotary evaporator (RE100-Pro, Da Long Xing Chuang Experimental Instrument Co., Ltd., China). The lipid extract was further dried under nitrogen at 35 °C. Finally, the lipid sample was sealed under nitrogen, stored at −80 °C, and analyzed within 1 week.

2.5. PV analysis

The PV of lipids in the shrimp samples was determined following the SAC (Standardization Administration of the People's Republic of China) (2023)'s standard analytical protocol. PV was expressed in milliequivalents per kilogram of lipid (meq/kg). During the analysis, direct sunlight exposure was avoided, and a blank control group was used for comparison.

2.6. TBARS analysis

The TBARS value was determined according to Pabast et al. (2018)'s method. Briefly, a 0.5 g of dried shrimp was added to a solution containing 30 mL of 4 % PCA and 0.5 mL of 7.2 % BHT. The mixture was homogenized using a homogenizer (FJ200-SH, Shanghai Huxi Industry Co., Ltd., China) at 7000 ×*g* for 30 s and then filtered. The filtrate (5 mL) was then mixed with 5 mL of 0.02 M thiobarbituric acid solution and incubated in a water bath (HWS-12, Shanghai Yiheng Scientific Instrument Co., Ltd., China) at 90 °C. Absorbance was measured at 532 nm using a spectrophotometer (TU-1810, Beijing Persee General Instrument Co., Ltd., China). TBARS values were expressed as milligrams of malondialdehyde (MDA) equivalents per kilogram of shrimp.

2.7. Textural property analysis

The textural properties of dried *P. hardwickii* were assessed using Zheng et al. (2024)'s method. The dried samples were placed on a food texture analyzer (TMS-PRO, FTC, USA) equipped with a TA/0.5S spherical probe. The parameters were set as follows: a pre-test, test, and post-test speed of 1 mm/s each, a deformation of 55 %, a trigger force of 5 g, and a test distance of 5 mm.

2.8. Electronic tongue analysis

Electronic tongue analysis was conducted according to Liu et al. (2025)'s method. Five grams of dried shrimp were homogenized with 25 mL purified water in a conical flask for 10 min. After standing for 1 h, the supernatant was centrifuged at 1000 ×*g*, 4 °C for 10 min, filtered through gauze, and transferred to a small beaker. The analysis was performed using an electronic tongue (iTongue20, Zhe Jiang Zhe Ke Instrument Equipment Co., Ltd., China) with initial and final voltages of 1 V and − 1 V, respectively.

2.9. Hematoxylin-eosin and Van Gieson staining analyses

The microstructure of the *P. hardwickii* muscle during hot air drying was evaluated using hematoxylin-eosin (HE) and Van Gieson staining, following Shui et al. (2021)'s method. In brief, muscle tissue from the second abdominal ganglion was excised, fixed in 4 % paraformaldehyde solution, dehydrated, embedded, sectioned, and stained. The HE- and VG-stained sections were examined under an optical microscope (BX51, Olympus, Japan).

2.10. VOCs analysis

The changes in volatile flavor compounds during hot air drying were analyzed using GC-IMS with the FlavourSpec® Flavor Analyzer (G.A.S., Inc., Dortmund, Germany), with minor modifications according to Xi et al. (2021)'s method. The retention index, retention time, and ion migration time were used for VOC identification. Chromatographic separation was performed using an MXT-WAX capillary column (Restek, Inc., 30 m × 0.53 mm × 1 μm, USA), with the column temperature maintained at 60 °C. Nitrogen served as the carrier gas, and the total run time was set at 30 min.

2.11. UHPLC-MS/MS-based lipidomics analysis

Lipidomics analysis was conducted using shrimp samples dried for 0, 8, and 16 h to explore changes in the lipid profiles of *P. hardwicki* during hot air drying. At each time point, three shrimp meat samples were pooled together, and three technical replicates were obtained from these pooled samples.

The LC-MS/MS analysis was performed using a Thermo UHPLC-Q Exactive HF-X Vanquish Horizon system equipped with an Accucore C30 column (100 mm × 2.1 mm i.d., 2.6 μm, Thermo, USA) at Majorbio Bio-Pharm Technology Co. Ltd. (Shanghai, China). Chromatographic conditions were as follows: 2 μL sample was injected onto the Accucore C30 column for separation. Mobile phase A consisted of 10 mM ammonium acetate in acetonitrile (50 %, containing 0.1 % formic acid), and mobile phase B consisted of 2 mM ammonium acetate in acetonitrile/isopropanol/water (10/88/2, containing 0.02 % formic acid). For mass spectrometry, both positive and negative ion scanning modes were used, with a mass range of *m/z* 200–2000. The aus gas heater temperature was set to 370 °C, and collision energies of 20, 40, and 60 V were applied in a cyclic manner. Data were acquired in a data-dependent acquisition (DDA) mode (Gao et al., 2024).

2.12. Data analysis

Data and correlation analyses were conducted using Origin 2022 (OriginLab Corp, Northampton, MA, USA) and SPSS 20 (SPSS Inc., Chicago, IL, USA). Pearson correlation coefficient two-tailed tests were conducted to assess correlations among muscle quality parameters, lipid oxidation, and VOCs, as well as the relationships between different key volatile flavor differential markers and key differential lipids. One-way analysis of variance was conducted to assess significant differences, followed by Duncan's post-hoc test for multiple comparisons. Statistical significance was set at $P < 0.05$.

3. Results and discussion

3.1. Appearance and color changes

Color is a key indicator of the quality of aquatic products, as it directly influences the market value of the final product (Li et al., 2020). The changes in shrimp appearance during drying can serve as an indicator of quality. (Fig. 1A) illustrates the appearance changes of dried *P. hardwicki* samples at different drying times. Freshly cooked shrimp (0 h) and those in the initial drying phase (0–6 h) displayed an appealing orange-red color, which may be attributed to the release of astaxanthin from the carotenoid-protein complex as a result of protein degradation during boiling (Niamnuy, Devahastin, & Soponronnarit, 2007). As drying progressed, the shrimp shells gradually transitioned from a fresh red color to a red-white hue, while the shrimp heads gradually browned, and the overall redness of the shells decreased. This color shift may be related to the Maillard reaction, lipid oxidation, and astaxanthin degradation during drying (Li et al., 2020).

As shown in (Fig. 1B–D), the color differences in dried shrimp samples evolved throughout the drying process due to several factors. The L^* value steadily increased with extended drying time, from 50.68 at 0 h to 71.44 at 16 h. This trend is consistent with the findings of Pathare et al. (Pathare et al., 2013), who reported that reduced moisture content during drying significantly increased light reflectance of the sample surface, thereby increasing the L^* value. The formation of white spots on dried *P. hardwickii*, observed visually in (Fig. 1A), likely contributed to this increase in lightness. The a^* and b^* values followed similar trends, initially increasing and then decreasing. During the early drying stages (0–6 h), the a^* and b^* values gradually increased from 10.67 and 17.57 to their respective peaks of 13.65 and 25.90, likely due to astaxanthin release. However, as drying continued, both values gradually declined, which may have resulted from the oxidative degradation of pigments under prolonged high temperature and low humidity conditions, reducing the red and yellow tones (Geng et al., 2019). Furthermore, melanin formation through browning reactions may have further masked the red and yellow hues.

3.2. Changes in texture properties

Texture, closely associated with the deformation of myofibrillar proteins and collagen, directly reflects structural changes and the physical state of aquatic products. As shown in (Fig. 1E, G, and H), the

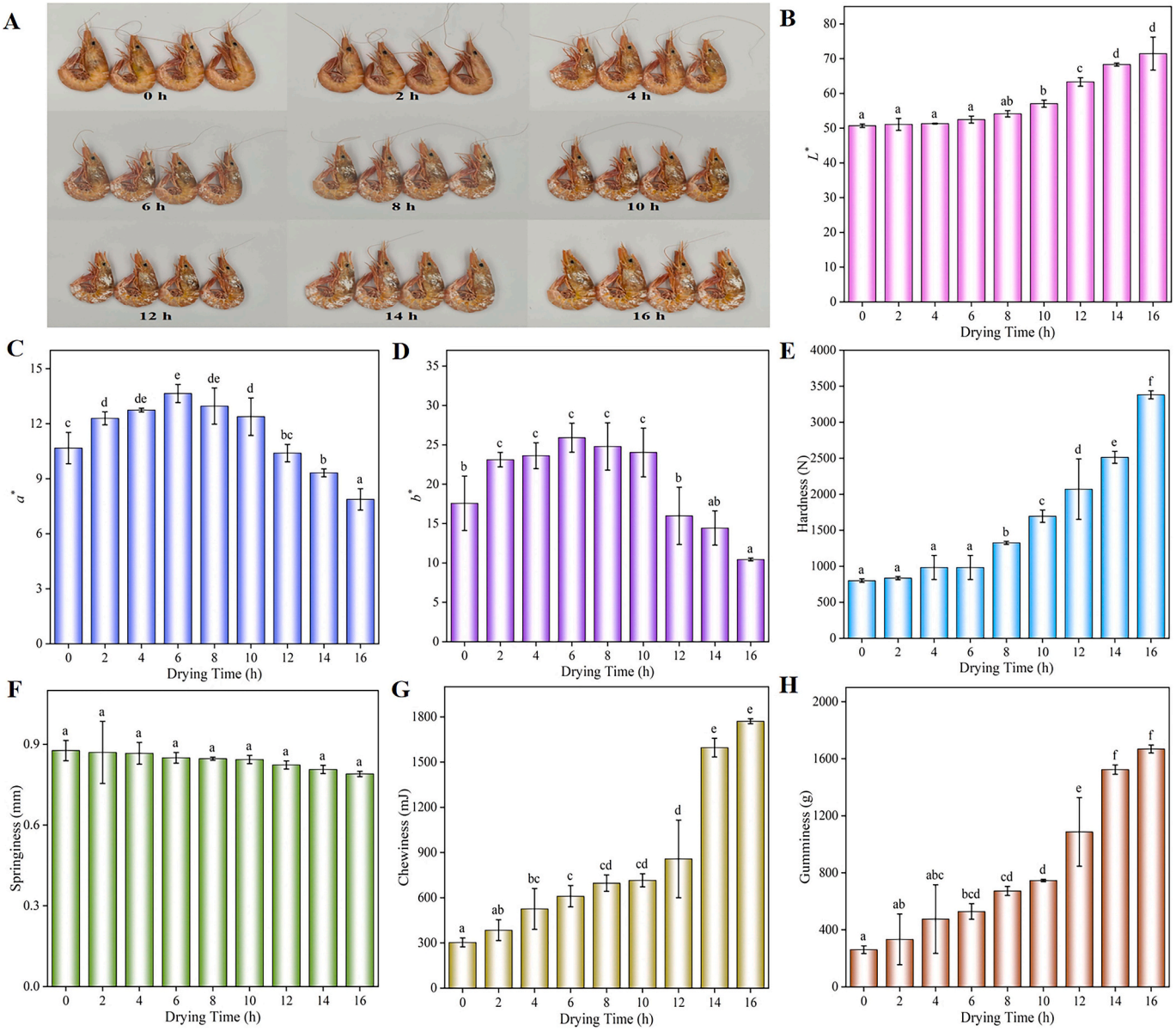

Fig. 1. Appearance (A), L^* (B), a^* (C), b^* (D), hardness (E), springness (F), chewiness (G), and gumminess (H) of *Parapenaeopsis hardwickii* during hot air drying. Different lowercase letters indicate significant differences among shrimp samples during hot air drying ($P < 0.05$).

hardness, chewiness, and gumminess of *P. hardwickii* increased gradually with drying time, reaching maximum values of 3380.06 N, 1770.67 mJ, and 1668.38 g at 16 h, respectively. The increased hardness and gumminess were likely related to water loss during drying. As moisture decreases, shrimp muscle fibers shrink during drying, and actin and myosin degradation disrupts the muscle fiber structure (Wang et al., 2014). Chewiness followed a similar upward trend, particularly during the 12–16 h period, when the increase was statistically significant ($P < 0.05$). This was likely linked to the increased hardness and muscle density. Chen et al. (2022) demonstrated that the longer the drying time and the higher the drying temperature, the greater the degree of protein denaturation, as well as the hardness and chewiness, which were consistent with the results of this study. Furthermore, Zhu et al. (2022) investigated the effects of five different drying methods on the quality of semi-dried *Takifugu obscurus* fillets and found that the texture changes in pufferfish fillets may be due to protein denaturation caused by waterless cytosol. These previous research findings further elucidated the experimental phenomena described above.

As shown in (Fig. 1F), the decrease in springiness during drying was not statistically significant ($P > 0.05$), which may be linked to the structural characteristics of the dried shrimp. During drying, most of the free water migrates from the intercellular space to the surrounding environment through phase transition (Khan et al., 2017). These results reflect the combined effects of multiple texture properties.

3.3. PV and TBARS changes

PV is commonly used to assess the degree of initial lipid oxidation, with increased PV indicating the formation of peroxide molecules, the primary products of lipid oxidation in muscle tissue. These peroxides are highly unstable and easily decompose into acids, aldehydes, ketones, and other small molecules. TBARS values primarily reflect secondary lipid oxidation, typically indicating MDA formation during oxidation (Wang et al., 2023). As shown in (Fig. 2A and B), both PV and TBARS values increased with drying time, suggesting that primary and secondary lipid oxidation occurred throughout drying, consistent with the findings of Zhao et al. (2022).

However, in the later drying stages, PV increases became

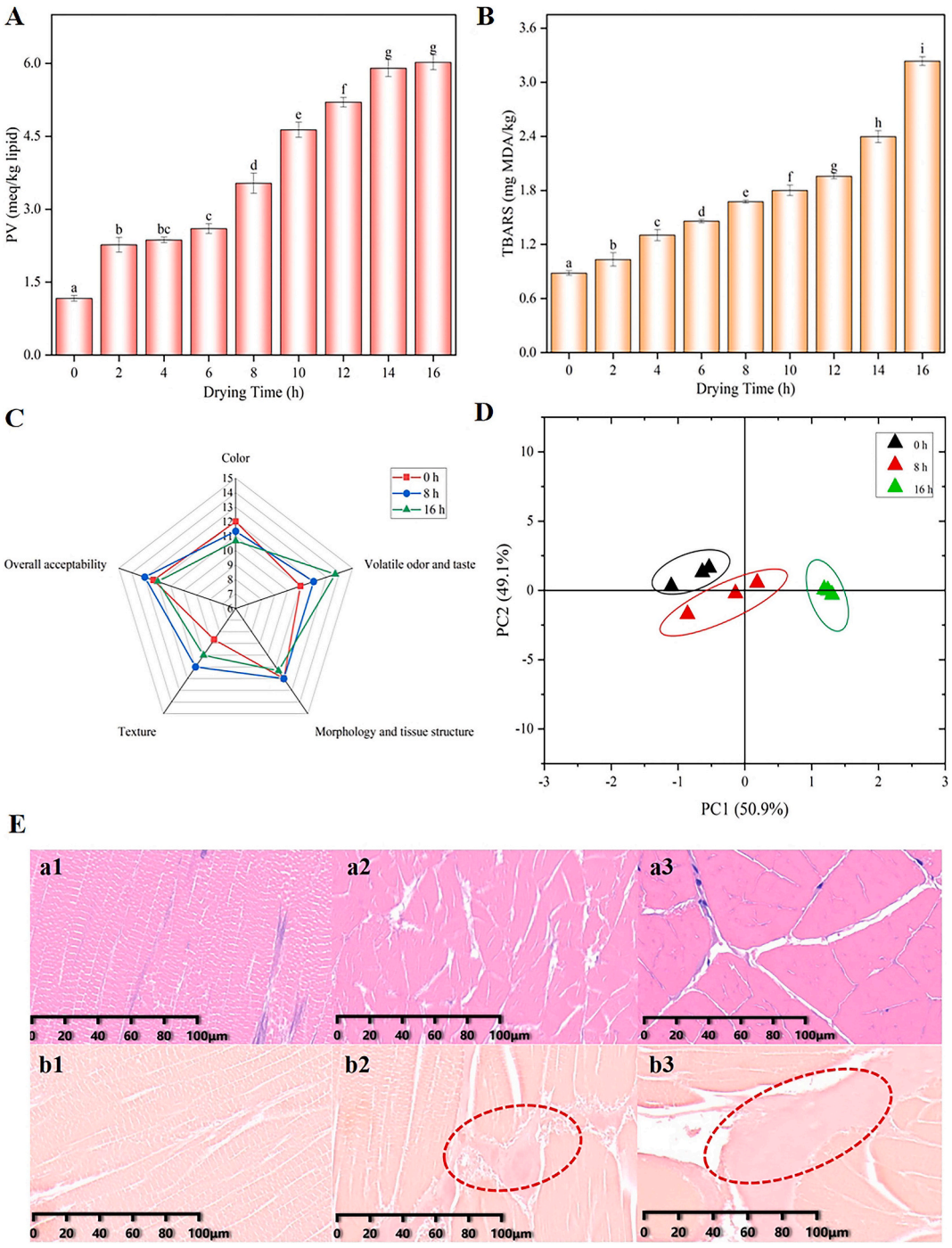

Fig. 2. Peroxide value (PV) (A), thiobarbituric acid reactive substances (TBARS) (B), sensory evaluation (C), principal components analysis of electronic tongue (D), and histological microstructures (E) of *Parapenaeopsis hardwickii* during hot air drying. Different lowercase letters indicate significant differences among the dried shrimp samples during hot air drying ($P < 0.05$). a1–a3: Hematoxylin and eosin staining micrographs; b1–b3: Van Gieson staining micrographs. a1 and b1: shrimp dried at 57 °C for 0 h; a2 and b2: shrimp dried at 57 °C for 8 h; a3 and b3: shrimp dried at 57 °C for 16 h.

nonsignificant ($P > 0.05$), peaking at 6.02 meq/kg lipid. By contrast, TBARS values increased significantly ($P < 0.05$) throughout drying, especially after 14 h of drying. This trend aligned with PV changes observed in PV, likely due to the instability of hydroperoxides formed during lipid oxidation. These hydroperoxides are readily decomposed into secondary oxidation products, such as MDA (Xie et al., 2020). Wang et al. (2023) similarly found that PV, TBARS, and 4-hydroxy-2-nonenal increased continuously during hot air drying of *P. vannamei*, supporting the conclusion that hot air drying promotes progressive lipid oxidation, consistent with the present study results.

3.4. Sensory evaluation and electronic tongue analysis

Sensory evaluation directly reflects consumer preferences and acceptance of sensory attributes such as color, volatile odor, taste, texture, and morphology of aquatic products. As shown in (Fig. 2C), the color scores of shrimp samples decreased as drying time increased. By contrast, the volatile odor and taste scores improved with prolonged drying. Shi et al. (Shi et al., 2024) observed similar trends when comparing different drying methods for *P. vannamei*, noting that hot air drying reduced the fishy odor and enhanced sweetness. The texture

score peaked for shrimp dried for 8 h, likely because the muscle fibers became compact, with moderate hardness and a desirable mouthfeel. Shrimp dried for 16 h ranked second in texture score, potentially due to excessive hardness caused by prolonged drying, which reduced sensory appeal. This aligns with the hardness increase observed in the texture analysis. Additionally, the tissue and morphology of dried shrimp samples remained relatively consistent, contributing to consistently high sensory scores.

The electronic tongue is a novel technique for analyzing low-volatile or non-volatile compounds in food, utilizing a human taste recognition system, and is often combined with principal component analysis (PCA). In this study, PCA was employed to determine whether there were differences in the taste of dried shrimp samples at different drying time points. The PCA score plot represented the distance between samples in the form of scattered points, with the distance of each point indicating the difference between samples. The closer a sample is projected onto the coordinate axis, the higher the similarity in taste, and vice versa. According to (Fig. 2D), the contribution rates of PC1 and PC2 were 50.9 % and 49.1 %, respectively, with a total contribution rate of 100 %. The characteristic regions of the electronic tongue detection signals corresponding to 0 h, 8 h, and 16 h of drying were clearly distinguishable, with no overlap. In particular, there was a clear distinction between the 0 h and 16 h samples, indicating a significant difference in the taste of shrimp before and after drying. This finding was similar to the differences observed in the volatile odor and taste scores from the sensory evaluation.

3.5. Histological changes

The structural changes in shrimp muscle tissue during the drying process can be directly observed under the optical microscope. (Fig. 2E) presents the microstructural changes of shrimp muscle at different drying times using HE and VG staining. In the HE-stained images (a1–a3), myofibrils appeared red, while the white areas represent the inter-fiber gaps. In the VG-stained images (b1–b3), myofibrils appeared flesh color (most area), collagen fibers appeared pink (red circle area), and the white areas indicated gaps between collagen fibers. The staining results showed that at 0 h (a1, b1), the shrimp muscle fibers were densely packed and evenly distributed, with minimal gaps between them. After 8 h of drying (a2, b2), the gaps between myofibrils became larger, and the fiber distribution appeared more diffuse. By 16 h (a3, b3), significant tearing and the largest gaps were observed, with the overall structure appearing increasingly disordered and loose. This progressive breakdown can be attributed to the dehydration, thermal denaturation, and contraction of myofibrillar proteins, all of which contribute to the deterioration of muscle tissue integrity (Xu et al., 2023).

These microstructural observations align with the texture analysis discussed above, where an increase in drying time led to greater hardness, chewiness, and gumminess of the shrimp muscle, which was a result of the combined effect of these texture characteristics. Together, these findings demonstrate that hot air drying leads to the progressive degradation of shrimp muscle structure, with the muscle tissue at 0 h being more compact than that at 8 or 16 h.

3.6. Volatile flavor compounds analysis

Volatile flavor compounds are essential quality attributes of dried shrimp and key factors influencing consumer acceptance. As shown in (Fig. 3A), the characteristic volatile flavor profiles of shrimp dried for 0, 8, and 16 h were distinct and non-overlapping. Notably, the 0-h and 16-h samples were clearly distinguishable, highlighting significant differences in VOCs before and after drying.

The three-dimensional spectra (Fig. 3B) provide a visual comparison of the aroma components across the three sample groups. The X-axis presents drift time, the Y-axis denotes the retention index, and the *Z*-axis reflects the intensity of detected signal peaks. The blue background represents the baseline, while the red peaks indicate the presence of high-concentration compounds. Overall, differences in both aroma components and their concentrations were observed among the three sample groups, suggesting substantial changes in aroma profiles over the drying process. To further explore these changes, two-dimensional differential analysis was performed (Fig. 3C) by using the 0-h sample as the baseline. For the 8-h and 16-h samples, blue areas represent compounds present in lower concentrations compared to 0 h, while red areas represent compounds found in higher concentrations. Notably, a large cluster of differential signals appeared within the drift time was range of 1.0–1.5 s and retention indices between 200 and 1000. The volatiles detected at 8 and 16 h showed significant differences from those at 0 h ($P < 0.05$), confirming clear alterations in the volatile profiles. The detected signal peaks were extracted, revealing that the overall aroma of the 8-h and 16-h dried shrimp samples differed from that of the 0-h samples due to differences in VOCs.

To more intuitively and specifically understand the differences in volatile substances between shrimp samples dried for different times, fingerprint analysis was conducted, as shown in (Fig. 3D). A total of 33 VOCs were detected across the three groups, including 5 aldehydes, 8 alcohols, 4 ketones, 2 esters, 2 pyrazines, and 8 compounds in other categories (Table S2). Aldehydes, commonly formed through lipid oxidation, are particularly significant contributors to the characteristic flavor of meat products due to their low odor thresholds and unique aromas (Zhang et al., 2021). Alcohols, although present, contribute less to overall flavor due to their relatively higher odor thresholds. Thus, aldehydes had a significantly greater impact on flavor perception than alcohols. As for ketones, their contribution to shrimp flavor is lower than that of aldehydes and alcohols, also due to their relatively higher odor thresholds.

The region “a” shown in (Fig. 3D) indicated that the VOCs in shrimp dried for 8 and 16 h using hot air were significantly lower than those in the shrimp samples dried for 0 h ($P < 0.05$). These compounds included hexanal (raw greasy and grassy aroma), dimethyl sulfide (fishy odor), 2-methylpropanol (pungent), 1-hexanol (aromatic), 1-propanol (slightly bitter and pungent), 2-methylbutanol (milky), heptanal (nutty and fatty aroma), 1-pentanol (burnt and creamy aroma), acetone (distinct aroma), nonanal (fatty aroma), 1-hydroxy-2-propanone (sweet aroma), 3-hydroxy-2-butanone (fatty aroma), and acetic acid (pungent and sour). Regions “b” and “c” in (Fig. 3D) showed a significant increase in VOCs ($P < 0.05$) after 8 and 16 h of hot air drying, compared to the 0-h samples. These compounds included 2,3-butanedione (sweet and creamy aroma), pentanal (fruity and bakery-like aroma), 3-methylbutanal (burnt sweet and roasted), ethanol (distinctive and slightly irritating odor), and trimethylamine (fishy odor). Among these, trimethylamine had the highest response value, followed by ethanol, 3-methylbutanal, 2,3-butanedione, and pentanal. Trimethylamine formation may result from the thermal decomposition of trimethylamine oxide (Sun et al., 2022). Similar findings were reported by Liang et al. (2022), who observed trimethylamine formation during processing while studying the physicochemical, flavor, and sensory characteristics of *P. vannamei* under different thermal processing methods. Regions “d” and “e” in (Fig. 3D) indicated that certain VOCs ($P < 0.05$) significantly increased after 16 h of hot air drying, compared to the 0-h and 8-h samples. These compounds included 3-methyl-2-butanol (aromatic flavor), 3-pentanol (distinctive flavor), 2-methylpyrazine (meaty and nutty flavor), 2,5-dimethylpyrazine (chocolatey and creamy aromas), and benzaldehyde (almond and fruity aromas). Of them, 2-methylpyrazine and 2,5-dimethylpyrazine were detected at relatively high concentrations. Similarly, Sun et al. (2022) found that dried shrimp subjected to hot air drying contained the most types of pyrazines.

From these identified compounds, 25 flavor compounds with G.A.S. annotations were selected as potential characteristic aroma markers for in-depth partial least squares discriminant analysis (PLS—DA) analysis (Fig. 3E and F). PLS—DA reduces data dimensionality using PCA,

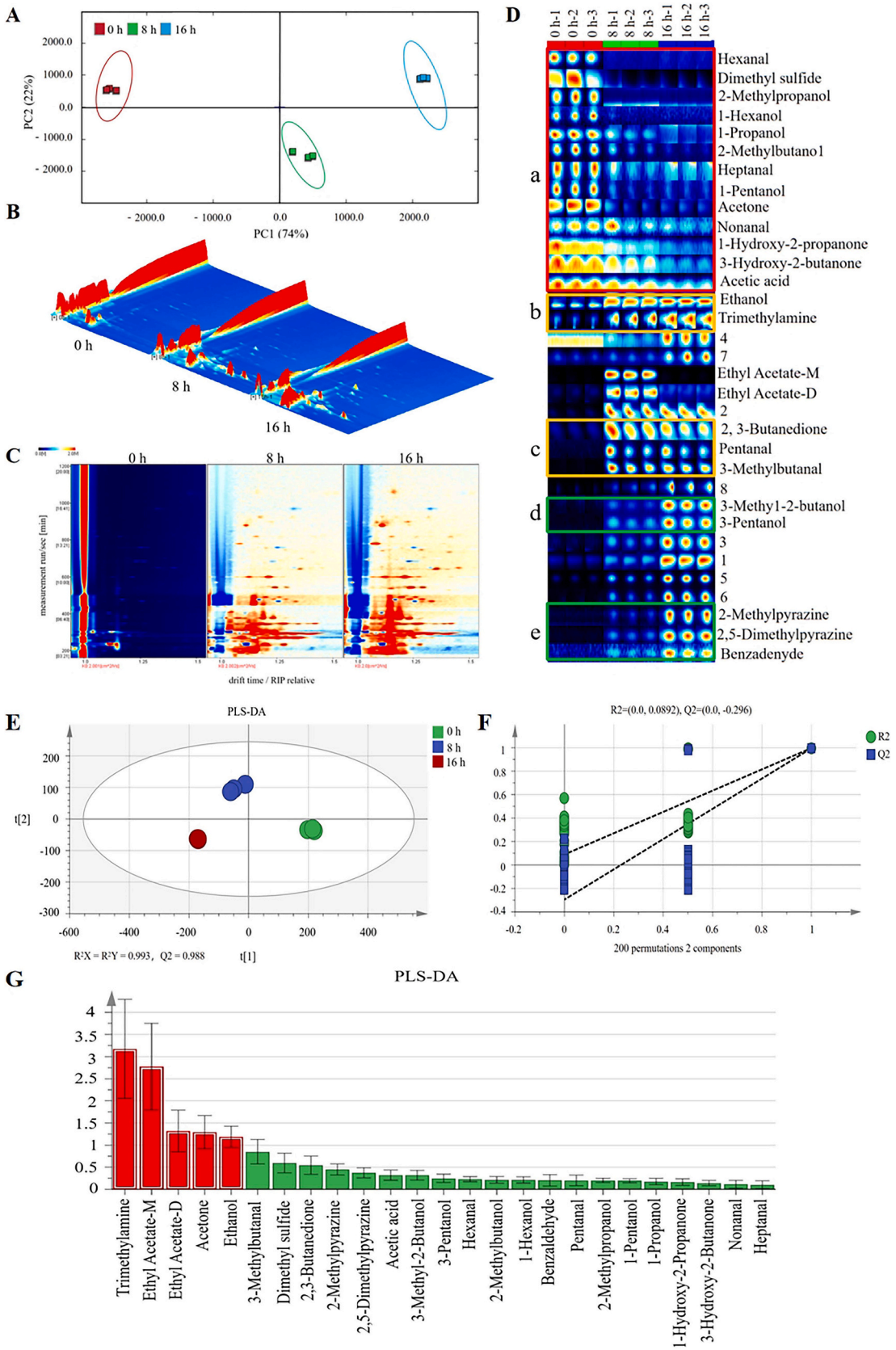

Fig. 3. Principal components analysis of volatile flavor compounds (A), three-dimensional topographic map (B), two-dimensional differential comparison map (C), fingerprinting plot (D), scatter plot (E), 200 permutation test model (F), and variable importance in projection values (G) of partial least squares discrimination analysis in *Parapenaeopsis hardwickii* during hot air drying. Fingerprints of volatile substances of samples, where each cell represents an aroma substance.

followed by least squares regression to establish a linear relationship between variables for classification. The prediction parameters for the PLS—DA model were $R^2X = R^2Y = 0.993$, $Q^2 = 0.988$. Both R^2 and Q^2 were greater than 0.5, and this indicated that the model fit was acceptable. After 200 permutation tests, the Q^2 regression line intersected below zero on the Y-axis, confirming the model was not overfitted and that the model validation was effective. These results are considered useful for identifying and analyzing the aroma profile of shrimp samples. The Variable Importance in Projection (VIP) analysis identified the key volatile differential markers responsible for differentiating *P. hardwickii* samples during hot air drying. Compounds with VIP > 1 (Fig. 3G) were identified, including 2 esters (ethyl acetate-M, ethyl acetate-D), 1 alcohol (ethanol), 1 ketone (acetone), and 1 amine (trimethylamine).

Ethyl acetate is a key contributor to the flavor of aquatic products. It imparts a pleasant fruity, floral, and sweet aroma to shrimp meat and plays a significant role in the overall flavor profile (Jana et al., 2023). Alcohols (specifically ethanol) is formed through the enzymatic oxidative decomposition of unsaturated fatty acids or carbonyl compound reduction (Guo et al., 2018). The ethanol content of shrimp samples subjected to different drying times exhibited significant differences ($P < 0.05$). This finding is consistent with Jiang et al., who also reported higher ethanol content in hot air-dried scallops. The presence of acetone may be due to the decarboxylation of organic acids into ketones caused by uneven heating (Sun et al., 2023). Trimethylamine, a primary amine found in aquatic products, has a very strong fishy odor and a low sensory threshold, making it a key factor contributing to the overall fishiness of shrimp. Consequently, shrimp samples dried for 8 and 16 h exhibit a more pronounced fishy odor.

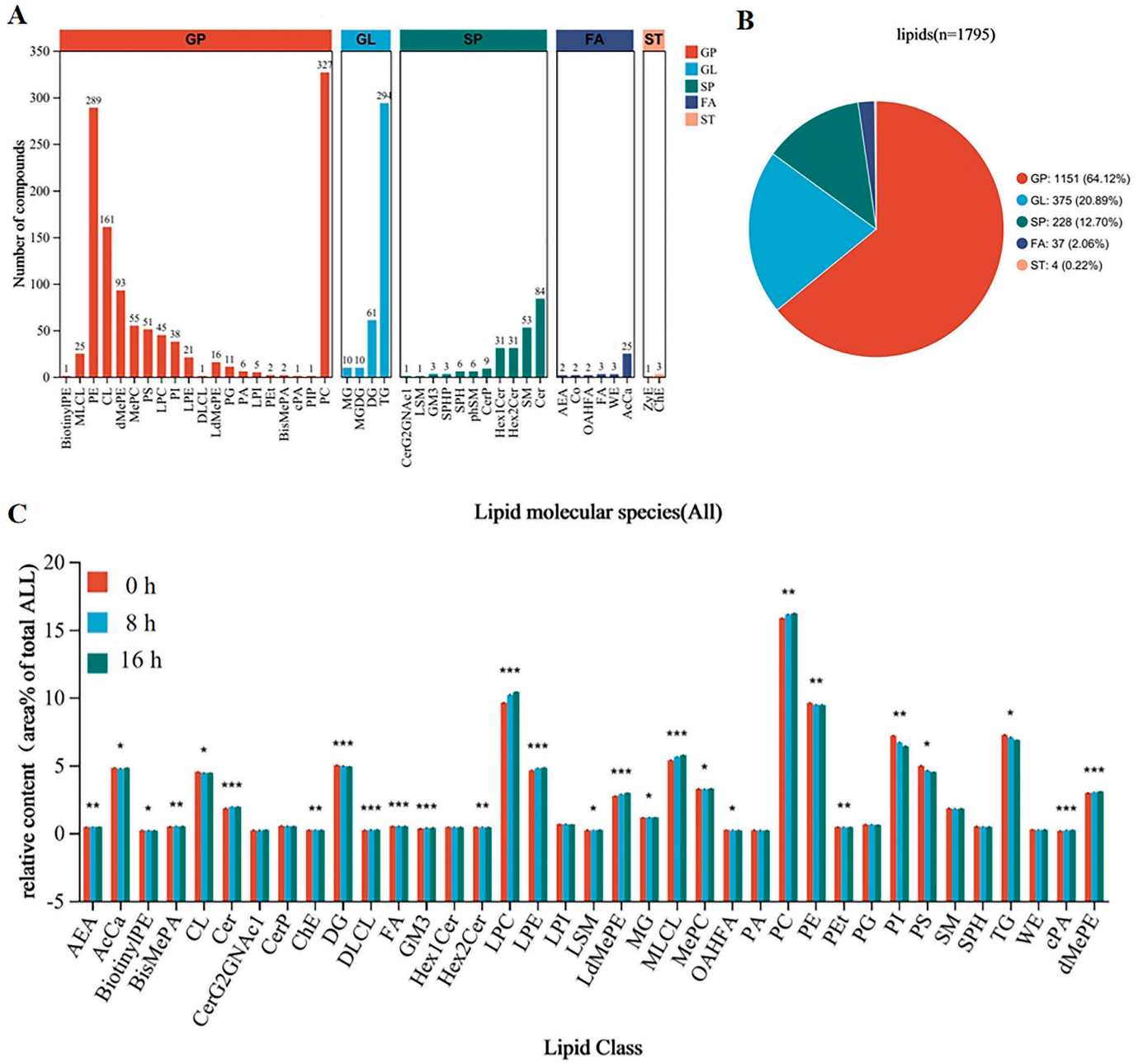

Fig. 4. Number of all lipid species identified (A), percentage of all lipid species identified (B), and content distribution of all lipid species identified (C) of *Parapenaeopsis hardwickii* during hot air drying. An asterisk (*) indicates that the same lipid molecules show significant differences among different groups. * $0.01 < P \leq 0.05$, ** $0.001 < P \leq 0.01$, *** $P \leq 0.001$.

3.7. Dynamic changes in lipids in P. hardwickii meat

Lipidomics provides a systematic and comprehensively analysis of lipids in dried shrimp. (Fig. 4A and B) present the results of identification of 1795 lipid metabolites classified into 5 major categories: glycerophospholipid (GP), glycerolipid (GL), sphingolipid (SP), fatty acyl (FA), and sterol lipid (ST) (Table S3). Among these, GP accounted for the highest proportion (64.12 %), followed by GL (20.89 %) and SP (12.70 %). These findings align with those of Zhao et al. (2022), who identified similar patterns in dried *P. vannamei*, with GP (576), GL (108), and SP (64) representing the most abundant lipid species. These lipid molecules were further classified into 43 subclasses, with the most abundant subclasses in GP, GL, SP, FA, and ST being phosphatidylcholine (PC), triglyceride (TG), ceramides (Cer), acylcarnitine (AcCa), and cholesterol ester (ChE), respectively.

(Fig. 4C) illustrates the changes in lipid content and composition across shrimp samples before and after drying. Across all shrimp samples, the relative content (percentage of total lipids) of Cer, lysophosphatidylcholine (LPC), lysophosphatidylethanolamine (LPE), lysodimethylphosphatidylethanolamine (LdMePE), monolysocardiolipin (MLCL), PC, and dimethylphosphatidylethanolamine (dMePE) significantly increased with drying time ($P < 0.05$). These seven lipids were present at relatively high levels, indicating their importance in the composition of shrimp samples. However, the rate of lipid content increase between 8 and 16 h was lower than that between 0 and 8 h, suggesting that hot air drying promotes the formation of these lipids, but the effect slows over time. Notably, PC and LPC were the most abundant lipids, followed by phosphatidylethanolamine (PE), TG, and PI, indicating their critical role in shrimp composition. The observed increases in LPC and LPE content are consistent with previous findings (Wu et al., 2024). Studies have shown that lipid content influences aroma retention more than lipid type (Ammari & Schroen, 2018), indicating that PC, LPC, PE, TG, and may play significant roles in maintaining the aroma of shrimp.

During drying, the relative contents of phosphatidylinositol (PI), phosphatidylserine (PS), and TG decreased significantly ($P < 0.05$). These reductions may be attributed to oxidative degradation during hot air drying. This finding aligns with those of Zhang et al. (2023), which confirmed that both PI and PS and TG in meat are prone to oxidation. This is primarily due to the high content of unsaturated fatty acids, which are readily oxidized during processing, thereby influencing meat product flavor (Li et al., 2021). Of them, TG serves as a crucial energy storage form in cells and is a crucial player in cell growth and metabolism. This reduction in TG may result from cell membrane disruption and adipose tissue phosphorylation caused by heating (Chen et al., 2023). Pan et al. (2022) also demonstrated that TG oxidation is an effective method for producing aroma compounds. Therefore, Cer, LPC, LPE, LdMePE, MLCL, PC, dMePE, PI, PS, and TG may serve as markers for distinguishing shrimp samples subjected to different drying times.

3.8. PCA and PLS-DA of P. hardwickii meat during hot air drying

To visualize and analyze the differences in lipid composition across shrimp samples, PCA was performed in this study. The three shrimp samples were clearly separated in the PCA score plot, indicating significant differences in lipid composition (Fig. 5A). To further enhance lipid separation from shrimp samples and minimize noise from unrelated variables, PLS-DA was employed for further analysis. The PLS-DA model's prediction parameters were $R^2Y = 0.99$ and $Q^2 = 0.893$, indicating that the model was both stable and reliable, with strong predictive ability (Fig. 5B). (Fig. 5C) further reveals that following 200 permutation tests, the intercept between Q^2 and the Y-axis was negative and < 0.05, confirming the absence of overfitting ($P < 0.05$). This validates that the model can be used for analyzing differential lipids in shrimp samples during hot air drying.

The VIP values of lipid species in shrimp samples were estimated during hot air drying (Fig. 5D). Results identified 158 lipids with significant contributions (VIP > 1), among which GP accounted for 93.67 % of the total. This confirms that the key differential lipids in *P. hardwickii* subjected to different drying times are primarily GP. Additionally, Cer, LPC, LPE, LdMePE, MLCL, PC, dMePE, PI, and PS were identified as useful markers for distinguishing between shrimp samples. (Fig. 5E) highlights the top 30 lipids (VIP > 1.8) that significantly contributed to the differences among shrimp samples during hot air drying, comprising 26 GP and 4 SP. This indicates that these 30 lipid species re strong candidates for distinguishing shrimp meat dried for 0, 8, and 16 h.

3.9. Correlation analysis

3.9.1. Correlation between basic physicochemical parameters and volatile flavor compounds

A Pearson correlation heatmap was used to explore the relationship between basic physicochemical parameters and volatile flavor compounds in shrimp samples. Positive correlations are shown in red, whereas negative correlations are shown in blue. PV and TBARS exhibited significant positive correlation with L^*, hardness, chewiness, and gumminess, but significant negative correlation with springiness (Fig. 6A). This suggests that shrimp muscle quality was closely linked to lipid oxidation during hot air drying. Several volatile compounds, including acetone, hexanal, dimethyl sulfide, 2-methylpropanol, 1-hexanol, 1-propanol, 2-methylbutanol, 1-pentanol, nonanal, 1-hydroxy-2-propanone, 3-hydroxy-2-butanone, and acetic acid, were negatively correlated with PV and TBARS. This indicated that lipid oxidation during hot air drying caused the disappearance of these VOCs and the formation of new volatile compounds. This aligns with the flavor fingerprint results (Fig. 4D). Conversely, compounds such as ethanol, trimethylamine, pentanal, 3-methylbutanal, 3-methyl-2-butanol, 3-pentanol, 2-methylpyrazine, 2,5-dimethylpyrazine, and benzaldehyde were significantly positively correlated with PV and TBARS, further supporting that lipid oxidation in shrimp contributes to the formation and accumulation of flavor compounds.

3.9.2. Correlation between different key volatile flavor markers and key differential lipids

(Fig. 6B) presents the correlation between 5 key volatile flavor markers and 30 key differential lipids in shrimp samples. Acetone showed significant negatively correlations with 26 differential lipids, except for CerG2GNAc1 (d18:2/18:1), PE (8:0/11:2), PC (16:1e/17:1), and PS (18:1e/20:5). Ethanol exhibited significant positive correlations with 27 differential lipids, excluding CerG2GNAc1 (d18:2/18:1), PC (16:1e/17:1), and PS (18:1e/20:5). This highlights the close relationship between the formation of acetone and ethanol and these key differential lipids. Four LPEs (20:2e, 18:2e, 18:1e, and 16:1e) were strongly correlated with all 5 key volatile flavor markers, suggesting that these four LPEs are the primary lipids contributing to the formation of characteristic flavor compounds during hot air drying. GP-containing LPE is a key substrate for the formation of key volatile flavor markers in shrimp during hot air drying. Moreover, PE (8:0/11:2), PE (10:0/11:2), and PC (16:1e/17:1) were significantly correlated with ethyl acetate-M and ethyl acetate-D, indicating that these three lipids may serve as key precursors for the formation of these two esters. These results demonstrate that hot air drying promotes lipid transformation and the generation of distinct flavors, with varying drying times producing different flavor profiles in shrimp meat.

4. Conclusion

This study investigated the changes in basic physicochemical parameters, volatile flavor compounds, and lipid composition in *P. hardwickii* subjected to hot air drying for 0, 8, and 16 h. As drying time increased, L^*, hardness, chewiness, gumminess, PV, and TBARS in the

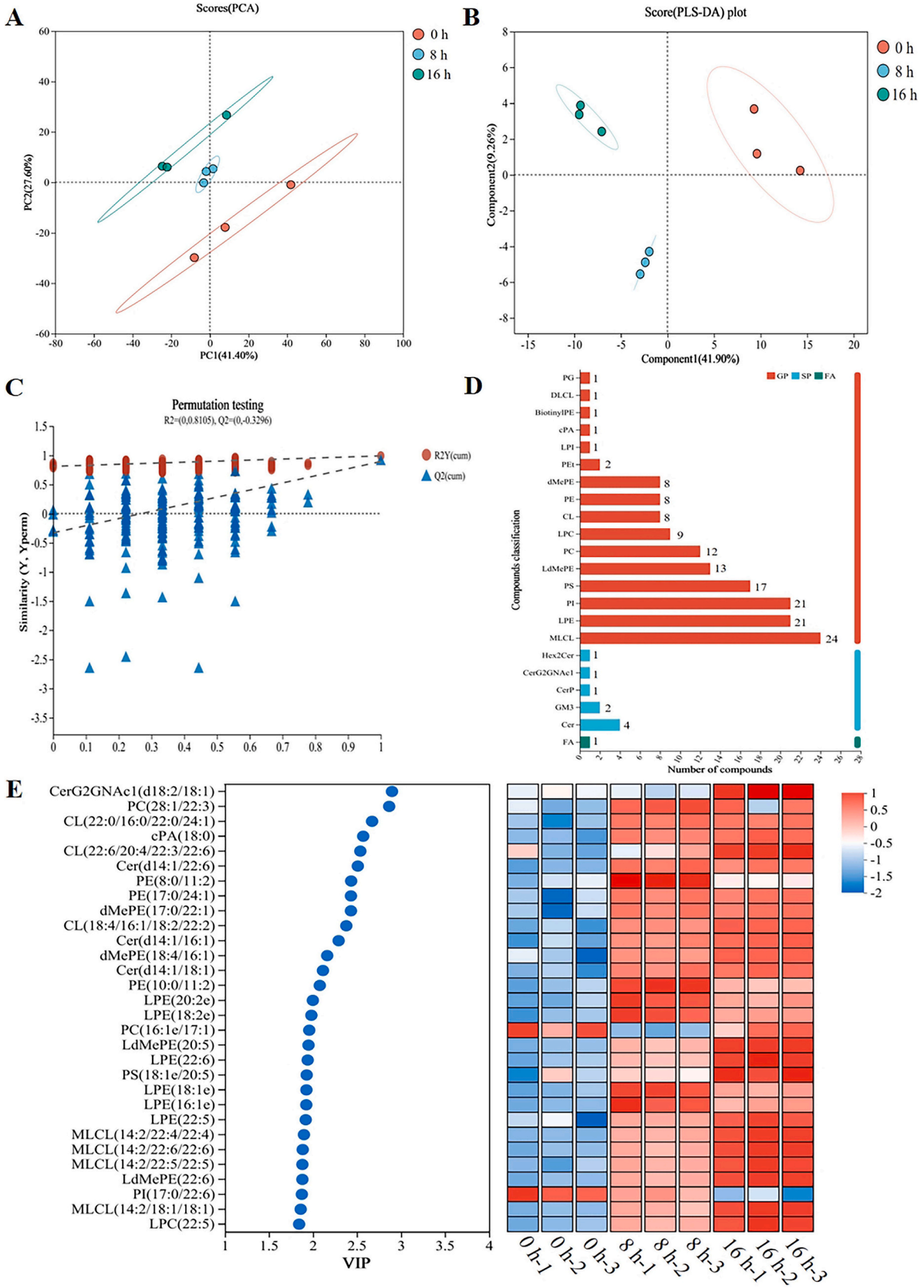

Fig. 5. Principal components analysis score plot (A), partial least squares discriminant analysis (PLS-DA) score plot (B), and 200 permutation test model (C), bar chart of 158 differential lipids (D), and variable importance in projection scores of 30 key differential lipid species in projections of PLS-DA (E). A–C is the pos mode of lipidomics of *Parapenaeopsis hardwickii* during hot air drying.

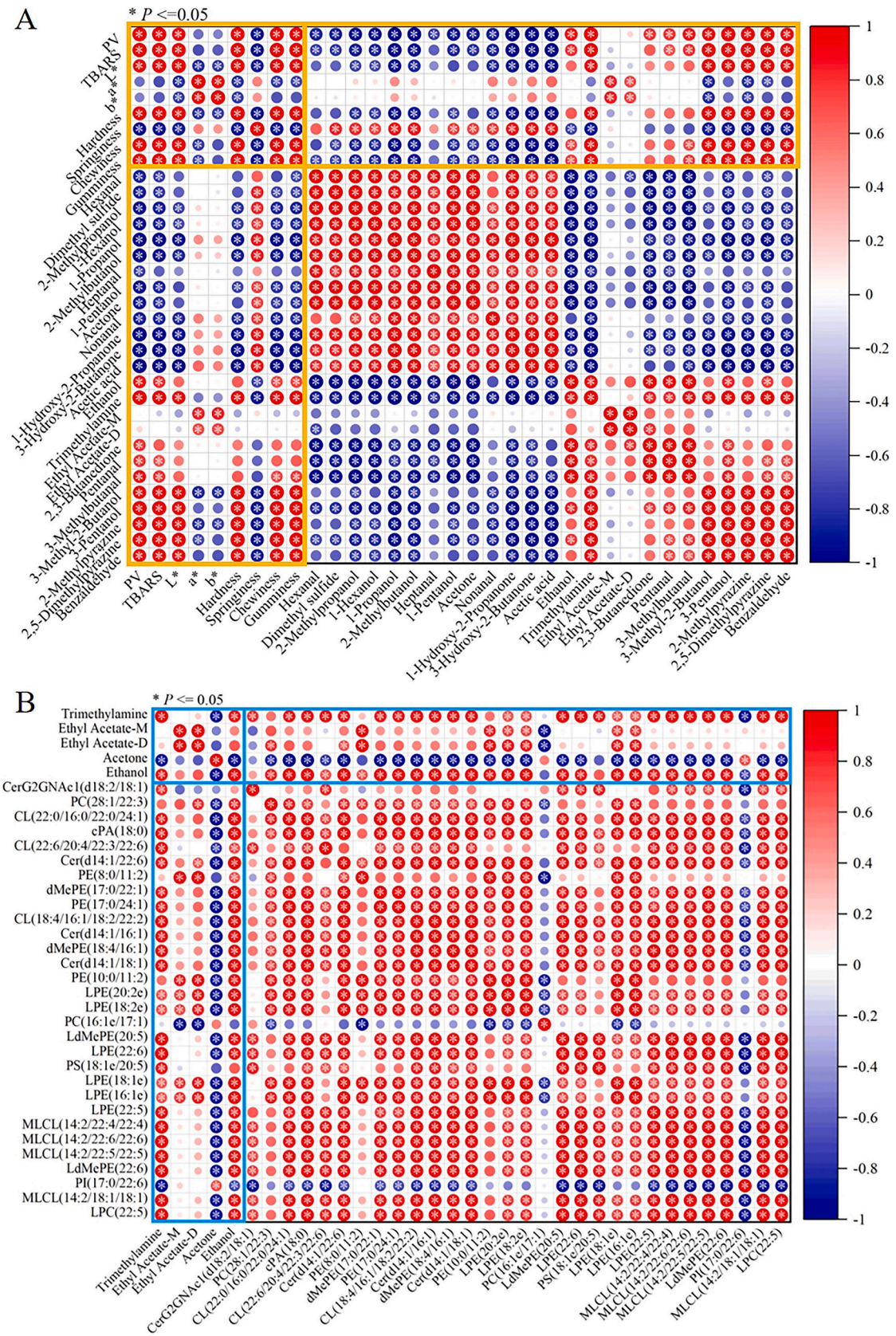

Fig. 6. Pearson correlation analysis of basic physicochemical parameters and volatile flavor compounds (A), and correlation analysis of key volatile flavor differential markers and key differential lipids (B) of *Parapenaeopsis hardwickii* during hot air drying. * $P < 0.05$.

shrimp muscle increased, whereas elasticity decreased. Additionally, a^* and b^* values initially increased and then decreased. Microstructure analysis showed that the spaces between muscle myofibrils widened, and the fibers became more disordered and loosely arranged. These findings indicate that as the quality of shrimp muscle is significantly affected by drying time, largely due to lipid oxidation. VOC analysis revealed that hot air drying led to a significant increase in various volatile compounds in in shrimp meat. Concentrations of 2,3-butanedione, pentanal, 3-methylbutanal, ethanol, trimethylamine, 3-methyl-2-butanol, 3-pentanol, 2-methylpyrazine, 2,5-dimethylpyrazine, and benzaldehyde also increased substantially. The key volatile markers identified were ethyl acetate-M, ethyl acetate-D, acetone, ethanol, and trimethylamine. Lipidomics analysis identified 158 lipids significantly associated with changes during drying, with 30 key lipids identified as critical to the process. In particular, LPE (20:2e), LPE (18:2e), LPE (18:1e), and LPE (16:1e) were identified as the primary lipids contributing to characteristic flavor formation, while PE (8:0/11:2), PE (10:0/11:2), and PC (16:1e/17:1) were linked to the formation of ethyl acetate compounds. This study fills the gap in previous knowledge about the interaction between shrimp muscle quality and volatile flavor substances, key lipids and flavor differential markers during hot air drying. It provides valuable theoretical insights for the flavor quality control of dried *P. hardwickii* and offers useful references for future research. However, further research is warranted to explore changes in protein quality and proteinomics during hot air drying.

CRediT authorship contribution statement

Wenxiong Zheng: Writing – review & editing, Formal analysis, Data curation. **Ronglin Yang:** Writing – review & editing. **Shanshan Shui:** Writing – review & editing, Supervision, Data curation. **Feili Zhan:** Writing – review & editing. **Lucheng Wang:** Writing – review & editing. **Rui Lu:** Writing – review & editing. **Soottawat Benjakul:** Writing – review & editing. **Bin Zhang:** Writing – review & editing, Supervision, Data curation.

Declaration of competing interest

The authors confirm that they have no conflict of interest or personal relationships that may influence the work reported in this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2025.102473.

Data availability

Data will be made available on request.

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