

Hot-air drying affects the nutrient retention and color-odor quality of forage oats

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Abstract

This study aimed to systematically elucidate the synergistic effects of hot-air drying temperature on the nutritional quality, color, and aroma characteristics of forage oats. Forage oats were subjected to the following treatments: shade drying (control, CK) and hot-air drying at 65 °C (D65), 75 °C (D75), 85 °C (D85), and 95 °C (D95). Nutritional quality assays, electronic nose analysis, and GC–MS analysis were then performed. The results showed that drying temperature markedly reshaped oat quality: the 75°C treatment exhibited higher water-soluble carbohydrate (WSC) and crude protein (CP) contents, the lowest acid detergent fiber (ADF) content, and superior color; the 95°C treatment showed enhanced browning, reduced CP, and enrichment of thermal reaction-derived volatile organic compounds (VOCs) such as pyrazines and benzaldehyde. The electronic nose effectively discriminated among the treatments, and its key sensor responses were significantly correlated with nutritional and color indicators. In conclusion, 75°C achieved a better balance among nutrient retention, color, and aroma quality under the present experimental conditions, providing a basis for the optimization of drying parameters and rapid quality monitoring of forage oats.

1 Introduction

Efficient preservation of high-quality forage is an important foundation for stabilizing ruminant production, reducing post-harvest losses, and improving the utilization efficiency of grassland resources, while drying is a key step in converting high-moisture fresh forage into safely storable hay. Drying is not merely a process of water removal: excessively slow water loss prolongs respiration and enzymatic metabolism in plant tissues, thereby increasing the loss of soluble nutrients, whereas an excessive thermal load may aggravate pigment degradation, protein damage, and non-enzymatic browning. In a study on sustainable forage drying, Zhang et al. [1] pointed out that the evaluation of drying technologies should not focus solely on dehydration rate but should also consider nutrient retention, energy consumption, and final product quality. Zhang et al. [2] suggested that agricultural drying is developing toward low-carbon, intelligent, and quality-oriented systems, in which process energy efficiency and product quality need to be optimized synergistically. Therefore, the core of modern forage drying has shifted from “rapid water removal” to achieving a balance between dehydration efficiency and quality preservation.

Forage oat (*Avena sativa* L.) is characterized by strong adaptability, high forage yield, and relatively good nutritional value, and is an important gramineous forage in temperate and high-cold regions. Its hay quality is generally evaluated using indicators such as water-soluble carbohydrates (WSC), crude protein (CP), neutral detergent fiber (NDF), and acid detergent fiber (ADF), while color can intuitively reflect pigment stability and potential thermal damage. Kaplan et al. [3] compared various alfalfa drying methods, including sun drying, shade drying, hot-air drying, microwave drying, freeze drying, and combined drying, and found that different drying technologies significantly altered protein, crude fiber, fatty acids, color, and energy consumption, while exhibiting different trade-offs between nutrient preservation and processing efficiency. These results indicate that evaluating drying performance solely

based on final moisture content or a single nutritional indicator is inadequate for comprehensively reflecting the effects of thermal treatment on overall forage quality.

In addition to nutrition and color, odor is also an important attribute affecting forage quality perception and animal feed intake. Volatile organic compounds (VOCs) constitute the primary chemical basis of forage odor. Bandla et al. [4] found that silage VOCs can exert negative, neutral, or positive effects on forage preference and intake in ruminants, indicating that volatile components are relevant to both quality characterization and animal perception. During drying, indigenous VOCs may decrease through volatilization, oxidation, or degradation, while thermal action can simultaneously generate new volatiles via lipid oxidation, precursor conversion, and Maillard-related reactions. Meng et al. [5] found that different hot-air temperatures significantly altered VOCs as well as Maillard precursors such as reducing sugars and amino acids, and that key aroma compounds were closely associated with these precursors. Li et al. [6] further revealed through untargeted metabolomics that different drying methods exerted selective preservation effects on volatile/semi-volatile and non-volatile metabolites. Liu et al. [7] observed in black tea that combined hot-air and roasting drying increased VOCs associated with sweet, nutty, and floral aromas while reducing green odor-related volatiles. Okonkwo et al. [8] similarly demonstrated that different drying technologies can systematically reshape the flavor profiles of plant materials through volatilization loss, oxidation, and thermal reactions. These studies suggest that drying temperature may simultaneously regulate two interrelated quality processes: nutrient retention and aroma reconstruction.

However, existing forage drying studies have mainly focused on drying kinetics, energy consumption, nutrient composition, and overall color [1, 3], whereas a systematic understanding of how different thermal loads simultaneously drive changes in the nutritional quality, browning process, and volatile odor of forage oats is still lacking. On the other hand, studies on drying-induced VOC changes have mostly focused on foods, tea, and other plant materials; how endogenous and thermally generated volatiles in forage oats vary with temperature, and whether these changes respond in concert with nutritional and color indicators, have not yet been fully elucidated. Electronic nose (E-nose) can rapidly obtain the overall odor fingerprint of complex volatile systems using cross-responsive sensor arrays, while gas chromatography–mass spectrometry (GC–MS) can further resolve specific VOCs. Feng et al. [9] indicated that combining VOC detection with machine learning can provide non-destructive, continuous, and real-time analytical means for food quality; Gite et al. [10] further emphasized that reference analytical data such as GC–MS are crucial for ground-truth validation and improved discriminative performance of E-nose models. Girmatsion et al. [11] systematically summarized advances in machine learning-supported E-nose technology for food quality and safety evaluation. Melikoglu [12] pointed out that data fusion and intelligent algorithms are enhancing the practical application capability of E-nose, but model generalizability and sensor robustness remain issues to be addressed for further application. Shi et al. [13] found in Pacific white shrimp (*Litopenaeus vannamei*) subjected to different drying methods that GC–MS combined with orthogonal partial least squares discriminant analysis and variable importance analysis could screen key VOCs discriminating different drying treatments. Although the above methods have shown good discriminative ability in multiple types of materials, whether E-nose

responses can further characterize drying-induced changes in nutrition, color, and browning in forage oats still requires verification.

In response to the above issues, this study used shade drying as the control and established hot-air drying treatments at 65, 75, 85, and 95°C to systematically evaluate the effects of different drying temperatures on the nutritional quality, browning degree, $L^*a^*b^*$ color parameters, and overall odor response of forage oats. GC–MS was further employed to resolve the VOC composition and differential characteristics of representative treatments, and the results were integrated with orthogonal partial least squares discriminant analysis (OPLS-DA), clustering analysis, metabolic pathway annotation, and correlation analysis to explore the linkages between odor responses and physicochemical quality. This study aimed to elucidate the quality response of forage oats to hot-air drying temperature from an integrated nutritional–color–odor perspective, thereby providing a basis for the optimization of drying parameters and rapid quality monitoring based on odor sensing technology.

2 Materials and Methods

2.1 Sample preparation

Fresh forage oats were collected from the experimental planting base at the East Campus of Inner Mongolia Agricultural University. Forage oats with uniform growth and free from pests and diseases were randomly selected as experimental materials. Weeds, roots, withered yellow leaves, and soil were removed, and the samples were chopped into 3–5 cm segments. The samples were then subjected to different drying treatments: shade drying (CK), hot-air drying at 65°C (D65), 75°C (D75), 85°C (D85), and 95°C (D95), with three replicates per group. After the forage oat samples were dried to constant weight, they were cooled for 30 min and reweighed until the difference between two consecutive weights was less than $\pm 0.5\%$. Specifically, for the shade-drying treatment, the plants were placed in a cool, ventilated indoor area and dried until no further weight change occurred. For each hot-air drying treatment, the forage oat samples were placed in an electric forced-air drying oven (Memmert, UN260) and dried at 65, 75, 85, or 95°C, respectively, until constant weight.

2.2 Analysis of color difference and browning degree

The color difference was determined according to the method of Guclu et al. [14]. Several forage oat samples were randomly selected, and the surface chromaticity was measured using a colorimeter (3nh YS3010) after calibration with a white plate and a black plate. L^* represents the lightness of dried forage oats, a^* represents the red–greenness, and b^* represents the yellow–blueness.

The browning degree was determined according to the method of Siewe et al. [15]. An aliquot of 0.5 g plant sample was accurately weighed into a 50 mL centrifuge tube, and 40 mL of 30% (v/v) methanol solution was added. The mixture was shaken uniformly on a shaker at 4°C for 30 min. The extract was then centrifuged at 4500 r/min for 40 min, and the supernatant was collected and transferred to a 96-well clear microplate. The absorbance at 420 nm was measured using a microplate reader.

2.3 Forage quality analysis

A 250 g sample was collected from each treatment group for quality analysis and dried to constant weight at the corresponding treatment temperature. The dried samples were ground, passed through a 1 mm sieve, and stored in sealed bags until analysis. Dry matter (DM) content was determined [16]. Crude protein (CP) was measured using a Dumatherm analyzer. Acid detergent fiber (ADF) and neutral detergent fiber (NDF) were determined using an ANKOM fiber analyzer (Model: A2000i; Beijing ANKOM Technology Co., Ltd., China) [17]. Water-soluble carbohydrate (WSC) content was determined by the anthrone–sulfuric acid colorimetric method [18].

2.4 Odor response intensity analysis

The odor response intensity of the samples was determined using an electronic nose (Model: AIRSENSE/PEN3; Ensoul Technology Ltd., Germany). The sensor specifications are presented in Table 1. Briefly, 2 g of forage oat sample was accurately weighed into a 20 mL injection vial. The pre-injection purge time, preparation time, and zeroing time were set to 90, 5, and 5 s, respectively. Both the injection flow rate and the sample chamber flow rate were maintained at 300 mL/min. The measurement duration was 120 s, with data recorded every 2 s and a sampling interval of 1 s. The injection needle was purged for 90 s between measurement cycles to ensure baseline stability. Each treatment was analyzed in triplicate. The sample response intensity was calculated as the ratio of the resistance of the sample volatile gases to that of the corresponding carrier gas [19].

Table 1
Performance description of the sensor

Serial number	Sensor name	Performance description
1	W1C	Sensitive to aromatic components
2	W5S	Sensitive to nitrogen oxides
3	W3C	Sensitive to aromatic ammonia
4	W6S	Sensitive to hydrides
5	W5C	Sensitive to aromatic alkanes
6	W1S	Sensitive to methyl compound
7	W1W	Sensitive to terpenes and inorganic sulfides
8	W2S	Sensitive to alcohols, aldehydes, and ketones
9	W2W	Sensitive to organic sulfides
10	W3S	Sensitive to alkanes

2.5 Analysis of volatile organic compounds

Samples were ground with liquid nitrogen and vortex-mixed thoroughly. A 500 mg aliquot was weighed into a headspace vial, followed by the addition of 2 mL of saturated NaCl solution, and the vial was sealed with a headspace silicone septum. The samples were incubated at 60°C with shaking for 5 min. Subsequently, the SPME fiber was inserted, and headspace extraction was performed at 60°C for 15 min. VOCs were separated and identified using an Agilent 8890 GC coupled with a 7000D mass spectrometer. The SPME fiber was aged at 250°C for 5 min and then desorbed into a DB-5MS capillary column with helium as the carrier gas at a constant flow rate of 1.2 mL/min and an inlet temperature of 250°C. The temperature program was set with a maximum temperature of 280°C: the initial temperature was held at 40°C for 3.5 min, increased to 100°C at 10°C/min, then to 180°C at 7°C/min, and finally to 280°C at 25°C/min, where it was held for 5 min. Mass spectrometric conditions were as follows: electron impact (EI) ion source; ion source temperature, 230°C; quadrupole temperature, 150°C; MS interface temperature, 280°C; electron energy, 70 eV; and selected ion monitoring (SIM) mode for precise scanning of ions used for qualitative and quantitative analysis. Qualitative and quantitative analyses were performed using MassHunter software. The relative contents of VOCs were calculated by the peak area normalization method. Metabolites were annotated using the KEGG database.

3 Results

3.1 Color changes of forage oats

As shown in Table 2, the different temperature treatments significantly affected the color parameters of forage oats. With increasing treatment temperature, the browning degree ($A_{420\text{ nm}}$) generally exhibited an upward trend, being lowest in CK, while D95 was significantly higher than the other treatment groups ($P < 0.05$). The L^* value was highest in D75, followed by D95, and lowest in D65, with significant differences among all treatments ($P < 0.05$). The a^* value shifted from negative to positive with increasing temperature, being highest in D95, followed by D85, and lowest in D65. The b^* value was highest in D75, significantly higher than the other treatments ($P < 0.05$), followed by D95, and lowest in CK.

Table 2
Changes in color of forage oats under different temperatures

Treatment	Browning($A_{420\text{ nm}}$)	L^*	a^*	b^*
ck	1.02 ± 0.01c	29.35 ± 0.04c	-0.86 ± 0.02c	15.15 ± 0.09c
D65	1.41 ± 0.02b	26.81 ± 0.11e	-1.11 ± 0.02d	15.2 ± 0.16c
D75	1.44 ± 0.02ab	33.05 ± 0.01a	-0.96 ± 0.01c	16.91 ± 0.02a
D85	1.62 ± 0.03ab	28.55 ± 0.12d	-0.03 ± 0.02b	15.18 ± 0.02c
D95	1.71 ± 0.21a	31.45 ± 0.06b	0.36 ± 0.02a	15.60 ± 0.03b
Note: Different letters indicate significant differences among treatment groups ($P < 0.05$).				

3.2 Nutritional quality of forage oats

The nutritional quality indicators exhibited pronounced component-dependent responses to the different treatments (Fig. 1A–E). Significant differences in WSC were observed among the treatment groups ($P < 0.05$). WSC was higher in D65, D75, and D85 than in CK; the WSC content in D95 was lower than that in D65, D75, and D85, but still higher than that in CK. NDF did not differ significantly among the five treatments ($P > 0.05$). ADF was lowest in D75, and D95 was significantly higher than D75 and CK ($P < 0.05$). DM generally increased with treatment intensity, being highest in D95; the figure shows significant differences between CK and D75, D85, and D95, between D65 and D85 and D95, and between D75 and D95 ($P < 0.05$). CP displayed an opposite late-stage trend, reaching its highest level in D75, followed by a decline to the lowest level in D95; D95 was significantly lower than CK and D75 ($P < 0.05$). These results indicate that the treatments primarily altered the levels of soluble carbohydrates, ADF, DM, and CP, whereas NDF remained relatively stable.

3.3 Odor response intensity of forage oats

The electronic nose response profiles revealed that different treatments produced distinguishable odor fingerprints (Fig. 2A). The response amplitudes of the 10 sensors did not change synchronously. Among them, the W1W, W5S, and W2W sensors exhibited relatively large differences among treatments, corresponding to inorganic sulfides/terpenes, nitrogen oxides, and organic sulfides, respectively. The largest inter-sample difference was observed for W1W, followed by W5S and W2W. The sensor response intensities were highest in the D95 and CK groups, followed by D85 and D75, and lowest in D65. Orthogonal partial least squares discriminant analysis (OPLS-DA) was further employed to analyze these differences (Fig. 2B). Component 1 and Component 2 explained 15.3% and 70.8% of the variation, respectively, with a cumulative explanation rate of 86.1%. The forage oat hay samples subjected to different drying temperatures were significantly separated between groups and clearly clustered within groups, indicating marked odor differences among groups and small within-group differences. Samples from different treatment groups formed their own clusters in the score space. CK and D95 were relatively distant, indicating greater odor differences, whereas D65, D75, and D85 were closely distributed, indicating smaller odor differences.

3.4 VOCs composition of forage oats

The chemical class composition of VOCs covered 15 categories, among which terpenoids accounted for the highest proportion, followed by esters, ketones, heterocyclic compounds, and alcohols (Fig. 3A). Based on the integrated consideration of color, nutritional quality, and odor response intensity, VOCs were determined for the CK, D75, and D95 groups. OPLS-DA results showed that the OPLS-DA scores of VOCs were completely separated among the CK, D75, and D95 groups, indicating that drying temperature significantly affected the VOCs of forage oats. Component 1 and Component 2 explained 58.3% and 22.0% of the variation, respectively, with a cumulative explanation rate of 80.3% (Fig. 3B). The composition, retention time, and relative content of selected compounds in each group are presented in Table 3. A total of 17, 23, and 25 compounds were separated between CK and D75, D75 and D95, and CK and D95, respectively. 3(2H)-Furanone, dihydro-2-methyl- maintained a relatively high and stable relative

content across the three groups. Various nitrogen-containing heterocyclic and aromatic aldehyde compounds, such as Benzaldehyde, Pyrazine, 2-ethyl-5-methyl-, Pyrazine, 2,5-dimethyl-, Pyrazine, methyl-, and Cinnamaldehyde, (E)-, were significantly accumulated in the D95 group. 3-Octen-2-one and Hexane, 1,1'-[ethylidenebis(oxy)]bis- were significantly accumulated in the CK group. 2-Methoxy-4-vinylphenol was significantly accumulated in the D75 group.

Table 3
Composition of VOCs in forage oats

NO	RT	CAS	Compounds	Relativecontent(%)		
				CK	D75	D95
1	4.44	3188-00-9	3(2H)-Furanone,dihydro-2-methyl-	6.91 ± 0.41a	6.58 ± 0.07a	6.26 ± 0.09a
2	4.62	109-08-0	Pyrazine,methyl-	0.06 ± 0.01b	0.37 ± 0.04b	2.53 ± 0.22a
3	6.02	123-32-0	Pyrazine,2,5-dimethyl-	0.11 ± 0.01c	0.61 ± 0.05b	3.36 ± 0.18a
4	6.86	100-52-7	Benzaldehyde	0.66 ± 0.07b	0.82 ± 0.02b	11.18 ± 0.57a
5	7.22	100-47-0	Benzonitrile	0.08 ± 0.01b	0.45 ± 0.05b	3.12 ± 0.37a
6	7.42	29460-90-0	2-Isopropylpyrazine	0.07 ± 0.01b	0.23 ± 0.01b	2.08 ± 0.15a
7	7.48	14667-55-1	Pyrazine,trimethyl-	0.06 ± 0.00c	0.19 ± 0.01b	0.67 ± 0.07a
8	7.49	13360-64-0	Pyrazine,2-ethyl-5-methyl-	0.14 ± 0.03c	1.03 ± 0.06b	5.38 ± 0.55a
9	7.64	1003-29-8	1H-Pyrrole-2-carboxaldehyde	0.05 ± 0.01b	0.12 ± 0.01b	0.71 ± 0.07a
10	7.65	4313-03-5	2,4-Heptadienal,(E,E)-	1.15 ± 0.08c	1.60 ± 0.14b	2.58 ± 0.17a
11	8.08	1669-44-9	3-Octen-2-one	0.85 ± 0.06a	0.44 ± 0.04b	0.47 ± 0.02b
12	8.08	18402-82-9	3-Octen-2-one,(E)-	0.79 ± 0.09a	0.45 ± 0.04b	0.48 ± 0.01b
13	8.23	122-78-1	Benzeneacetaldehyde	0.11 ± 0.01c	0.21 ± 0.01b	0.46 ± 0.03a
14	8.27	90-02-8	Benzaldehyde,2-hydroxy-	0.01 ± 0.00b	0.06 ± 0.00b	0.22 ± 0.04a
15	8.62	505-29-3	1,4-Dithiane	0.04 ± 0.01c	0.13 ± 0.02b	0.32 ± 0.03a
16	8.63	30086-02-3	3,5-Octadien-2-one,(E,E)-	3.00 ± 0.14a	2.31 ± 0.26b	2.49 ± 0.28ab

Note: Different letters indicate significant differences among treatment groups (P < 0.05). CK, shade drying; D75, hot-air drying at 75°C; D95, hot-air drying at 95°C.

NO	RT	CAS	Compounds	Relativecontent(%)		
				CK	D75	D95
17	8.63	20125-84-2	3-Octen-1-ol,(Z)-	2.96 ± 0.14a	2.27 ± 0.26b	2.43 ± 0.28ab
18	8.93	13925-07-0	Pyrazine,2-ethyl-3,5-dimethyl-	0.07 ± 0.03c	0.81 ± 0.06b	2.32 ± 0.39a
19	9.13	93-58-3	Benzoicacid,methylester	0.02 ± 0.00b	0.07 ± 0.03b	0.37 ± 0.04a
20	9.25	33467-74-2	3-Hexen-1-ol,propanoate,(Z)-	0.66 ± 0.06b	0.56 ± 0.06b	1.03 ± 0.06a
21	9.25	124-19-6	Nonanal	0.48 ± 0.05b	0.41 ± 0.04b	0.72 ± 0.06a
22	10.12	35628-00-3	2,7-Octadien-4-ol,2-methyl-6-methylene-,(S)-	0.05 ± 0.01b	0.08 ± 0.01b	0.17 ± 0.02a
23	10.29	105-21-5	2(3H)-Furanone,dihydro-5-propyl-	0.07 ± 0.01b	0.09 ± 0.01b	0.15 ± 0.02a
24	10.89	13679-72-6	2-Acetyl-3-methylthiophene	0.74 ± 0.03c	1.74 ± 0.04b	2.26 ± 0.09a
25	11.66	67-47-0	5-Hydroxymethylfurfural	0.02 ± 0.00a	0.02 ± 0.00a	0.02 ± 0.01a
26	12.42	14371-10-9	Cinnamaldehyde,(E)-	0.30 ± 0.07c	1.98 ± 0.07b	4.06 ± 0.55a
27	12.42	104-55-2	2-Propenal,3-phenyl-	0.22 ± 0.02b	2.62 ± 0.71a	2.50 ± 0.50a
28	13.06	7786-61-0	2-Methoxy-4-vinylphenol	0.29 ± 0.06b	1.60 ± 0.34a	0.32 ± 0.05b
29	14.64	623-05-2	Benzenemethanol,4-hydroxy-	0.02 ± 0.00c	0.04 ± 0.01b	0.13 ± 0.01a
30	16.08	5405-58-3	Hexane,1,1'-[ethylidenebis(oxy)]bis-	1.12 ± 0.04a	0.87 ± 0.05b	0.37 ± 0.03c
Note: Different letters indicate significant differences among treatment groups (P < 0.05). CK, shade drying; D75, hot-air drying at 75°C; D95, hot-air drying at 95°C.						

3.5 Differential VOCs in forage oats

Drying temperature significantly affected the VOC composition of forage oats. K-means analysis classified 931 compounds into 9 subclasses (Fig. 4). Subclass 1 (mainly Pyrazine, methyl-, Pyrazine, 2,5-dimethyl-, and Benzaldehyde) exhibited higher contents in the D95 group; Subclass 2 (mainly 2-Acetyl-3-methylthiophene, alpha-Murolene, and (Z)-1-Methyl-4-(6-methylhept-5-en-2-ylidene)cyclohex-1-ene)

exhibited higher contents in the D95 group; Subclass 3 (mainly cis-.beta.-Farnesene, Naphthalene, 2-methyl-, and Aromandendrene) exhibited higher contents in the CK group; Subclass 4 (mainly 2,4-Heptadienal, (E,E)-, Pyrazine, 2-ethyl-3,5-dimethyl-, and Valerena-4,7(11)-diene) exhibited higher contents in the D95 group; Subclass 5 (mainly Naphthalene, 1,6-dimethyl-, Pyrazine, 2,3-dimethyl-5-(2-methylpropyl)-, and 2-Oxetanone, 4-methyl-) exhibited higher contents in the D75 group; Subclass 6 (mainly endo-Borneol, 2-Heptanol, and Ethanone, 1-(4-methylphenyl)-) exhibited higher contents in the D95 group; Subclass 7 (mainly 3-Octen-2-one, piperitone, and Cis-Nerolidol) exhibited higher contents in the CK group; Subclass 8 (mainly 2-Methoxy-4-vinylphenol, cinnamyl alcohol, and alpha-Ionone) exhibited higher contents in the D75 group; Subclass 9 (mainly Isobornyl formate, Phenol, 2,4,5-trimethyl-, and 2,5-Thiophenedicarboxaldehyde) exhibited higher contents in the CK group.

Boxplots displaying 12 representative differential VOCs are shown in Fig. 5. Pyrazine, methyl-, Pyrazine, 2,5-dimethyl-, Benzaldehyde, Pyrazine, 2-ethyl-5-methyl-, 2,4-Heptadienal, (E,E)-, Benzeneacetaldehyde, Pyrazine, 2-ethyl-3,5-dimethyl-, Nonanal, and 2-Acetyl-3-methylthiophene were present at higher contents in the D95 group. 3-Octen-2-one and 3,5-Octadien-2-one, (E,E)- were present at higher contents in the CK group. 2-Methoxy-4-vinylphenol was present at a higher content in the D75 group.

3.6 Functional annotation and enrichment of VOCs

The KEGG annotation results for VOCs are shown in Fig. 6. The annotations were predominantly associated with metabolism-related pathways, among which the most enriched pathways were Metabolic pathways (32 compounds), followed by Biosynthesis of secondary metabolites (14 compounds) and Phenylpropanoid biosynthesis (5 compounds).

3.7 Correlation between odor response intensity and differential VOCs

The correlation bubble plot revealed structured associations between electronic nose sensor responses and nutritional, browning, and color indicators (Fig. 7). WSC was significantly positively correlated with W1C, W3C, and W5C ($P < 0.05$), and significantly negatively correlated with W1S and W2S ($P < 0.05$). W5S was significantly positively correlated with ADF and a^* ($P < 0.05$). W1W exhibited the most extensive significant associations: it was significantly positively correlated with ADF, DM, A420 nm, L, and a ($P < 0.05$), while significantly negatively correlated with CP ($P < 0.05$). W2W was also significantly positively correlated with ADF, DM, L, and a ($P < 0.05$).

4 Discussion

This study systematically evaluated the effects of shade drying and hot-air drying at 65–95°C on the color, nutritional quality, odor response, and volatile organic compounds (VOCs) of forage oats. The results demonstrated that the effect of drying temperature on quality was markedly non-linear: D75 exhibited a relatively favorable overall status in terms of WSC, CP, ADF, and color retention, whereas D95

was accompanied by enhanced browning, decreased CP, and substantial accumulation of thermal reaction-derived VOCs. These findings indicate that moderate heating facilitates rapid dehydration and partial quality retention, whereas an excessive thermal load promotes nutrient loss and flavor reconstruction.

4.1 Effect of drying temperature on color and browning of forage oats

Overall color is the most intuitive indicator for assessing thermal damage during drying. In this study, the browning index generally increased with increasing treatment temperature, and a^* gradually shifted toward positive values, while L^* and b^* reached relatively high levels at D75 and then declined, indicating that the response of overall color to temperature was non-linear. Plant materials may exhibit reduced sustained enzymatic browning during the initial drying stage owing to rapid dehydration and inactivation of oxidases; however, as the thermal load continued to increase, chlorophyll degradation, pigment oxidation, and non-enzymatic browning gradually became dominant [20–22]. Huang et al. [23] similarly found that color changes during hot-air drying depend on the combined effects of temperature and exposure time rather than a single temperature effect. Therefore, the higher L^* and b^* values at D75 indicate that this temperature achieved a better balance between dehydration and overall color retention under the present experimental conditions, whereas the higher A420 and a^* values at D95 reflect stronger thermally induced browning.

4.2 Effect of drying temperature on the nutritional quality of forage oats

WSC was the most sensitive to drying temperature, being higher in the D65, D75, and D85 treatments than in shade drying, but declining at D95. Harvested plant tissues can still maintain respiration and enzymatic metabolism, and slow dehydration continuously consumes soluble sugars; increasing the drying rate can shorten the high-moisture phase, thereby reducing respiratory losses [24, 25]. Deinum et al. [26] also pointed out that drying conditions can significantly alter the preservation of non-structural carbohydrates in forage. Therefore, the higher WSC at moderate temperatures mainly reflects the preservation effect conferred by rapid dehydration; when the temperature increased to D95, thermal degradation of sugars and their participation in processes such as the Maillard reaction increased substrate consumption [27, 28], thereby explaining the trend of WSC shifting from an increase to a decline. Wei et al. [29] similarly demonstrated in oat hay that different drying methods and thermal intensities can significantly alter soluble nutritional components, supporting the notion that drying conditions are important determinants of nutrient preservation in forage.

Fiber and protein fractions further reflected the selectivity of temperature effects. NDF remained relatively stable among treatments, whereas ADF was lowest at D75 and increased at D95, indicating that short-term thermal treatment did not synchronously alter all cell wall components. The determination of NDF and ADF is influenced not only by the fiber itself; protein–sugar complexes formed

during thermal treatment and detergent-insoluble nitrogenous components can also alter fiber fractionation results [17, 26]. Therefore, the higher ADF at D95 more likely reflects relative concentration following the loss of soluble components and an increase in heat-damaged components, rather than the substantial de novo formation of structural fiber within a short time. DM generally increased with increasing temperature, consistent with the pattern that high temperature accelerates moisture migration and evaporation [22, 29]. In contrast, CP reached a relatively high level at D75, then declined, and was lowest at D95. This may be because high temperature can promote protein oxidation, cross-linking, and glycosylation, thereby reducing the availability of reactive amino acids and proteins [27].

4.3 Effect of drying temperature on electronic nose odor responses

The electronic nose results showed that W1W, W5S, and W2W were the main response channels distinguishing the different drying treatments, and each treatment formed clear clusters in the OPLS-DA score space, indicating that temperature significantly altered the overall odor fingerprint of forage oats. Similarly, Liu et al. [30] found in alfalfa that different quality states could be effectively distinguished by electronic nose responses; Liu et al. [31], after comparing multiple drying methods, also found that sensors such as W1W, W2W, and W5S were highly sensitive to drying-induced odor differences. Electronic nose sensors possess cross-responsive characteristics, and thus their signals reflect the integrated changes of multiple classes of VOCs rather than the individual contribution of a single compound [6, 32, 33]. In this study, both CK and D95 exhibited relatively strong responses, but they were relatively distant from each other in the OPLS-DA space, indicating that similar response intensity does not imply identical volatile composition: shade-dried samples were more conducive to retaining volatiles derived from native plant and lipid sources, whereas high temperature can generate new highly responsive compounds through thermal oxidation, the Maillard reaction, and Strecker degradation [34, 35]. This also explains the non-monotonic change in which the response was lowest at D65 and increased again at D95.

4.4 Effect of drying temperature on the overall VOC composition of forage oats

The volatile profiling results further confirmed the overall odor differences reflected by the electronic nose. A total of 15 classes of VOCs were detected in this study, among which terpenoids accounted for the highest proportion, followed by esters, ketones, heterocyclic compounds, and alcohols. CK, D75, and D95 were completely separated in the OPLS-DA, and the number of differential compounds between CK and D95 was the largest. Terpenoids are important secondary metabolic volatiles in plants, and their contents are jointly regulated by biosynthesis, tissue release, oxidation, and volatilization loss [36]. Wang et al. [37], in a study on the volatile metabolome of oats, similarly demonstrated that terpenoids, esters, and other secondary metabolites are important components constituting the characteristic odor of oats. X. Li et al. [35] confirmed that industrial thermal processing can significantly reshape the VOC composition of oats. Liu et al. [31] also observed pronounced changes in VOC classes and OPLS-DA

distribution in *Atractylodes lancea* subjected to different drying methods, further indicating that drying is an important regulatory step governing plant volatile composition.

4.5 Effect of drying temperature on differential VOCs

K-means analysis classified 931 VOCs into 9 subclasses with distinct temperature response patterns, indicating that drying temperature did not proportionally alter all volatiles but rather selectively promoted or inhibited different chemical reaction networks. In D95, various pyrazines, including methylpyrazine, 2,5-dimethylpyrazine, 2-ethyl-5-methylpyrazine, and 2-ethyl-3,5-dimethylpyrazine, were significantly enriched. Pyrazines are typical thermally derived nitrogen-containing heterocyclic compounds, primarily formed through the Maillard reaction involving reducing sugars and amino compounds, as well as subsequent Strecker reactions [28, 38, 39]. In oat systems, Klensporf et al., X. Li et al., and McGorin [34, 35, 40] have all reported that heating promotes the formation of pyrazines and other roasted aroma compounds. Therefore, the synchronous increase in multiple pyrazines in D95 corroborates the enhanced browning observed in overall color, indicating that 95°C substantially strengthened the formation of thermal reaction-derived odorants. In D95, benzaldehyde, benzeneacetaldehyde, (E,E)-2,4-heptadienal, nonanal, and 2-acetyl-3-methylthiophene also increased markedly, suggesting that high-temperature odor reconstruction is not driven solely by the Maillard reaction. Aldehydes and ketones can originate from the oxidation of unsaturated fatty acids, aromatic aldehydes can also be produced via Strecker degradation of amino acids, and sulfur-containing heterocyclic compounds are generally associated with thermal reactions of sulfur-containing precursors [28, 41]. Li et al. [41] observed during accelerated storage of oats that lipid oxidation, the Maillard reaction, and Strecker degradation synergistically drove changes in volatiles; Bai et al. and Zhang et al. [42, 43] also confirmed that oat processing can significantly alter the proportions of aldehydes, ketones, and nitrogen-containing heterocyclic compounds. These studies are consistent with the present results, indicating that the volatile profile changes under D95 reflect the combined enhancement of multiple thermochemical reactions. In contrast to D95, CK exhibited higher contents of C8 oxygenated compounds such as 3-octen-2-one and 3,5-octadien-2-one. These compounds are generally associated with lipid oxidation and native plant flavor, and their decrease at high temperature can be collectively explained by volatilization loss, further oxidation, and inactivation of the related lipoxygenase system. Li et al. [35] found during oat processing that thermal treatment simultaneously altered lipolysis/oxidation-related enzyme activities and volatile composition, consistent with the trends observed in this study. D75 was most notably characterized by the specific enrichment of 2-methoxy-4-vinylphenol. This volatile phenol is closely related to the transformation of phenolic precursors derived from the phenylpropanoid pathway, and plant bound aroma precursors can be released and transformed through enzymatic or non-enzymatic pathways during processing [44]. Wang et al. [37] also pointed out that compounds derived from secondary metabolism are important constituents distinguishing the volatile characteristics of oats. Therefore, D75 was not a simple transitional state between CK and D95, but formed a volatile combination with independent characteristics, which was consistent with its relatively favorable nutritional and color performance.

4.6 Functional annotation and metabolic pathways of differential VOCs

KEGG annotation showed that the differential VOCs were mainly involved in Metabolic pathways, Biosynthesis of secondary metabolites, and Phenylpropanoid biosynthesis, indicating that drying-induced odor changes are closely associated with primary metabolism and the transformation of secondary metabolic precursors. Terpenoids, aromatic compounds, and volatile phenols all depend on plant secondary metabolism for precursor supply, among which terpenoids are formed through a highly diverse terpenoid biosynthetic network [36], whereas bound aromatic precursors can be released and converted into free volatiles during processing [44]. Liu et al. [30] similarly found in alfalfa that VOC differences were associated with multiple metabolic pathways, while Liu et al. [31] observed enrichment of secondary metabolite- and terpenoid-related pathways in *Atractylodes lancea* subjected to different drying methods. The widely targeted volatilomics study by Yuan et al. [45] also demonstrated that volatile profiles can reflect systematic changes in plant metabolic status.

4.7 Correlation between electronic nose responses and nutritional quality as well as color indicators

Correlation analysis showed that WSC was positively correlated with W1C, W3C, and W5C, and negatively correlated with W1S and W2S; W5S was positively correlated with ADF and a. W1W exhibited the most extensive associations, being significantly positively correlated with ADF, DM, browning degree(A_{420nm}), L^* , and a^* , and significantly negatively correlated with CP; W2W was also positively correlated with ADF, DM, L^* , and a^* . These findings indicate that the volatile changes captured by the electronic nose share a common temperature response with dehydration degree, fiber composition, protein retention, and overall color changes. Liu et al. [30] found in alfalfa that electronic nose signals could be significantly linked to nutritional quality and characteristic VOCs, and Liu et al. [31] also reported strong correlations between electronic nose responses and differential VOCs. Given its advantages of rapidity, minimal sample pretreatment, and suitability for batch detection, the electronic nose can be used to construct rapid discrimination models for the drying quality of forage oats, and W1W, W2W, and W5S can therefore serve as priority sensors for this purpose [32, 33, 46].

Conclusion

In this study, the effects of different drying temperatures on the nutritional quality, color changes, odor response intensity, and VOCs of forage oats were investigated using electronic nose and GC–MS. The results demonstrated that drying temperature systematically reshaped the quality of forage oats by simultaneously regulating moisture removal, preservation of nutritional components, browning reactions, and the balance between endogenous and thermally generated VOCs. Under the present experimental conditions, D75 exhibited a favorable nutritional–color–odor balance, whereas D95 was characterized by markedly enhanced thermal reaction-derived flavor formation and reduced nutritional quality.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that there are no known competitive economic or personal conflicts of interest that may have an impact on this study.

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Author Contribution

Conceptualization, methodology, data curation, writing-original draft preparation and writing- review and editing: R.Z.W. Methodology: Y.C.L. Investigation and resources: W.Q.M, P.J.S, M.J.L . Project administration and funding acquisition: Z.J.W., G.T.G., Y.S.J. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The authors will supply the relevant data in response to reasonable requests.

References

1. Zhang J, Cai C, Yan C, Wang G. Sustainable drying technologies for forage: A comprehensive review of research progress, strategies, opportunities, and future developments. *Sustain Energy Technol Assess.* 2025;77:104324.
2. Zhang J, Karim A, Sutar PP, Mujumdar AS, Wang Z-X, Shi Y-S, et al. Sustainable development of drying technologies for agricultural products: recent advances, challenges, and future prospects. *Renew Sustain Energy Rev.* 2026;226:116419.
3. Kaplan M, Çetin N, Çiftci B, Karpuzcu S. Comparison of drying methods for biochemical composition, energy aspects, and color properties of alfalfa hay. *Biomass Conv Bioref.* 2025;15:10331–46.
4. Bandla N, Südekum K-H, Gerlach K, Review. Role of silage volatile organic compounds in influencing forage choice behavior and intake in ruminants. *Anim Feed Sci Technol.* 2024;307:115853.
5. Meng L, Nie Y, Zhou Q, Zheng T, Song J, Zhang C, et al. Effect of hot-air drying processing on the volatile organic compounds and maillard precursors of *Dictyophora Rubrovalvata* based on GC-IMS, HPLC and LC-MS. *Food Chem.* 2025;463:141074.
6. Li S-F, Hao X-F, Hu Y-J, Shang B, Feng S-H, Hu J-Z, et al. An integrated study of quality variations for *Eucommia ulmoides* Oliver staminate flower processed with different drying treatments by untargeted metabolomics coupled with chemometrics. *Ind Crops Prod.* 2024;221:119468.
7. Liu F, Zhu H, Li C, Wang Y, Zhang J, Tang X, et al. A combined drying process involving hot air and roasting for improving summer congou black tea quality. *Food Res Int.* 2025;201:115584.
8. Okonkwo CE, Onyeaka H, Olaniran AF, Isaac-Bamgboye FJ, Nwaiwu O, Ukwuru M, et al. Changes in flavor profile of vegetable seasonings by innovative drying technologies: A review. *J Food Sci.* 2024;89:6818–38.
9. Feng Y, Wang Y, Beykal B, Qiao M, Xiao Z, Luo Y. A mechanistic review on machine learning-supported detection and analysis of volatile organic compounds for food quality and safety. *Trends Food Sci Technol.* 2024;143:104297.
10. Gite SS, Karmakar M, Mokashi S, Dalbhagat CG, Kambhampati V, Raigar RK, et al. Exploration of simulated human olfactory system and its integration with machine learning algorithms for food quality assessment: A review. *Trends Food Sci Technol.* 2025;159:104977.
11. Girmatsion M, Tang X, Zhang Q, Li P. Progress in machine learning-supported electronic nose and hyperspectral imaging technologies for food safety assessment: A review. *Food Res Int.* 2025;209:116285.
12. Melikoglu M. The electronic nose: A critical global review of advances in analytical methods and real-world applications. *Microchem J.* 2025;218:115363.
13. Shi J, Xiao N, Zhang Q, Tian Z, Li M, Shi W. Evaluation of aroma characteristics of *Penaeus vannamei* with different drying methods using HS-SPME-GC-MS, MMSE-GC-MS, and sensory evaluation. *Food Chem.* 2024;449:138957.

14. Guclu G, Keser D, Kelebek H, Keskin M, Emre Sekerli Y, Soysal Y, et al. Impact of production and drying methods on the volatile and phenolic characteristics of fresh and powdered sweet red peppers. *Food Chem.* 2021;338:128129.
15. Siewe FB, Kudre TG, Bettadaiah BK, Narayan B. Effects of ultrasound-assisted heating on aroma profile, peptide structure, peptide molecular weight, antioxidant activities and sensory characteristics of natural fish flavouring. *Ultrason Sonochem.* 2020;65:105055.
16. Zhang Q, Wu B, Nishino N, Wang X, Yu Z. Fermentation and microbial population dynamics during the ensiling of native grass and subsequent exposure to air. *Anim Sci J.* 2016;87:389–97.
17. Van Soest PJ, Robertson JB, Lewis BA. Methods for Dietary Fiber, Neutral Detergent Fiber, and Nonstarch Polysaccharides in Relation to Animal Nutrition. *J Dairy Sci.* 1991;74:3583–97.
18. Owens VN, Albrecht KA, Muck RE, Duke SH. Protein Degradation and Fermentation Characteristics of Red Clover and Alfalfa Silage Harvested with Varying Levels of Total Nonstructural Carbohydrates. *Crop Sci.* 1999;39:1873–80.
19. Bai B, Qiu R, Ge G, Liu M, Liu Y, Zhao M, et al. Mechanism of Alfalfa in Enhancing Goose Egg Yolk Flavor: An Analysis Based on Metabolomics and Quantitative Lipidomics. *Food Front.* 2026;7:e70199.
20. Buvé C, Pham HTT, Hendrickx M, Grauwet T, Van Loey A. Reaction pathways and factors influencing nonenzymatic browning in shelf-stable fruit juices during storage. *Comp Rev Food Sci Food Safe.* 2021;20:5698–721.
21. Heaton JW, Marangoni AG. Chlorophyll degradation in processed foods and senescent plant tissues. *Trends Food Sci Technol.* 1996;7:8–15.
22. Thamkaew G, Sjöholm I, Galindo FG. A review of drying methods for improving the quality of dried herbs. *Crit Rev Food Sci Nutr.* 2021;61:1763–86.
23. Huang Y, Sun Y, Lu T, Chen X. Effects of hot-air drying on the bioactive compounds, quality attributes, and drying and color change kinetics of coffee leaves. *J Food Sci.* 2023;88:214–27.
24. Pelletier S, Tremblay GF, Bertrand A, Bélanger G, Castonguay Y, Michaud R. Drying procedures affect non-structural carbohydrates and other nutritive value attributes in forage samples. *Anim Feed Sci Technol.* 2010;157:139–50.
25. Rebolé A, Treviño J, Barro C, Alzueta C, Caballero R. Chemical changes associated with the field drying of oat forage. *Field Crops Res.* 1996;47:221–6.
26. Deinum B, Maassen A. Effects of drying temperature on chemical composition and in vitro digestibility of forages. *Anim Feed Sci Technol.* 1994;46:75–86.
27. Poojary MM, Lund MN. Chemical Stability of Proteins in Foods: Oxidation and the Maillard Reaction. *Annu Rev Food Sci Technol.* 2022;13:35–58.
28. Shakoor A, Zhang C, Xie J, Yang X. Maillard reaction chemistry in formation of critical intermediates and flavour compounds and their antioxidant properties. *Food Chem.* 2022;393:133416.

29. Wei M, Wang Y, Zhang Y, Liu J, Zhao B, Lu S, et al. Effects of preservatives and drying methods on the nutrient composition and mould counts of hay and pellet processing of Oats. *Sci Rep*. 2025;15:15646.
30. Liu Y, Wang Z, Sun L, Bao J, Si Q, Liu M, et al. Analysis of forage quality, volatile organic compounds and metabolic pathways in alfalfa (*Medicago sativa* L.) at different stages based on electronic nose and GC-MS. *Chem Biol Technol Agric*. 2024;11:22.
31. Liu Y, Wang M, Wang Z, Liu G, Su Y, Hao J, et al. Effects of drying methods on the functional components and volatile organic compounds of *Atractylodes chinensis*. *BMC Plant Biol*. 2026;26:1117.
32. Mohd Ali M, Hashim N, Abd Aziz S, Lasekan O. Principles and recent advances in electronic nose for quality inspection of agricultural and food products. *Trends Food Sci Technol*. 2020;99:1–10.
33. Wesolý M, Przewodowski W, Ciosek-Skibińska P. Electronic noses and electronic tongues for the agricultural purposes. *TRAC Trends Anal Chem*. 2023;164:117082.
34. Klensporf D, Jeleń HH. Effect of heat treatment on the flavor of oat flakes. *J Cereal Sci*. 2008;48:656–61.
35. Li X, Oey I, Kebede B. Effect of industrial processing on the volatiles, enzymes and lipids of wholegrain and rolled oats. *Food Res Int*. 2022;157:111243.
36. Nagegowda DA, Gupta P. Advances in biosynthesis, regulation, and metabolic engineering of plant specialized terpenoids. *Plant Sci*. 2020;294:110457.
37. Wang T, An J, Chai M, Zhu Z, Jiang Y, Huang X, et al. Volatile metabolomics reveals the characteristics of the unique flavor substances in oats. *Food Chemistry: X*. 2023;20:101000.
38. Ren A, Zhang Y, Bian Y, Liu Y, Zhang Y, Ren C, et al. Pyrazines in food samples: Recent update on occurrence, formation, sampling, pretreatment and analysis methods. *Food Chem*. 2024;430:137086.
39. Yu H, Zhang R, Yang F, Xie Y, Guo Y, Yao W, et al. Control strategies of pyrazines generation from Maillard reaction. *Trends Food Sci Technol*. 2021;112:795–807.
40. McGorrrin RJ. Key Aroma Compounds in Oats and Oat Cereals. *J Agric Food Chem*. 2019;67:13778–89.
41. Li X, Oey I, Leong SY, Kebede B. Understanding the volatile flavour changes during accelerated shelf-life testing of oats using chemometrics and kinetic modelling. *Food Chem*. 2023;405:134864.
42. Bai X, Zhang M, Zhang Y, Zhang Y, Guo X, Huo R. Effects of Pretreatment on the Volatile Composition, Amino Acid, and Fatty Acid Content of Oat Bran. *Foods*. 2022;11:3070.
43. Zhang Y, Zhang M, Bai X, Zhang Y, Zhang J, Huo R. Influence of stir-frying on the lipid stability and flavor substances in oat flour during storage using HS-SPME-GC-MS and electronic nose. *Food Qual Saf*. 2023;7:fyac066.
44. Liang Z, Fang Z, Pai A, Luo J, Gan R, Gao Y, et al. Glycosidically bound aroma precursors in fruits: A comprehensive review. *Crit Rev Food Sci Nutr*. 2022;62:215–43.

45. Yuan N, Sun L, Du S, Ge G, Wang Z, Li Y, et al. Effects of Harvesting Period and Storage Duration on Volatile Organic Compounds and Nutritive Qualities of Alfalfa. *Agriculture*. 2022;12:1115.

46. Li Y, Wang Z, Zhao T, Li H, Jiang J, Ye J. Electronic nose for the detection and discrimination of volatile organic compounds: Application, challenges, and perspectives. *TRAC Trends Anal Chem*. 2024;180:117958.

Figures

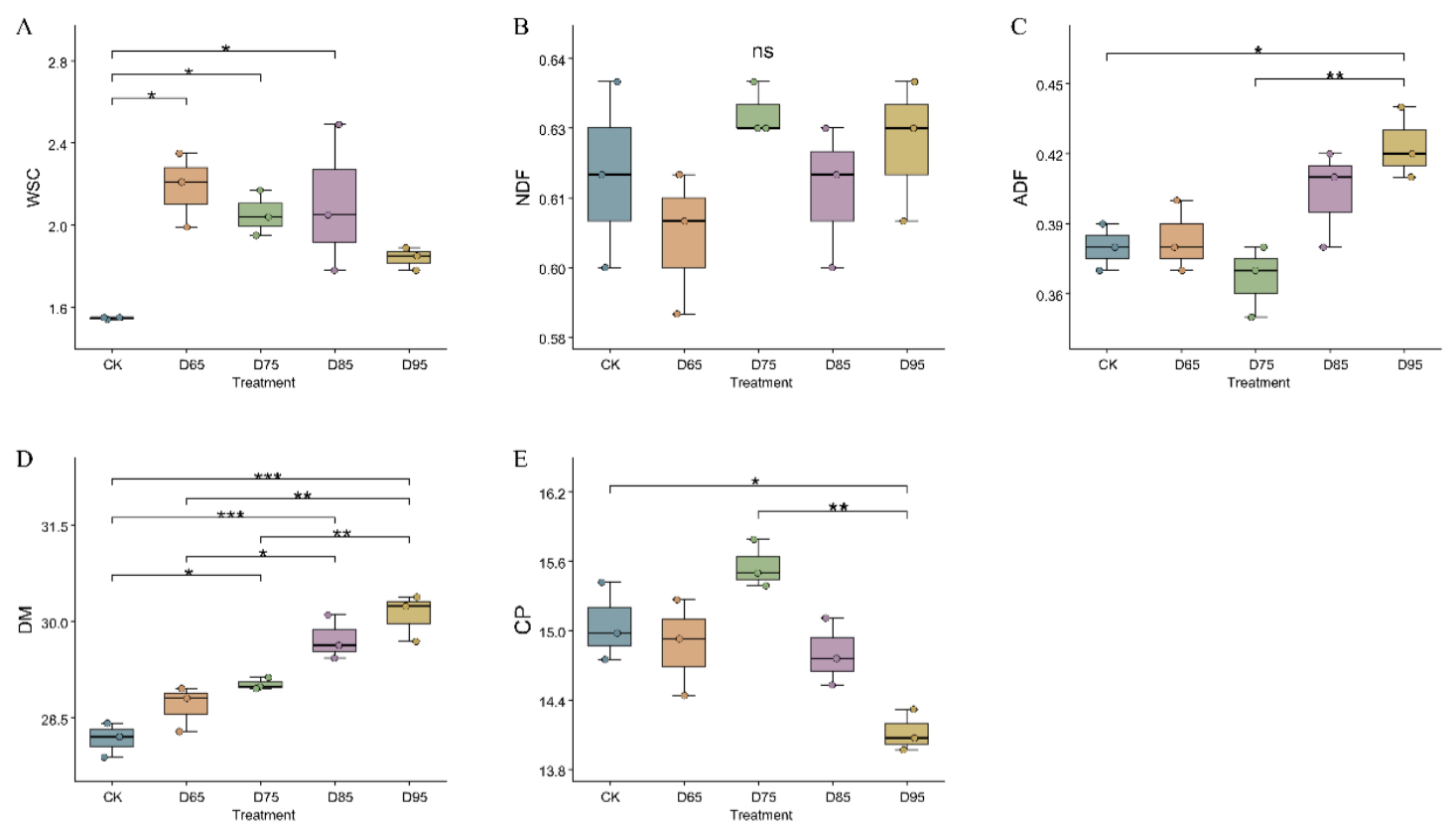


Figure 1

Nutritional quality of forage oats under different drying temperatures. * indicates significant differences among different temperature treatments ($P < 0.05$).

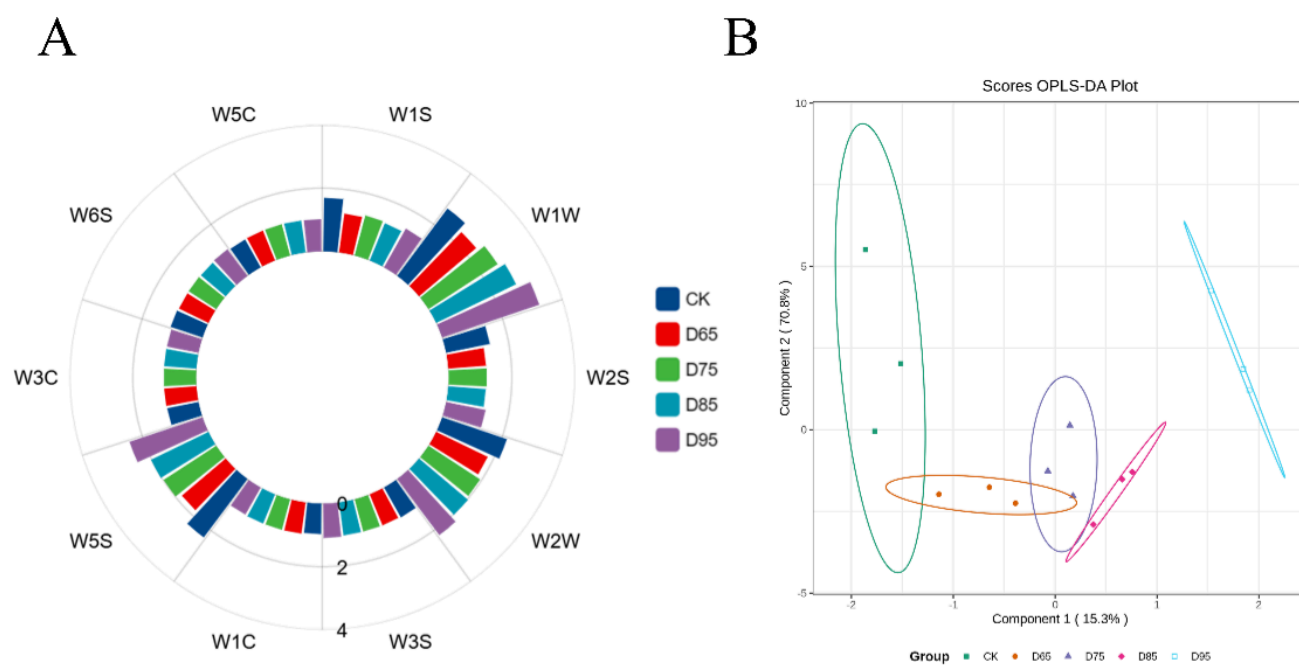
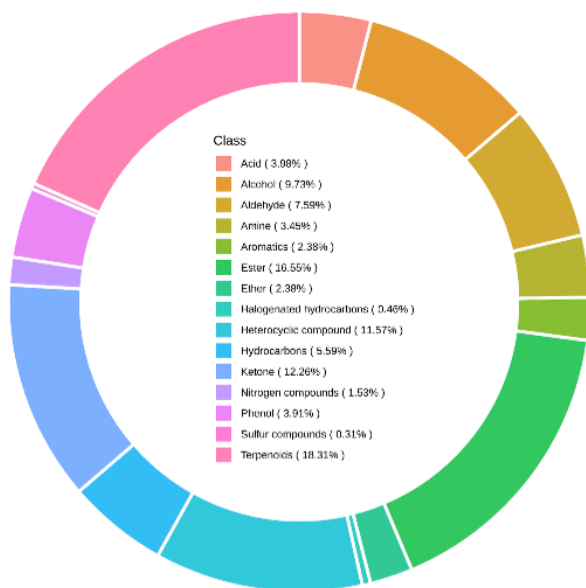


Figure 2

Radar chart of electronic nose response intensity (A). OPLS-DA score plot of response intensity (B). CK, shade drying; D65, hot-air drying at 65 °C; D75, hot-air drying at 75 °C; D85, hot-air drying at 85 °C; D95, hot-air drying at 95 °C. $R^2X = 0.96$, $R^2Y = 0.962$, $Q^2 = 0.868$.

A



B

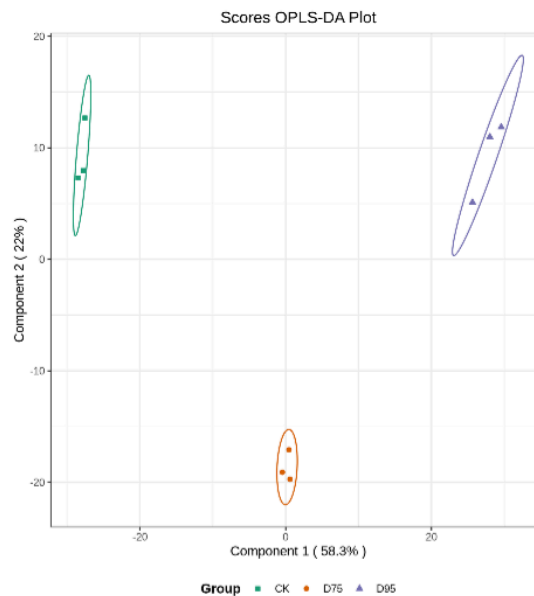


Figure 3

Donut chart of VOCs classification (A). OPLS-DA score plot of VOCs (B). CK, shade drying; D65, hot-air drying at 65 °C; D75, hot-air drying at 75 °C; D85, hot-air drying at 85 °C; D95, hot-air drying at 95 °C. $R^2X = 0.803$, $R^2Y = 0.998$, $Q^2 = 0.985$.

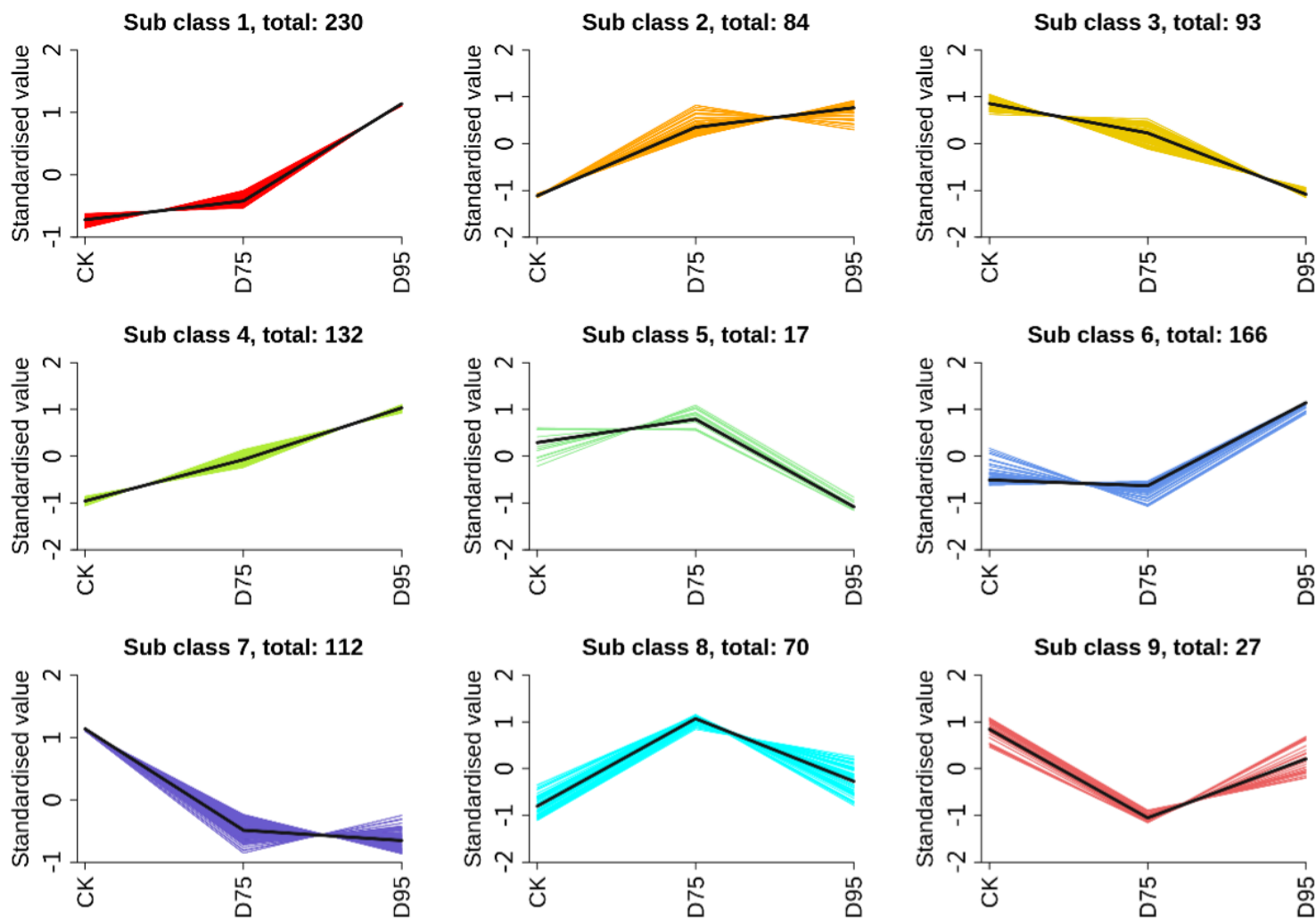


Figure 4

K-means cluster analysis of VOCs. The x-axis represents different samples, and the y-axis represents the normalized content of each metabolite. CK, shade drying; D75, hot-air drying at 75 °C; D95, hot-air drying at 95 °C.

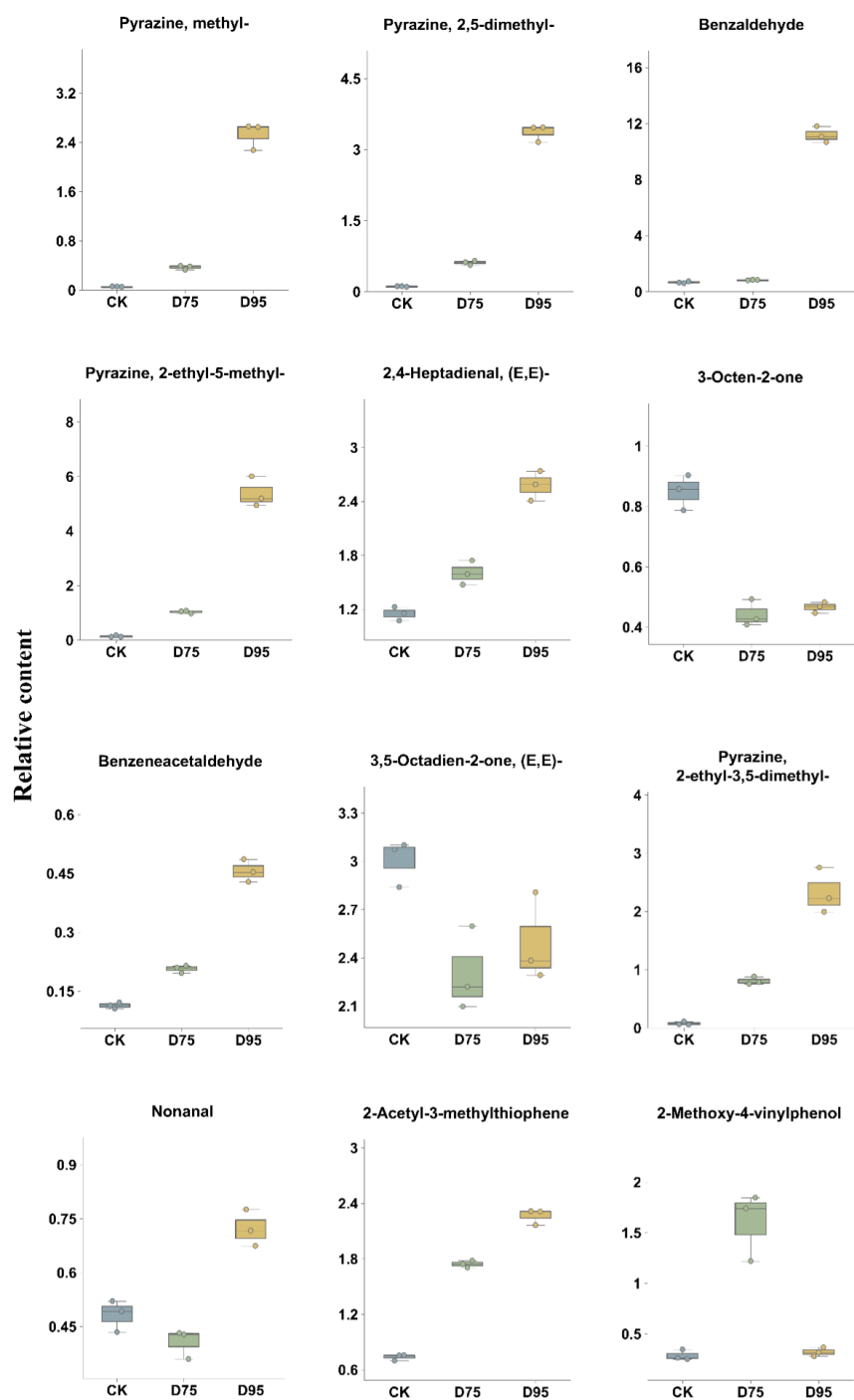


Figure 5

Box plots of 12 differential VOCs. CK, shade drying; D75, hot-air drying at 75 °C; D95, hot-air drying at 95 °C.

KEGG Classification



Figure 6

KEGG classification of VOCs.

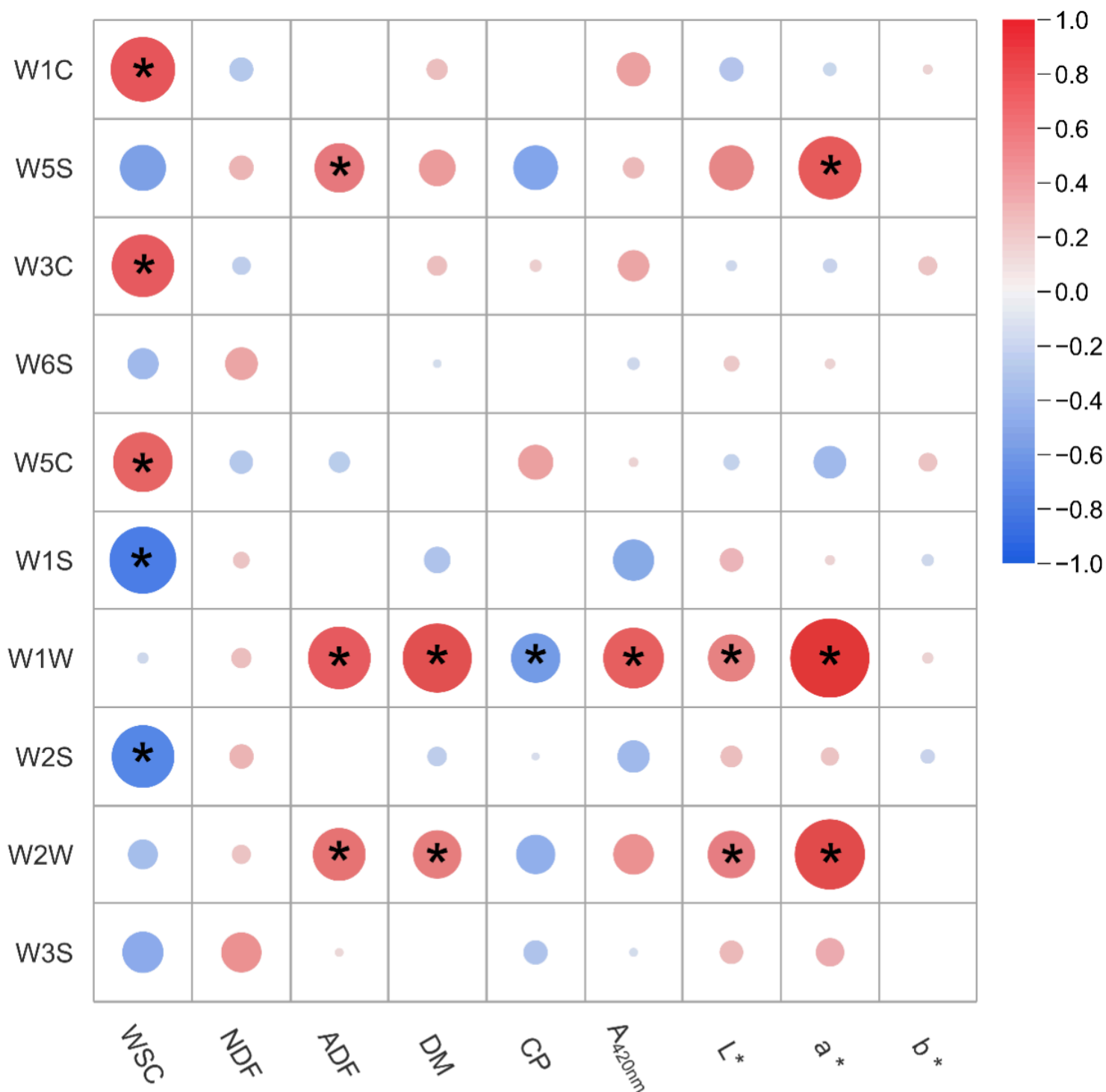


Figure 7

Correlations between odor response intensity and nutritional quality as well as color indices. Red represents positive correlations, blue represents negative correlations, and * indicates $P < 0.05$.