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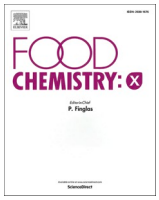

Characterisation of the volatile compounds in nine varieties and three breeding selections of celery using GC–IMS and GC–MS

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ABSTRACT

Celery (*Apium graveolens* L.) is a popular vegetable crop planted worldwide. In this study, the volatile compound characteristics of three *A. graveolens* var. *dulce* varieties (type D), and six *A. graveolens* var. *secalinum* varieties (type S), and three breeding selections were analysed and 41 and 73 volatile compounds were identified using GC–MS and GC–IMS, respectively. The results showed that type S emitted more terpenes and phthalides than type D varieties. Both GC–MS and GC–IMS could discriminate between type S and type D. Six potential biomarkers, i.e., sabinene, (*E*)-caryophyllene, α-phellandrene, limonene, γ-terpinene, and hexanal, were identified using both models. Both GC–MS and GC–IMS could discriminate between parent and breeding selection. The relative contents of seven (GC–IMS OPLS–DA model) and ten (GC–MS OPLS–DA model) volatile compounds showed over-parent heterosis. This study provides a technical reference for distinguishing celery varieties in the same habitat and preliminarily reveals the aroma relationship between breeding selections and their parents.

1. Introduction

Celery (*Apium graveolens* L.) is a popular vegetable crop planted worldwide. It inhibits hypertension, diabetes, and obesity and can reduce high uric acid levels (Khairullah et al., 2021); thus, it is considered a healthy food. Aroma is an important characteristic for evaluating celery quality. Researchers have identified many aromatic substances in different celery parts, products, and varieties using various detection methods. Aromatic substances include alcohols, ketones, esters, terpenes, and butylphthalides (Turner et al., 2021a). Variety, harvest time, cultivation environment, and cultivation methods can affect the aroma of celery (Malhotra, 2012).

Celery can be divided into three morphological types based on its edible parts. *Apium graveolens* var. *dulce,* commonly referred to as celery, has solid and succulent petioles; *Apium graveolens* var. *secalinum*, commonly referred to as the Chinese celery, has slender and hollow petioles; and *Apium graveolens* var. *rapaceum,* commonly known as root celery, develops enlarged hypocotyls and roots (Quiros, 1993). Current celery varieties on the market belong to these three morphological types. In addition, breeders have cultivated varieties with traits between the two celery types by hybridising *A. graveolens* var. *dulce* and *A. graveolens* var. *secalinum*. Breeders must consider aromatic traits during the breeding process to meet the requirements of different consumers. To date, little research has been conducted on the characterisation of aromatic compounds in celery varieties. Turner et al. (2021b) observed differences in the aromatic characteristics of eight celery varieties (*A. graveolens* var. *dulce*), and the influence of geographical location was more significant than that of the genotype. However, the aromatic characteristics of *A. graveolens var. dulce* and *A. graveolens* var. *secalinum* and breeding selection for this species have not yet been reported.

Some producers often use varieties with similar appearances but poor quality to replace high-quality varieties to save seed costs, resulting in celery products of uneven quality. This harms the interests of breeders and causes consumer dissatisfaction. Many studies, such as those on black soybeans (He et al., 2023), quinoas (Song et al., 2021) and tea (Yue et al., 2023), have shown that varieties can be distinguished by analysing the differences in aroma components. Currently, different methods are used to analyse the aromatic components of celery, with gas chromatography–mass spectrometry (GC–MS) being the leading technology used for volatile component analysis (Deng et al., 2003; Shojaei

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et al., 2011; Sorour et al., 2015). Gas chromatography-ion mobility spectrometry (GC–IMS) technology has been widely used in volatile compounds analyses in recent years, emerging as an analytical technique for measuring volatile compounds, agricultural products classification and quality supervision (Xie et al., 2023; Feng, Sun, et al., 2022; Feng, Wang, et al., 2022). Compared with the GC–MS method, GC–IMS is fast, sensitive, and inexpensive (Wang et al., 2020) and is suitable for testing large amounts of samples. However, research on the characterisation of volatile compounds in celery using GC–MS and GC–IMS is lacking.

In this study, the volatile compound characteristics of three *A. graveolens* var. *dulce* varieties, six *A. graveolens* var. *secalinum* varieties, and three breeding selections were analysed using GC–MS and GC–IMS. Principal component analysis (PCA) and orthogonal partial least squares-discriminant analysis (OPLS–DA) were used to distinguish celery samples. Volatile compounds with identification potential based on the OPLS–DA models were screened using the variable importance in the projection (VIP) method. This study provides a technical reference for discriminating different celery varieties and analysing the possibility of aroma breeding.

2. Materials and methods

2.1. Plant materials

Twelve celery varieties were used in this study (Fig. 1): three *Apium graveolens* var. *dulce* (type D) varieties, i.e., Ventura (VT), Queen (PC), and California King (CK); six *Apium graveolens* var. *secalinum* (type S) varieties, i.e., yellow heart celery (HY), red plum celery (PY), hollow celery (SCC), bao celery (BQ), white jade celery (SW), and Shenqin No. 4 (S4); and three breeding selections (maternal parent HY and male parent CK), i.e., Shangnong Yuqin (SHY), Shenqin No. 2 (S2), and Shenqin No. 3 (S3). Seeds of the 12 celery varieties were provided by the Shanghai Academy of Agricultural Sciences celery breeding project team. The germinated seeds were planted in trays. After 45 days, seedlings with four true leaves and a height of 10 cm were selected and planted in the greenhouse (temperature range:15–20 °C, relative humidity: 45 %–65 %) of the Zhuanghang Experimental Base in Fengxian District, Shanghai. Unified fertiliser and water management were conducted according to the commercial celery planting standard. All varieties were harvested on day 70 after transplanting. The third leaf of the celery was cut, the leaves and branches were removed, and the petiole was cut into small segments (2 cm in length) to be used for volatile substance analysis.

2.2. GC–IMS and GC–MS analysis

The GC–IMS and GC–MS analyses were performed using a Flavorspec flavour analyser (G.A.S, Germany) and an Agilent Model 8890 GC with a 7000D mass spectrometer (Agilent), respectively, according to our previous study (Yan et al., 2024) (Detail methods show in Supplementary method). For GC–IMS analysis, 3 g fresh celery petiole segments (2 cm) were immediately analysed after being stored at 4 °C. Celery petiole segments (2 cm) stored at −80 °C were freeze-dried and ground, and 0.5 g of celery powder were used to detect the volatile metabolites using GC–MS analysis.

2.3. Multivariate statistics

SPSS25.0 was used to analyse the significant differences among the volatile compounds (Duncan, $P < 0.05$). PCA and OPLS–DA were conducted using the SIMCA software 14.

Fig. 1. The picture of 12 celery varieties used in this study.

3. Results and discussion

3.1. Volatile compounds analysis by GC–IMS

As shown in the two-dimensional spectrum (Fig. 2A), four compounds were present in both monomer and dimer forms ((*E*)-ocimene, β-pinene, α-pinene, γ-terpinene), and four compounds were found in monomer, dimer, and trimer forms (terpinolene, limonene, α-terpinene, α-phellandrene). Therefore, 41 volatile compounds were identified in the celery samples (Table S1). Most of these compounds were small-molecule compounds (C4–C10), including 12 monoterpenes, 4 sesquiterpenes, 5 alcohols, 4 aldehydes, 4 ketones, 5 esters, 3 pyrazines, and 4 other compounds. Phthalides are the characteristic compounds of celery aroma (Bartschat et al., 1997; Kurobayashi et al., 2006). Phthalides were not detected using GC–IMS. Phthalides are large molecular volatile compounds (C12) with higher boiling points (Beck & Chou, 2007), and GC–IMS technology is not sensitive to volatile compounds with high boiling points (Feng, Sun, et al., 2022; Feng, Wang, et al., 2022).

Quantitative analysis of the volatile compounds was represented by the normalised peak volume calculated using the IMS system. Monoterpenes accounted for the highest proportion in the aroma spectra, ranging from 57.00 to 71.84 % for 12 celery samples and mainly included limonene (19.22–27.85 %), α-phellandrene (5.39–9.71 %) and γ-terpinene (8.09–11.54 %). Various studies have confirmed that monoterpenes are the most abundant compounds in celery aroma spectra (Orav et al., 2003; Turner et al., 2021b). This study found a higher proportion of α-phellandrene in the aroma spectra of celery than previous studies, which was speculated to be caused by the geographical location and climate of cultivation. The planting environment significantly impacts celery's aroma (Deng et al., 2003; Turner et al., 2021b, 2021c). Untreated fresh celery petioles were used as determination samples in the GC–IMS method. These results indicated that celery aroma spectra may differ depending on sample processing methods and analytical instruments.

The fingerprint of the detected volatile compounds was established using the gallery plot plugin of the LAV software (Fig. 2B and Fig. 2C). The fingerprints showed that the content of volatile compounds was significantly different among the nine celery varieties (three type Ds and six type Ss), the breeding selections SHY and S2 were similar with the maternal parent YH, and breeding selection S3 was similar with the male parent CK.

3.2. Volatile compound analysis using GC–MS

A total of 73 volatile compounds were detected in 12 celery varieties, including 26 monoterpenes, 16 sesquiterpenes, 6 phthalides, 6 alcohols, 6 aldehydes, 5 esters, 4 ketones, and 4 alkanes. The total ion chromatograms and detailed information on the volatile compounds were shown in Fig. S1 and Table S2, respectively. The relative contents of volatile compounds were calculated using internal standards. The volatile compounds among the 12 celery varieties were similar, and the monoterpenes, phthalides, and sesquiterpenes accounted for approximately 90 % of the total volatile compound content collected in the headspace. Among them, limonene was the most abundant, followed by γ-terpinene, 3-n butylphthalide, sedanenolide, β-selinene and hexanal. These results are similar with those reported previously (Turner et al., 2021b, 2021c).

3.3. Discrimination of celery varieties based on GC–MS and GC–IMS data

PCA can be used to distinguish the varieties and geographical sources of agricultural products (Segelke et al., 2020). The R^2X (cum) values of GC–MS PCA models and GC–IMS PCA models were 0.824 and 0.832, respectively, and the Q^2 (cum) values were 0.721 and 0.649, respectively, indicating that the two models were effective. As shown in the score charts of both models (Fig. 3A and Fig. 3B), six type D and three type S varieties were distributed on two sides of the Y-axis, indicating that both PCA models had good predictability for discriminating between the two celery types. As shown in Fig. 3A and Fig. 3B, the GC–IMS PCA model distinguished each variety, whereas the clusters of some varieties in the GC–MS PCA model significantly overlapped, demonstrating that the GC–IMS PCA model was more discernible than the GC–MS PCA model in distinguishing different varieties of the same celery type. Compared to GC–MS, GC–IMS does not require a sample pretreatment process; it can directly analyse the volatile compounds in fresh samples and intuitively reflect the differences in the aroma of the samples (Gu et al., 2021; Zhang et al., 2020).

The OPLS–DA model is a supervised pattern-recognition multivariate statistical method that can maximise the separation between sample groups and discriminate potential metabolites related to metabolic changes (Su et al., 2022). Two OPLS–DA models were established using the GC–MS and GC–IMS data (Fig. 3C and Fig. 3D). The prediction parameters of the GC–MS OPLS–DA model ($R^2X = 0.816$, $R^2Y = 0.985$, and $Q^2 = 0.982$) and the GC–IMS OPLS–DA model ($R^2X = 0.876$, $R^2Y = 0.997$, and Q^2 0.996) showed that both models had good predictive ability (Trygg & Wold, 2010). Permutation tests were conducted 200 times to verify the fit of the two OPLS–DA models. The original R^2 and Q^2 values on the right side were higher than those on the left, indicating that the two models were stable and reliable (Fig. 3E and Fig. 3F). Similar with the PCA, both OPLS–DA models divided the nine celery varieties into two categories (types D and S). Among the nine celery samples, the aroma characteristics of PC and VT were relatively similar; SW and PY also had similar aroma characteristics, as did BQ and SCC, and YH and S4 (Fig. 3C and Fig. 3D).

Typically, when the VIP value of a variable is >1, it is considered a key component of sample differentiation (Xu et al., 2021). The VIP values of 15 and 18 volatile compounds were > 1 in the GC–IMS OPLS–DA and GC–MS OPLS–DA models, respectively, indicating that these volatile compounds could distinguish between the two types of celery. Six of these potential biomarkers, i.e., sabinene, (*E*)-caryophyllene, α-phellandrene, limonene, γ-terpinene and hexanal, were identified in both models. Sedanenolide, 3-n-butylphthalide, and cis-ligustilide were identified as potential biomarkers in the GC–MS OPLS–DA model.

As shown in the box plots of the potential biomarkers in the two models, the terpenoid and phthalide contents in type S were higher than those in type D (Fig. 4 and Fig. 5). Terpenoids and phthalides are the primary sources of celery aroma (Lund et al., 1973; Oguro & Watanabe, 2011). In the GC-IMS OPLS-DA model, the content of four potential biomarkers (octanol, 2-methyl-1-propanol, cis-3-hexenyl acetate and (E)-3-hexen-1-ol) were higher in type D than in type S. In the GC–MS OPLS-DA model, the content of two potential biomarkers (1-Octen-3-ol and 1-Pentanol) were higher in type D than in type S. There is limited research on alcohols, aldehydes, and ketones, which are present in low abundance in celery. Although they do not possess the unique aroma of celery, they contribute to the overall aroma (Wilson, 1967).

3.4. Variations of volatile compounds in breeding selections and parents

Aroma is an important celery characteristic that affects consumer purchasing decisions. Two OPLS–DA models were established with two parental and three breeding selections as X variables and volatile compounds detected using GC–IMS and GC–MS as Y variables to analyse the variations in volatile compounds in breeding selections and parental lines. The prediction parameters of the GC–MS OPLS–DA model ($R^2X = 0.972$, $R^2Y = 0.988$, and $Q^2 = 0.973$) and GC–IMS OPLS–DA model ($R^2X = 0.962$, $R^2Y = 0.993$, and $Q^2 = 0.971$) showed that both models had good predictive ability (Fig. 6). Breeding selection was performed independently. In total, 17 and 23 differential volatile compounds (VIP > 1 and $P < 0.05$) were identified among the five celery genotypes using the GC–IMS OPLS–DA (Table 1) and the GC–MS OPLS–DA models (Table 2), respectively.

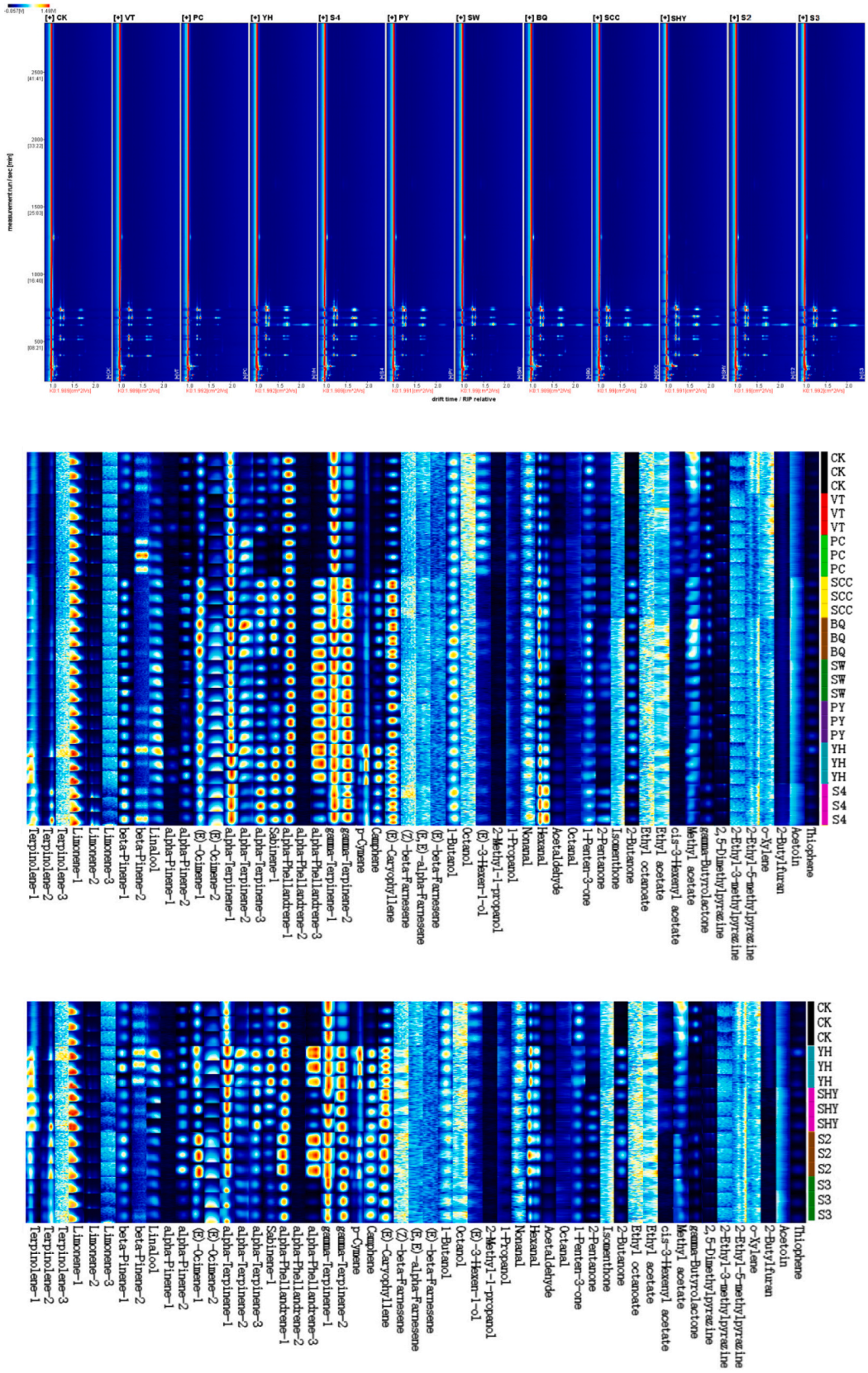

Fig. 2. Two-dimensional chromatogram spectrum of volatile compounds in12 celery varieties(A); The volatile compounds fingerprint of nine celery varieties(B) and three breeding selections(C).

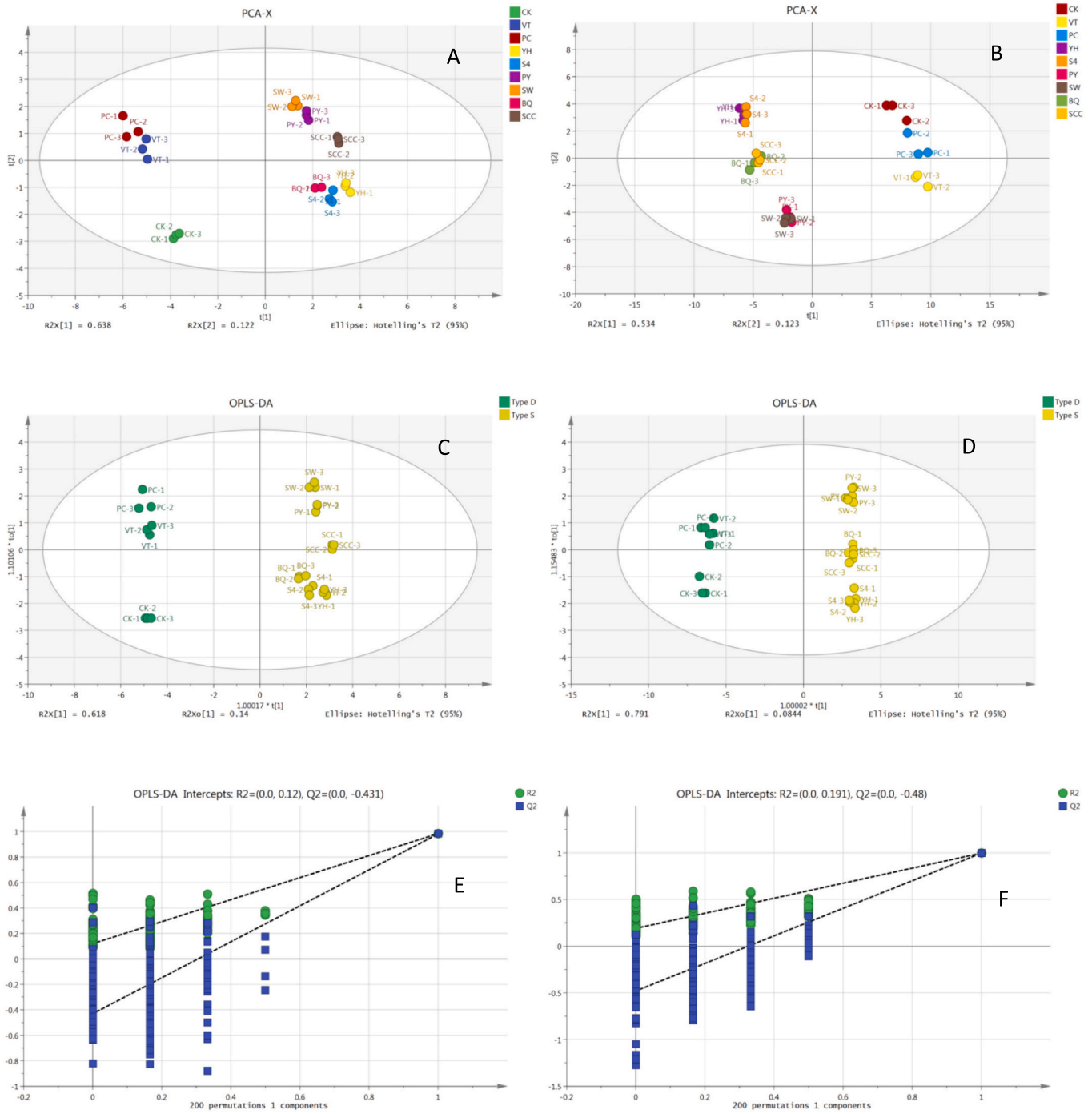

Fig. 3. PCA score plots of 9 celery varieties based on GC-IMS data(A) and GC–MS data(B); OPLS-DA score plots of 9 celery varieties based on GC-IMS data(C) and GC–MS data(D); The two hundred permutation tests of 9 celery varieties based on GC-IMS data(E) and GC–MS data(F).

These differential volatile compounds included the characteristic compounds of celery aroma (phthalides), the primary components that make up the celery aroma profile (terpenoids), alcohols, aldehydes, and ketones. As shown in Tables 1 and 2, the relative contents of most of the differential volatile compounds in the breeding selections were between those of the parental varieties. However, the relative contents of seven (GC–IMS OPLS–DA model) and ten (GC–MS OPLS–DA model) differential volatile compounds in the breeding selections were significantly higher than those in the parental lines, which indicated over-parent heterosis. Over-parent heterosis is a phenomenon in which some traits of hybrid offspring are superior to their parents in terms of growth potential, viability, resistance, and quality (Olvey, 1986) and has been applied in many crop breeding programs (Hou & Yi, 2023; Kumari et al., 2021; Németh-Zámbori et al., 2011). These results showed that various volatile compounds in celery changed during hybrid breeding, suggesting that hybrid breeding could improve the aroma characteristics of celery. However, owing to the limited sample size of this study, there may be a potential bias in sample selection. Therefore, further validation using larger breeding populations is required. Based on this study, we will design different hybrid combinations and analyse the aroma characteristics of the parent and large number of breeding selections in future studies. This will verify the genetic characteristics of celery volatile compounds in the hybrid breeding process and lay the foundation for breeders to improve the aroma of celery varieties.

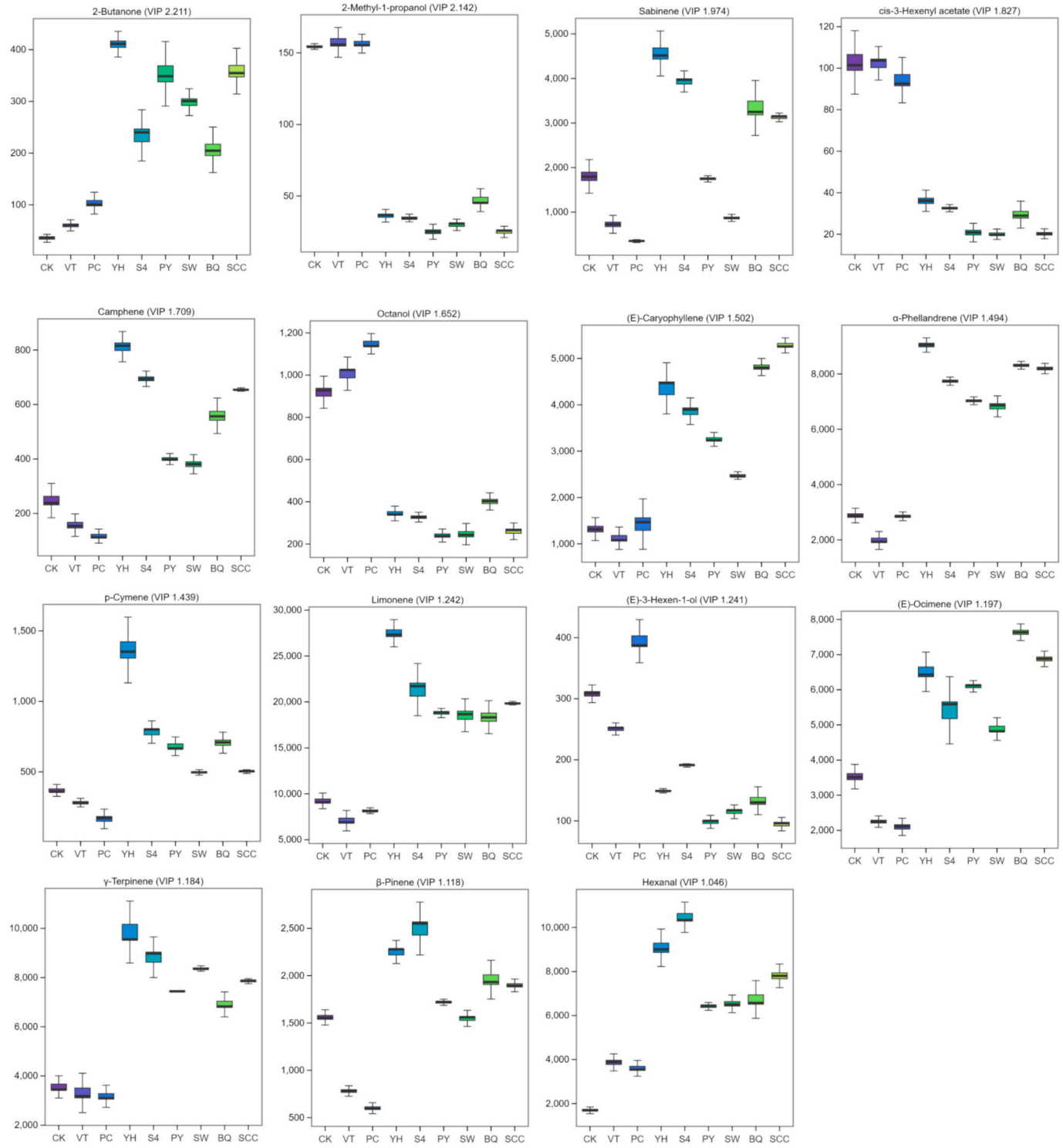

Fig. 4. Distribution of key aroma substances of nine celery varieties in the GC-IMS OPLS-DA model. The y-coordinate mean the signal intensity of the volatile compounds.

Currently, there is little research on celery aroma breeding, and the metabolic mechanism of volatile compounds in celery, which is an important factor limiting aroma breeding, remains unclear. Therefore, based on the identification of volatile compounds in this study, utilising published celery genome data and omics techniques, elucidating the metabolic pathways of volatile compounds in celery will help breeders conduct targeted breeding and develop varieties with distinct flavour characteristics.

4. Conclusion

In this study, GC–IMS and GC–MS technologies were used to identify the differences in the volatile compounds of three *Apium graveolens* var. *dulce* varieties (type D), six *Apium graveolens* var. *secalinum* varieties (type S) and three breeding selection. The ability of these two technologies to identify different celery varieties was first explored. The results showed that 41 and 73 volatile compounds were identified in celery using GC–IMS and GC–MS, respectively. Limonene was the most

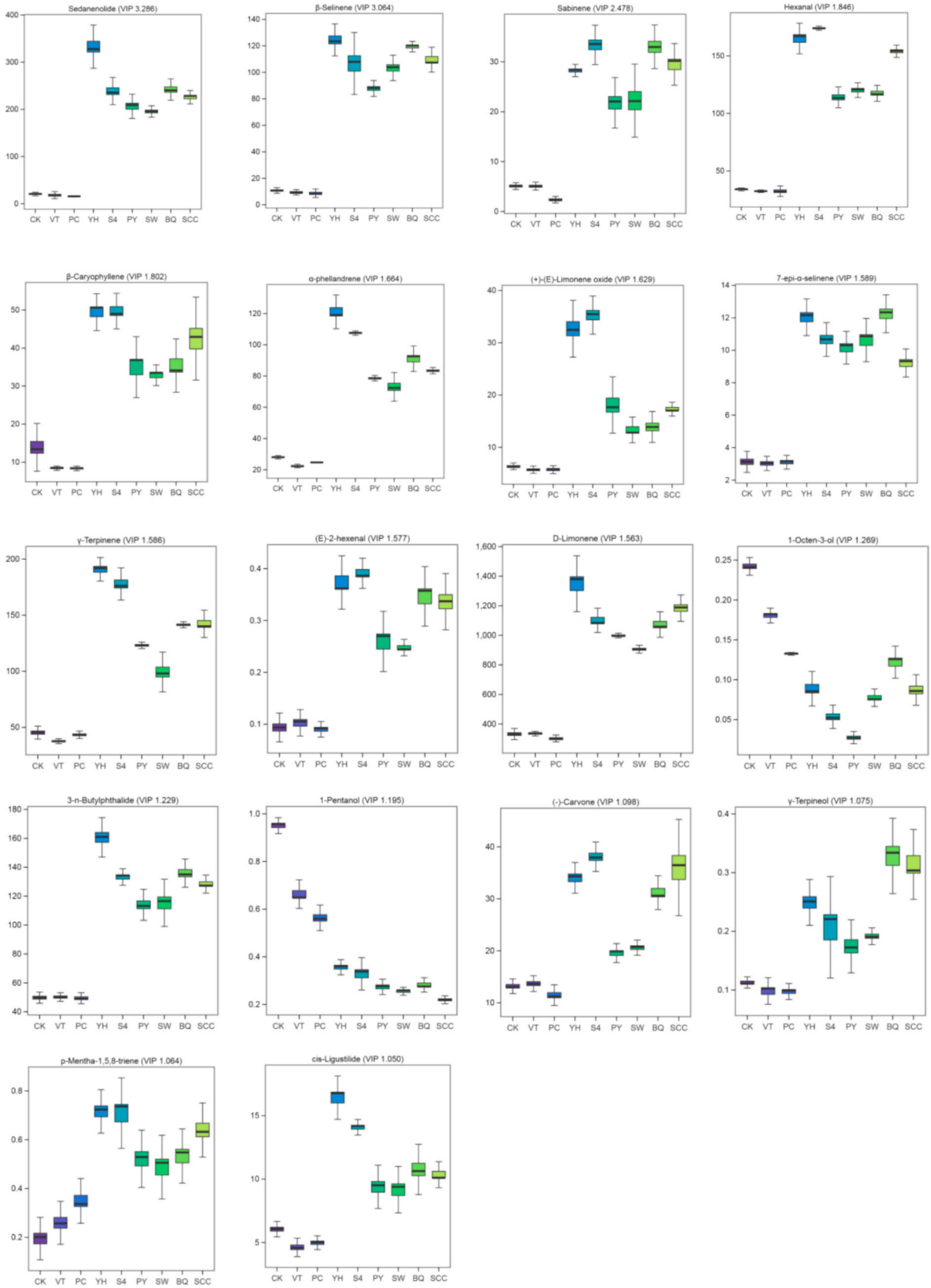

Fig. 5. Distribution of key aroma substances of nine celery varieties in the GC–MS OPLS-DA model. The y-coordinate mean the relative content (μg/mL) of the volatile compounds (calculated by comparison with of 50 μg/mL 3-hexanone used as internal standard).

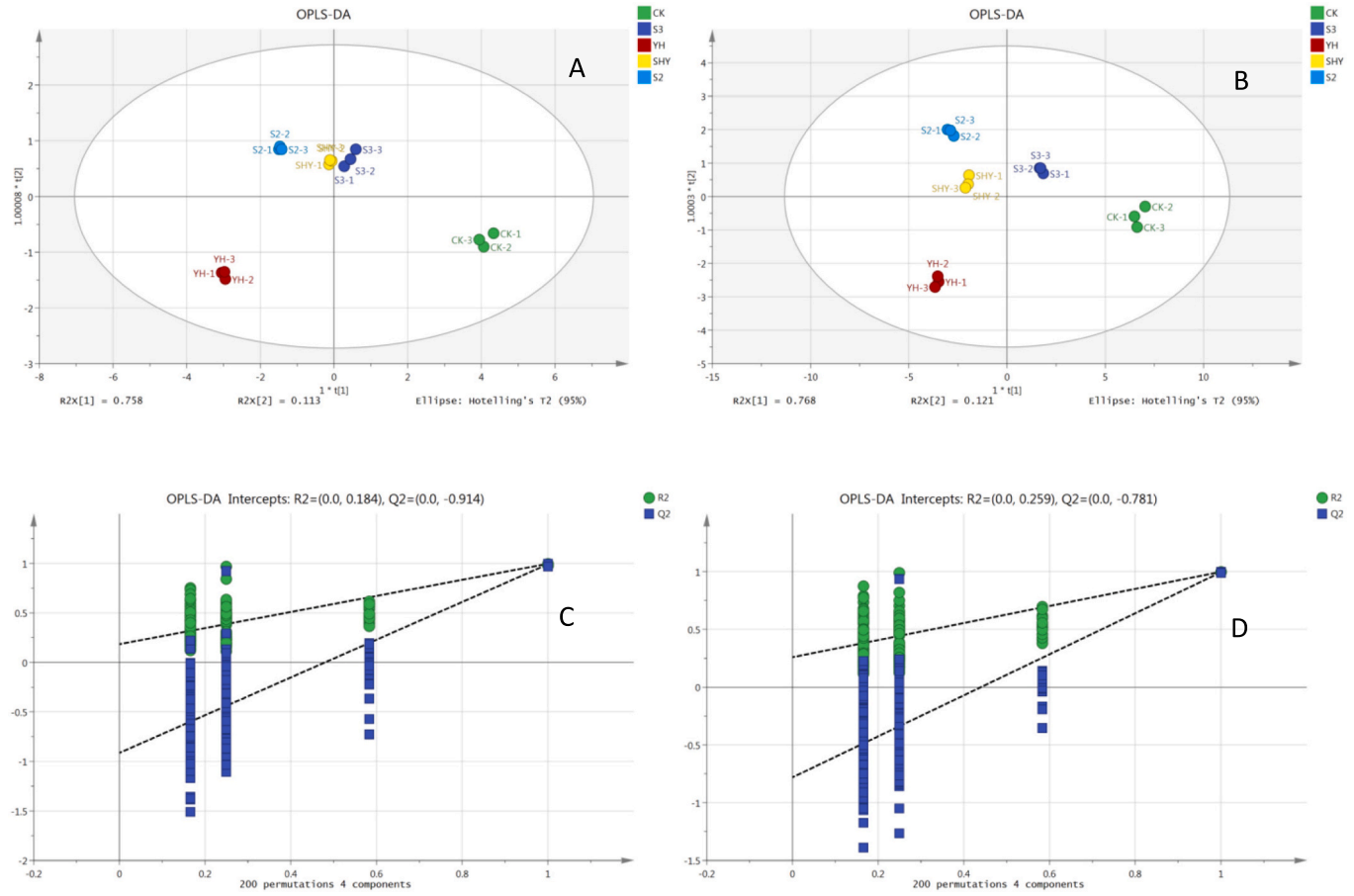

Fig. 6. OPLS-DA score plots and two hundred permutation tests of breeding selection and parents based on GC-IMS data and GC–MS data. (A) Score plot based on GC-IMS data; (B) Score plot based on GC–MS data; (C) The permutation test on the OPLS-DA of GC-IMS data;(D) The permutation test on the OPLS-DA of GC–MS data.

Table 1
The content of differential volatile compounds among two parent and three breeding selections in the GC-IMS OPLS-DA model.[a]

Compound	VIP	CK(maternal)	YH(male)	S3	S2	SHY
2-Butanone	2.502	34.902 ± 3.48a[a]	410.418 ± 10.07e	202.509 ± 2.50c	302.304 ± 11.43d	165.619 ± 5.83b
Linalool	1.645	189.605 ± 12.93a	604.832 ± 21.62e	223.994 ± 4.67b	275.369 ± 7.06c	399.799 ± 7.07d
2-Methyl-1-propanol	1.565	154.596 ± 0.87d	36.101 ± 1.88a	65.662 ± 3.91b	77.356 ± 3.95c	77.575 ± 2.60c
Camphene	1.549	250.252 ± 27.06a	811.167 ± 22.95c	796.161 ± 24.15c	796.779 ± 12.26c	524.902 ± 23.88b
2-Pentanone	1.452	67.142 ± 4.66a	79.895 ± 6.39a	138.114 ± 10.54b	131.314 ± 8.30b	151.886 ± 13.75b
cis-3-Hexenyl acetate	1.407	103.251 ± 6.38d	36.085 ± 2.10a	87.075 ± 6.09c	70.088 ± 1.83b	101.089 ± 5.65d
α-Pinene	1.359	779.911 ± 18.54a	1341.631 ± 50.42b	771.727 ± 39.05a	1623.806 ± 47.54d	1489.691 ± 36.69c
(*E*)-Caryophyllene	1.350	1319.555 ± 101.07a	4317.109 ± 250.80d	1601.579 ± 119.17a	2947.912 ± 47.45c	2409.187 ± 101.08b
α-Phellandrene	1.346	2883.584 ± 107.21a	9048.486 ± 105.97c	5842.128 ± 121.64b	9932.139 ± 332.07d	5978.465 ± 117.77b
p-Cymene	1.316	372.431 ± 19.74a	1368.674 ± 96.04d	528.059 ± 37.80b	686.985 ± 9.69c	610.501 ± 14.675bc
Sabinene	1.262	1804.491 ± 154.29a	4574.754 ± 211.21e	2236.832 ± 55.94b	2645.567 ± 43.89c	3488.068 ± 182.26d
Octanol	1.244	916.208 ± 32.17d	346.738 ± 15.13a	833.265 ± 5.47c	731.824 ± 8.80b	832.250 ± 23.08c
Limonene	1.210	9282.331 ± 383.04a	27,544.218 ± 624.62d	17,823.365 ± 427.83b	28,316.172 ± 820.74d	22,375.460 ± 1018.40c
(E)-Ocimene	1.146	3532.899 ± 143.30a	6539.675 ± 242.77c	4842.917 ± 206.72b	8855.508 ± 58.12d	6700.780 ± 113.32c
Hexanal	1.130	3692.715 ± 63.27a	9105.523 ± 354.76c	6518.925 ± 165.18b	10,293.683 ± 440.83d	8507.459 ± 131.92c
γ-Terpinene	1.090	3588.096 ± 311.434a	9953.184 ± 589.61d	6931.928 ± 324.82b	9890.168 ± 218.77d	7959.531 ± 162.64c
Acetoin	1.007	32.624 ± 2.16a	41.227 ± 3.02b	29.568 ± 0.814a	46.949 ± 4.06c	30.369 ± 0.58a

[a] The different letter mean significant difference among five celery genotypes.

abundant compound in the celery aroma spectra. The contents of most terpenoids and phthalides in type S were higher than those in type D, indicating that Chinese celery has a richer aroma diversity. Both GC–MS and GC–IMS discriminated between types S and D, and GC–IMS performed better than GC–MS in distinguishing different varieties of the same celery type. Based on GC–IMS and GC–MS data, OPLS–DA analysis screen 15 and 18 volatile compounds, respectively, which can be used as potential biomarkers to discriminate between the two types of celery varieties. Six of these potential biomarkers were identified in both models. Sedanenolide, 3-n-butylphthalide, and cis-ligustilide were identified as potential biomarkers in the GC–MS OPLS–DA model. The relative contents of seven (GC–IMS OPLS–DA model) and ten (GC–MS OPLS–DA model) differential volatile compounds in the breeding selections were significantly higher than those in their parental lines,

Table 2
The content of differential volatile compounds among two parent and three breeding selections in the GC–MS OPLS-DA model.

Compound	VIP	CK(maternal)	YH(male)	S3	S2	SHY
Sedanenolide	2.304	20.321 ± 1.55a[a]	334.616 ± 19.32e	85.832 ± 3.39b	186.963 ± 2.89d	163.295 ± 4.40c
β-Selinene	2.170	10.834 ± 0.90a	124.851 ± 5.04e	49.938 ± 0.21b	105.544 ± 6.21d	93.455 ± 4.67c
1-Octen-3-ol	1.834	0.243 ± 0.005e	0.090 ± 0.009c	0.149 ± 0.006d	0.038 ± 0.003a	0.066 ± 0.003b
sabinene	1.663	5.045 ± 0.30a	28.205 ± 0.53c	13.026 ± 1.06b	31.076 ± 1.42d	28.534 ± 0.32c
hexanal	1.660	33.738 ± 0.63a	164.417 ± 5.83d	89.150 ± 2.44b	131.550 ± 2.94c	171.925 ± 0.32e
1-hexanol	1.582	1.409 ± 0.08a	1.514 ± 0.03a	3.165 ± 0.07c	4.253 ± 0.09d	2.064 ± 0.07b
(*E*)-2-hexenal	1.543	0.094 ± 0.01a	0.378 ± 0.02c	0.308 ± 0.002b	0.485 ± 0.06d	0.393 ± 0.03c
(+)-(E)-Limonene oxide	1.511	6.374 ± 0.28a	32.749 ± 2.23c	15.317 ± 0.95b	32.839 ± 3.03c	30.795 ± 0.75c
D-Limonene	1.506	332.072 ± 15.25a	1338.675 ± 82.62d	394.842 ± 6.52a	1058.666 ± 34.85c	887.027 ± 19.4b
(−)-Carvone	1.377	13.236 ± 0.60a	33.945 ± 1.24c	22.263 ± 1.41b	49.285 ± 2.44d	49.085 ± 4.79d
cis-Carvyl acetate	1.372	1.776 ± 0.15b	1.192 ± 0.04a	1.146 ± 0.07a	1.081 ± 0.04a	2.010 ± 0.07c
7-epi-α-selinene	1.363	3.127 ± 0.27a	11.995 ± 0.48c	6.307 ± 0.08b	15.063 ± 0.38d	11.583 ± 0.94c
γ-Terpinene	1.328	45.140 ± 2.43a	190.506 ± 4.43e	70.365 ± 2.30b	112.722 ± 7.74d	90.460 ± 1.80c
α-phellandrene	1.324	27.971 ± 0.47a	121.823 ± 4.85e	40.439 ± 0.92b	76.275 ± 2.80d	65.573 ± 2.30c
γ-terpineol	1.195	0.113 ± 0.004ab	0.249 ± 0.02c	0.102 ± 0.008a	0.138 ± 0.02b	0.116 ± 0.008ab
p-Mentha-1,5,8-triene	1.150	0.193 ± 0.04a	0.714 ± 0.04c	0.297 ± 0.02b	0.381 ± 0.02b	0.391 ± 0.07b
Caryophyllene	1.139	14.062 ± 2.60a	49.060 ± 2.29d	26.035 ± 1.35b	49.802 ± 5.66d	40.357 ± 3.40c
Z-Butylidenephthalide	1.089	3.480 ± 0.21a	11.090 ± 0.62c	8.079 ± 0.76b	10.824 ± 0.42c	8.941 ± 0.27b
β-(E)-ocimene	1.069	0.994 ± 0.12a	1.538 ± 0.07b	0.869 ± 0.07a	1.799 ± 0.06c	1.775 ± 0.05c
β-Damascenone	1.065	0.191 ± 0.02a	0.474 ± 0.05b	0.252 ± 0.01a	0.248 ± 0.02a	0.230 ± 0.02a
cis-Ligustilide	1.053	6.050 ± 0.25a	16.304 ± 0.77c	11.299 ± 0.82b	19.505 ± 0.46e	18.044 ± 0.23d
camphene	1.035	11.777 ± 0.16a	28.960 ± 1.08c	15.523 ± 0.58b	31.471 ± 1.14d	29.783 ± 0.99 cd
δ-Cadinene	1.018	0.937 ± 0.14a	1.453 ± 0.10c	1.229 ± 0.03b	0.848 ± 0.009a	0.803 ± 0.02a

[a] The different letter mean significant difference among five celery genotype.

which showed over-parent heterosis. This work provides a technical reference to discriminate celery varieties in the same habitat and preliminarily reveals the aroma relationship between breeding selections and their parent. Overall, this study provides a feasible strategy for celery variety certification that can improve consumer satisfaction and assist breeders in developing celery flavour breeding.

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CRediT authorship contribution statement

Jun Yan: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Jingbo Chen:** Methodology, Investigation, Formal analysis. **Zhiwu Huang:** Investigation, Data curation. **Lizhong He:** Investigation. **Lingyun Wu:** Methodology. **Li Yu:** Supervision, Project administration, Funding acquisition. **Weimin Zhu:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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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.2024.101936.

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