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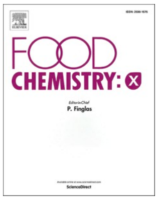

Analysis of volatile flavour compounds in different potato varieties and regions and the effect of soil elements on starch content

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ABSTRACT

This study aims to analyze the differences in flavor compounds of potatoes from various varieties and regions, as well as to explore the impact of soil elements on starch content in potatoes. Headspace solid-phase microextraction/gas chromatography–mass spectrometry (HS-SPME-GC–MS) was employed to identify volatile flavor compounds in 18 potatoes representing 4 different varieties from 5 different regions. The relative odor activity (rOAV) was utilized for principal component analysis to establish a comprehensive scoring model for potato volatile flavor compounds. In addition, the starch and amylose content of the potatoes were determined using enzymatic methods, and the correlation between soil elements and starch content in Dingxi potatoes was analyzed. The results indicated that the flavor scores for the samples "DX-DP," "DX-LS," "NM-XY," "JB-LS," "ZB-XS," and "GY-LS" were 15.184, 14.500, 13.992, −4.62, −7.199 and − 9.525, respectively, with "DX-DP" exhibiting the highest flavor score (15.184) and starch content (15.21 %). This study demonstrated that the overall quality of potatoes from Dingxi was superior, particularly for "DX-DP". Further analysis revealed that potato starch content was positively correlated with soil potassium and negatively correlated with total nitrogen and pH. In conclusion, this study provides insights into the relationship between potato genotypes and soil environments, offering valuable guidance for potato land selection and cultivation practices.

1. Introduction

As an important staple crop, potatoes are ranked fourth after maize, rice and wheat. Potato production is critical for ensuring global food security and is expected to contribute to 50 % of future food increments (Jansky, 2010). In addition, it is rich in carbohydrate content, minerals, fiber, proteins, antioxidant compounds such as polyphenols and carotenoids, vitamins E and C, which contribute to the nutrition and wellness of consumers, especially in developing countries. There is a huge demand for fresh potatoes in China, as more than 50 % of potatoes are consumed as fresh food. After being put on the market, aroma and texture are the main factors influencing consumers' choices. As the material basis of food flavor, volatile flavor compounds are mainly a class of organic compounds with special olfactory characteristics, including aldehydes, alcohols, esters, hydrocarbons, pyrazines and other compounds. Currently, more than 300 volatile flavor compounds have been detected in potatoes, and different cooking methods have shown different aroma characteristics due to different degradation processes (Jansky, 2010). In addition, it was found that there were obvious differences on aroma among potato varieties, which may be caused by the various compounds, contents and the lipase activities of potato precursor substances (e.g., fatty acids, sugars, etc.) in the processes of lipid degradation, Maillard reaction and carbohydrate decomposition (Oruna-Concha et al., 2002).

On the other hand, a number of studies have reported the nutritional quality of potato varieties grown in different regions. Starch is the main nutrient source of potato, and it is also an important factor affecting taste. The ratio of amylose (AMS) and amylopectin (AMP) fraction determines not only the properties of starch, but also the optimal applications of potatoes in various industries (Šimková et al., 2013).

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Therefore, it is essential to understand the starch proportion characteristics of potato varieties.

The quality attributes of potato tubers are determined by both genotypes and environmental factors including soil properties, climate and agronomic practices(Scavo et al., 2023). Genotype has a relatively constant effect, while the environment varies widely across locations, considerably influencing the performance of different potato genotypes (Lombardo et al., 2013). Dingxi, located in Gansu Province, is one of the main potato growing areas in China. The soil in this region is primarily loess, which typically has a low organic matter content, and the dry climate tends to lead to nutrient loss(Niu et al., 2016). In contrast, the black soil in Zhangbei and Inner Mongolia is more suitable for crop growth(Kang et al., 2013). Nevertheless, the quality of potato production in Dingxi has always been at the top of the list(Wang et al., 2023). Therefore, the study of local potatoes in Dingxi is helpful for potato selection and cultivation, effectively promoting the conservation and restoration of regional biodiversity, playing a significant role in the sustainable development of the local potato industry.

In this study, the varieties “Longshu NO 7”, “Xindaping”, “Atlantic” and “Xisen NO 6” were collected. Among them, “Xindaping” is a newly selected variety that is currently planted only in the Dingxi area. In order to understand the combined effects of potato varieties and soil environment on potato volatile flavor compounds and starch content. The volatile flavor compounds, starch content and soil elements of potatoes were determined and correlated.

2. Materials and methods

2.1. Potato samples collection and reagents

The potatoes used in this study were “Longshu NO 7” from “Dingxi” (DX-LS), “Jingbian” (JB-LS) and “Guyuan” regions (GY-LS), “Xindaping” from “Dingxi” (DX-DP), “Atlantic” from “Inner Mongolia” (NM-XY) and “Xisen NO 6” from “Zhangbei” (ZB-XS) (Table 1). N-hexane and C7-C30 saturated alkanes were purchased from Merck (New Jersey, USA). Other analytical grade reagents were obtained from Aladdin Bio-Chem Technology Co., Ltd. (Shanghai, China). Pure water was purchased from Wahaha Group Co., Ltd. (Hangzhou, Zhejiang, China).

2.2. HS-SPM-GC–MS detection of the volatile substances

2.2.1. Preparation of potato samples

Six potato varieties including “DX-DP”, “DX-LS”, “GY-LS”, “JB-LS”, “ZB-XS” and “NM-XY” were selected. Each variety was subjected to three replicates, resulting in a total of 18 samples. Each sample was steamed under normal pressure for 30 min to ensure thorough cooking. After steaming, the potatoes were quickly pureed, and 10 g of potato puree was placed into a 15 mL headspace vial for analysis within 30 min.

2.2.2. Instrument pre-treatment

The identification and quantification of volatile compounds were performed using gas chromatography–mass spectrometry (GC–MS) (QP2020 NX GC–MS, Shimadzu). Volatile extraction was carried out using headspace solid-phase microextraction (HS-SPME) with an autosampler (SPME, Lab lngenious). The DVB/CAR/PDMS SPME fiber (57299-U, Supelco) was introduced into the headspace of the vial for extraction. The fiber was injected into the automated system (QP2020 NX GC–MS, Shimadzu) and aged for 40 min at 270 °C, followed by a blank experiment until no chromatographic peaks were observed. The gas chromatography column (30 m × 0.25 mm × 0.25 μm, Agilent) was pretreated, with the oven temperature program starting at 40 °C (held for 3 min), increasing at a rate of 8 °C/min until reaching 305 °C (held for 10 min), then decreasing at a rate of 8 °C/min back to 40 °C (held for 10 min), followed by a blank experiment until no chromatographic peaks were observed.

2.2.3. Sample detection

The extraction conditions were set as follows: heating temperature at 80 °C, equilibration time at 20 min, adsorption time at 60 min and resolution time at 5 min. Helium was used as the carrier gas at a linear velocity of 1.0 mL/min. The injector temperature was maintained at 270 °C. The oven temperature program started at 40 °C (held for 5 min), increased at a rate of 10 °C/min until reaching 180 °C (held for 10 min), and then increased at a rate of 15 °C/min until reaching 300 °C (held for 15 min), using splitless injection. Mass spectra were recorded using electron impact (EI) ionization mode with an energy of 70 eV. The ion source and interface temperatures were set at 230 °C and 300 °C, respectively. Full scan mode was employed, with a scanning range of 29–550 *m/z* and a threshold of 1000.

2.2.4. Volatile compound qualification and rOAV calculation

n-Alkanes (C7-C30) were used as external references to calculate the retention indices (RIs). The volatile compounds were identified by their RIs and by comparing the mass spectra with the data system library (NIST17–1, NIST17, NIST17S). The contents of volatile compounds were quantified based on their peak areas, and the relative odor activity values (rOAVs) were calculated as the ratios of the relative contents to their odor thresholds in water for each volatile compound (Gemert, 2003).

2.3. Total starch, AMS and AMP determination

Samples from 6 potato varieties were selected, with four samples taken from each variety for analysis. The potatoes were cut into 0.5 cm thin slices, frozen at −80 °C for 2 h and then lyophilised for 5 days, milled and filtered through a sieve (mesh 125 μm). The total starch content and amylose were determined by using the starch determination kit (K-TSTA, Megazyme). AMP content (in %) was calculated as the difference from 100 − AMP content.

2.4. Soil elements determination

The soil elements in the “DX-LS” and “DX-DP” potato samples were analyzed according to the following Chinese standard methods: LY/T 1234–2015, HJ 804–2016, NY/T 1121.7–2014, NY/T 1121.24–2012 and NY/T 1121.2–2006. The detected soil elements included slowly available potassium, available potassium, available manganese, available phosphorus, total nitrogen, available zinc and pH.

2.5. Statistical analysis

All experiments were conducted in triplicate. Statistical analyses were performed using one-way analysis of variance (ANOVA) with IBM SPSS Statistics 27.0 (SPSS Inc., Chicago, IL, USA), comparisons were considered statistically significant at $p < 0.05$. Diagrams were generated using GraphPad Prism 9.5.1 (GraphPad Software, San Diego, CA, USA). For flavor data processing, principal component analysis (PCA) was applied with IBM SPSS Statistics 27.0, resulting in the extraction of

Table 1
Origin and varieties of potatoes.

Name	DX-DP	DX-LS	GY-LS	JB-LS	NM-XY	ZB-XS
Origin	Dingxi	Dingxi	Guyuan	Jingbian	Neimeng	Zhangbei
Variety	Xindaping	Longshu NO 7	Longshu NO 7	Longshu NO 7	Atlantic	Xisen NO 6

principal components, loading matrix, eigenvalues, eigenvectors and standardized values. A comprehensive evaluation model for flavor was subsequently established based on these parameters(Liu et al., 2023; Xiaodi et al., 2015). Metabo Analyst 5.0 (https://www.metaboanalyst.ca/) was employed for conducting partial least squares discriminant analysis (PLS-DA). The variable importance in the projection (VIP) value was extracted from PLS-DA. VIP $\geq$ 1 was used to determine inter-group differential metabolites(Ma et al., 2024a).

3. Results and discussion

3.1. Volatile compounds identification in different potato varieties

A total of 96 volatile compounds were identified from 18 potato samples (the chromatograms of the samples are shown in Figs. S1 and S2). As shown in Fig.1A, the identified compounds can be classified into 10 categories, namely alcohols (18), phenols (3), ethers (4), aldehydes (10), acids (4), terpenoids (3), hydrocarbons (31), esters (10), heterocyclics (1) and others (12). Among these, hydrocarbons are the most abundant in terms of quantity, while aldehydes exhibit the relatively highest contents among the identified compounds. There were significant variations in the categories and relative contents of volatiles among the samples, with “DX-DP” possessing the highest number of volatiles (42) and “NM-XY” possessing the lowest (24). Alcohols, aldehydes and hydrocarbons were the relatively abundant classes of volatiles in the samples, aldehydes were the predominant class, ranging from 20.96 % (DX-LS) to 41.12 % (ZB-XS) of the total volatile profile, which is consistent with the results of previous studies (Descours et al., 2013).

As shown in Fig. 1B, eight compounds including phenethyl alcohol, nonanoic acid, 2-pentyl furan, cis-2-penten-1-ol, 1-penten-3-ol, 2,4-di-tert-butylphenol, hexadecene and 2,2,4-trimethyl-1,3-pentanediol diisobutyrate were common to all samples. Notably, as the relatively higher components in all varieties, the rOAVs of 2-pentyl furan were higher, reaching 123.88, which makes an important contribution to the flavor of potatoes. In addition, it is noteworthy that terpenoids were not detected in “ZB-XS” and terpenoids were also not detected in “NM-XS”.

3.2. Key volatile compounds in the potatoes

The contributions of volatile flavor compounds to flavor characteristics in potatoes are determined by their relative component contents and aroma thresholds. Thus, although multiple volatiles were detected in different potatoes, only some of them contributed to overall flavor of potato, and the rest only played a modifying and synergistic role. Compounds with rOAV >1 are typically considered as key compounds, and those with 0.1 < rOAV <1 show an important modifying effect (Wang et al., 2022). By calculating the rOAVs, a total of 25 key compounds with rOAV >0.1 were identified (Table 2), including alcohols (7), aldehydes (4), esters (4), terpenoids (3), phenols (2), acids (2), heterocyclics (1), hydrocarbons (1) and ethers (1). The odor descriptions of these compounds are derived from TGSC (2023) and Ma et al.(Ma et al., 2024b). The variations in the concentrations of these compounds among different samples are shown in Fig. 2.

3.2.1. Aldehydes

Aldehydes were the major group of aromatic components in potatoes. In terms of odor description, aldehydes are often related to “fatty”, “fruity”, “green” and “floral sweet” scents. These aldehydes were widely distributed and have been found in potatoes (Morris et al., 2010a).

Among all the samples,benzeneacet aldehyde (ranged from 1.03 % to 13.57 %) and cis-2-penten-1-ol (rangined from 4.98 % to 11.59 %) were found in all varieties and accounted for a high proportion. Additionally, the aroma characteristics of potatoes were mainly attributed to cis-2-penten-1-ol, which was described as the typical “potato” odor(Morris et al., 2010a). The following compound wasbenzeneacet aldehyde, which gives the potato its “green sweet” and “almond” aromas, mainly from the degradation of lipids(Petersen et al., 1998). And pentadecanal was described to endow potatoes with a waxy flavor. Beyond that, all varieties except “NM-XY” contained citral, which gave potatoes a strong lemon flavor. Additionally, nonanal was a specific component of “JB-LS”, with a slight odor of oil rancidity(Thybo et al., 2006) γ-nonanolactone and γ- unsecalactone were specific components of “DX-LS”, contributing to the flavor of “coconut” and “peach”. Benzaldehyde as a special aroma compound of “ZB-XS” imparted a unique aroma of “almond” and “cherry”.

3.2.2. Alcohols

Alcohols were another significant group of aromatic components present in potatoes. As the by-products of unsaturated fatty acid oxidation, they were formed by converting aldehydes with alcohol dehydrogenases (ADH)(Ma et al., 2023) and contributed to pleasant fragrances such as “lean leaf”, “fruity” and “floral” odors (Qi et al., 2018). 1-penten-3-ol is a common alcohol among all potatoes varieties in this study that provided the flavor of “potato”, “tropical”, “creamy” and “green”(Morris et al., 2010b). 1-octen-3-ol was a special aroma component of “DX-DP” and “NM-XY” contributing to the flavor “mushroom”, “earthy”, “green”, and “oily”. This result was consistent

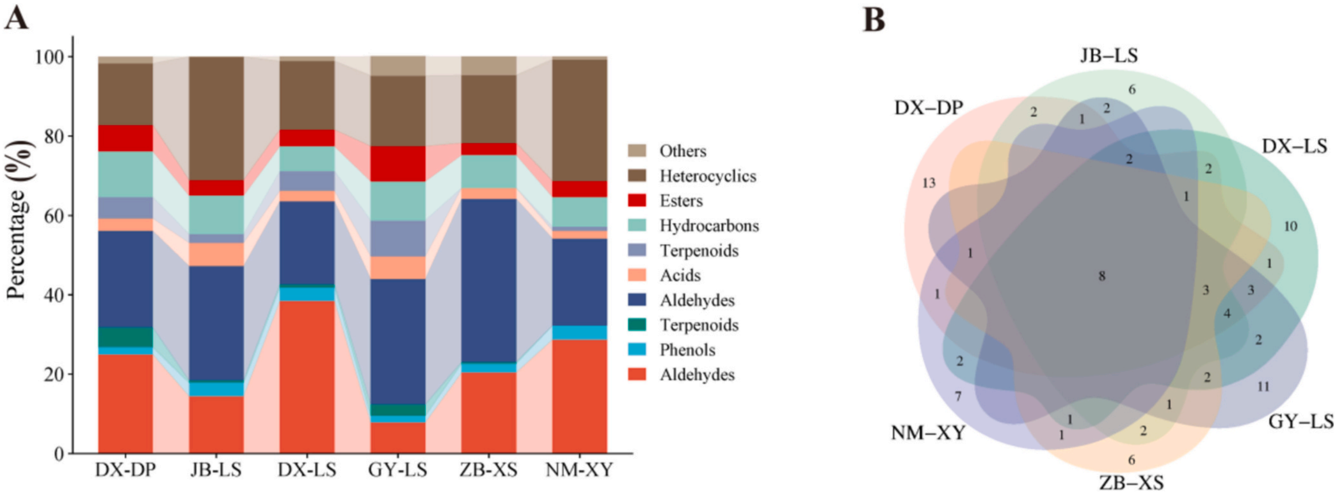

Fig. 1. Volatiles compounds identified in potatoes. (A) Bar chart of the relative content of volatiles classification in potato. (B) Venn diagram analysis of differential volatile compounds among “DX-DP”, “JB-LS”, “DX-LS”, “GY-LS”, “ZB-XS” and “NM-XY”.

Table 2
Key compounds identified in all potato varieties.

Compound	Retention time (min)	Odor description	Retention Index(RI)		Relative content (%)
			RIa	RIb	
Alcohols					
1-octen-3-ol*	10.702	mushroom cucumber earthy green oily fungal fatty	981	939.540	0–17.988
phenethyl alcohol*	13.176	rose floral	1060	1007.256	1.202–6.719
nonanol	13.820	fresh clean fatty floral rose orange dusty wet oily	1152.8	1060.478	0–2.260
geraniol*	15.302	orange	1249	1151.965	0–3.806
2-ethyl-1-hexanol	11.640	citrus fresh floral oily sweet	1038	962.130	0–3.949
benzyl alcohol	11.774	floral citrusy fruity	1057	915.854	0–7.153
1-penten-3-ol	15.760	Potato tropical creamy green	681	664.225	4.031–10.512
Aldehydes					
benzeneacet aldehyde*	11.963	green sweet floral hyacinth clover honey cocoa	1058	973.850	8.681–21.752
citral*	15.585	lemon strong	1247	1158.892	0–0.416
pentadecanal	22.056	waxy	1713	1659.882	0–0.555
cis-2-penten-1-ol	12.795	potato creamy	700.44	625.319	4.978–11.586
nonanal	13.820	oil rancidity	1102	1040.151	0–1.036
γ-nonanolactone	16.910	coconut	1350	1138.489	0–0.245
γ-unsecalactone	22.050	peach	1618	1614.194	0–0.178
benzaldehyde	10.334	cherry almond caramel fruity bitter	964	873.658	0–2.139
Esters					
palmitic acid ethyl ester	30.790	fruity creamy	1990	1932.874	0–0.669
methyl salicylate	14.419	wintergreen mint peppermint	1193	1043.346	0–1.605
2,2,4-trimethyl-1,3-pentanediol diisobutyrate*	19.848	musty	1587.5	1625.662	0.906–4.907
Terpenoids					
D-limonene*	11.667	lemony fruity	–	1060.378	0–6.718
α-pinene	17.186	honey	1384	1444.292	0–2.000
(*E*)–β-ionone*	18.509	floral woody sweet fruity berry tropical beeswax	1485	1426.730	0–1.237
Ethers					
1,2-dimethoxybenzene	13.649	creamy	1146	1020.126	0–1.097
Hydrocarbons					
hexadecene*	19.995	–	272.02	1629.954	0.646–1.702
Phenols					
guaiacol*	12.688	phenolic smoke spice vanilla woody	1097	944.031	0–1.926
2,4-di-tert-butylphenol	18.774	-	1521	1491.498	1.261–3.362
4-vinylguaiacol*	16.226	fermentation clove	1301	1121.108	0–0.504
Acids					
nonanoic acid	15.512	creamy	1237	1102.897	1.527–4.347

(*continued on next page*)

Table 2 (*continued*)

Compound	Retention time (min)	Odor description	Retention Index(RI)		Relative content (%)
			RIa	RIb	
decanoic acid	16.845	unpleasant rancid sour fatty citrus	1357	1191.083	0–0.289
octanoic acid	14.025	fruit	1191	1029.929	0–1.330
Heterocyclics					
2-pentyl furan*	10.896	fruity green earthy beany vegetable metallic	1010	986.977	15.495–31.087

1.Bold text indicates the rOAV of volatile compounds >0.1.
2.“*” and bold text indicates the rOAV of volatile compounds >1.
3.RIa means retention index by references, RIb means retention index by calculation.
4.Odor descriptions were obtained in TGSC (2023). “-”, no data found.

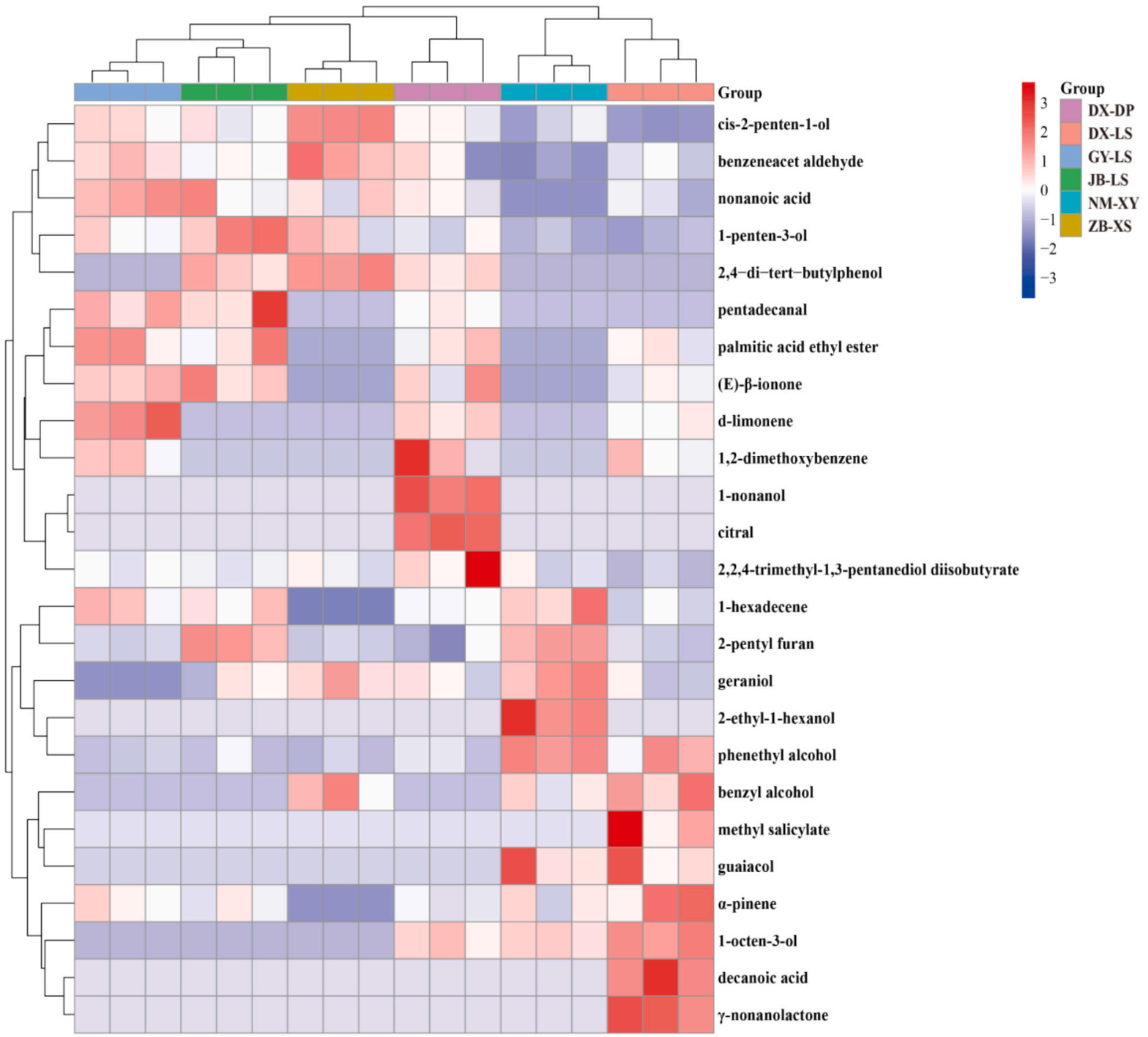

Fig. 2. Heatmap of key volatile components (rOAV >0.1) in potatoes.

with most previous studies (Oruna-Concha et al., 2001). Among all the samples, “DX-DP” contained the greatest number of alcohols, and possessed nonanol as its unique compound with flavor “fresh”, “rose”, “orange” and “fatty”. In addition, 2-ethylhexan-1-ol was a special aroma component of “ZB-XS” contributing to the special flavor of “oily”, “floral” and “sweet”. With rOAV >1 in all potatoes varieties in this study, phenethyl alcohol provided the flavor of “rose”. Additionally, 1-octen-3-ol was a special aroma component of “DX-DP” and “NM-XY” contributing to the flavor “mushroom”, “earthy”, “green”, and “oily”. This result was consistent with most previous studies (Li et al., 2019). Among all the samples, “DX-DP” contained the greatest number of alcohols, and possessed nonanol as its unique compound with flavor “fresh”, “rose”, “orange” and “fatty”. In addition, 2-ethylhexan-1-ol was a special aroma component of “ZB-XS” contributing to the special flavor of “oily”, “floral” and “sweet”.

3.2.3. Heterocyclics

2-pentyl furan was a common heterocyclic compound among all four potato varieties, with a relatively high rOAV ranging from 40.03 to 123.88 and its relative content was the highest in “DX-DP”, “JB-LS”, “GY-LS” and “NM-XS” samples. It was a significant aromatic component in potatoes, contributing to the flavors of “fruity”, “green”, “earthy”, “beany”, “vegetable” and “metallic”.

3.2.4. Esters

ADH and alcohol acyltransferase (AAT) are key enzymes in the ester biosynthesis pathway, and the formation of acety-CoA from fatty acid β-oxidation is a key step in the conversion of ADHs and AATs. Additionally, the presence of acetyl-CoA and AATs can generate esters from alcohols (Luo et al., 2021b). However, all four potato varieties contained esters, the contents in different varieties showed significant variations. The main ester constituent was 2,2,4-trimethyl-1,3-pentamediol diisobutyrate, providing a musty aroma. Additionally, the special compound methyl salicylate in “DX-LS” contributed to “wintergreen” and “mint” scents.

3.2.5. Terpenoids

Terpenoids, which are produced by repeated fusion of branched 5-carbon units based on isoprene, impart pleasant fragrances reminiscent of “citrus”, “herbal”, “floral” and “green leaf” scents with low odor thresholds(Luo et al., 2021a). A limited number of terpenoids were detected in this study, the primary terpenoid constituents were (*E*)-β-ionone, α-pinene and D-limonene. Except for “ZB-XS”, α-pinene was found in all other varieties in this study, providing a typical “turpentine” odor, consistent with terpenoids in baked potato flesh that have been reported previously (Duckham et al., 2002). (E)-β-ionone was identified in “DX-DP”, “JB-LS”, “DX-LS” and “GY-LS”, providing the flavor of “floral”, “woody”, “sweet”, “fruity”, “berry”, and “herbaceous”. Additionally, D-limonene was a component of “DX-DP”, “DX-LS” and “GY-LS” that enhanced the formation of flavor such as “lemon”.

3.2.6. Others

Hydrocarbons were the most abundant in terms of quantity, while the relative contents were small. The main hydrocarbons in potatoes were hexadecane, which was found in all varieties. Acids could balance unpleasant odors (Hao et al., 2024b). In this study, nonanoic acid was the major acidic compound that provided potatoes with a mild aroma of “coconut”. Decanoic acid was a special compound of “DX-LS”, adding unique flavor of “fatty” and “citrus”. In addition, octanoic acid was a special aroma compound of “GY-LS”, it imparted a flavor characterized by “fruit”. Guaiacol existed only in “DX-LS” and “NM-XY”, adding unique flavor of “smoky”, “spices”, “vanilla” and “woody”. 4-vinylguaiacol was commonly found in fermented foods and was only found in “DX-DP” in this study, providing its unique scents of “fermentation” and “clove” (Jiang et al., 2023).

3.3. Principal component analysis of volatile flavor compounds in different varieties of potato

3.3.1. Establishment of comprehensive evaluation model of volatile flavor compounds

In order to do further studies on the influence of volatile flavor compounds on potato flavor, 11 compounds with rOAV >1 were selected for principal component analysis, then four principal components with eigenvalues greater than 1 were extracted (Table 3). A total of 96.17 % of the variance was explained by principal component 1 (41.27 %), principal component 2 (22.91 %), principal component 3 (17.70 %) and principal component 4 (14.29 %), among which the cumulative contribution rate of the first three principal components reached 81.88 %, which explains most of the information of the original data. Therefore, the first three principal components were selected for analysis. As shown in Table 4, principal component 1 was decided by phenethyl alcohol, guaiacol and geraniol, the principal component 2 was determined by (*E*)-β-ionone, hexadecene and 2-pentyl furan, the principal component 3 was determined by geraniol, 2-pentyl furan and citral.

According to the eigenvectors of the 11 types of substances of the three principal components, the scores of each principal component can be calculated, represented by F1, F2 and F3, respectively, while F denotes the composite score. The linear relationship equations of the volatile flavor substances of potato obtained are as follows:

- $$F1 = 0.442 \times 1 + 0.428 \times 2 - 0.354 \times 3 + 0.301 \times 4 - 0.286 \times 5 - 0.272 \times 6 + 0.269 \times 7 + 0.151 \times 8 - 0.171 \times 9 - 0.224 \times 10 + 0.273 \times 11$$
- $$F2 = 0.164 \times 1 + 0.108 \times 2 - 0.394 \times 3 - 0.217 \times 4 + 0.340 \times 5 + 0.338 \times 6 + 0.328 \times 7 + 0.404 \times 8 + 0.389 \times 9 + 0.323 \times 10 - 0.050 \times 11$$
- $$F3 = 0.024 \times 1 + 0.011 \times 2 + 0.028 \times 3 + 0.369 \times 4 - 0.307 \times 5 - 0.166 \times 6 + 0.281 \times 7 - 0.414 \times 8 + 0.459 \times 9 + 0.387 \times 10 - 0.361 \times 11$$

(X1, X2, … X11 are the standardized value of 11 volatile flavor substances.

The contribution rate of the three principal components was taken as the weighting coefficient, the score of the principal components is a weighted average, and a comprehensive evaluation model equation of volatile flavor substances was established: $F = 41.27\ \%\ F1 + 22.91\ \%\ F2 + 17.70\ \%\ F3$. A higher comprehensive score indicates better aroma quality. According to the comprehensive scores of different varieties of potatoes, ranked from high to low were “DX-DP”, “DX-LS”, “NM-XY”, “JB-LS”, “ZB-XS”, “GY-LS” (Table 5, Fig. 3).

3.3.2. Discrepancy in key flavor compounds of among different potatoes varieties

Partial least squares discriminant analysis (PLS-DA) was conducted to further analyze the discrepancy in 11 key aromatic compounds among different potato varieties. As shown in Fig.4A, the result of PLS-DA indicated the differences in the composition of volatile flavor

Table 3

Principal component eigenvalues and contribution rates.

Principal component	Eigenvalue	Rate of contribution (%)	Cumulative contribution rate (%)
1	4.539	41.268	41.268
2	2.520	22.908	64.175
3	1.947	17.697	81.872
4	1.572	14.290	96.162

Table 4
Principal component loading matrix and eigenvectors.

Components	Principal component 1		Principal component 2		Principal component 3	
	loading	eigenvector	loading	eigenvector	loading	eigenvector
phenethyl alcohol	0.942	0.442	0.260	0.164	0.034	0.024
guaiacol	0.912	0.428	0.171	0.108	0.016	0.011
benzeneacet aldehyde	−0.755	−0.354	−0.626	−0.394	0.039	0.028
geraniol	0.642	0.301	−0.345	−0.217	0.515	0.369
(E)-β-ionone	−0.61	−0.286	0.539	0.340	−0.428	−0.307
1-octen-3-ol	−0.579	−0.272	0.537	0.338	−0.232	−0.166
D-limonene	0.574	0.269	0.521	0.328	0.392	0.281
1-hexadecene	0.321	0.151	0.641	0.404	−0.577	−0.414
2-pentyl furan	−0.365	−0.171	0.618	0.389	0.640	0.459
citral	−0.478	−0.224	0.512	0.323	0.540	0.387
2,2,4-trimethyl-1,3-pentanediol diisobutyrate	0.581	0.273	−0.08	−0.050	−0.503	−0.361

Table 5
Normalized principal component composite scores.

cultivars	Scores				Sorting
	F1	F2	F3	F	
DX-DP	0.092	0.325	0.222	15.184	1
DX-LS	0.210	0.212	0.055	14.500	2
NM-XY	0.324	0.030	−0.005	13.992	3
JB-LS	−0.031	−0.041	−0.135	−4.620	4
ZB-XS	−0.081	−0.255	0.112	−7.199	5
GY-LS	−0.195	0.050	−0.149	−9.525	6

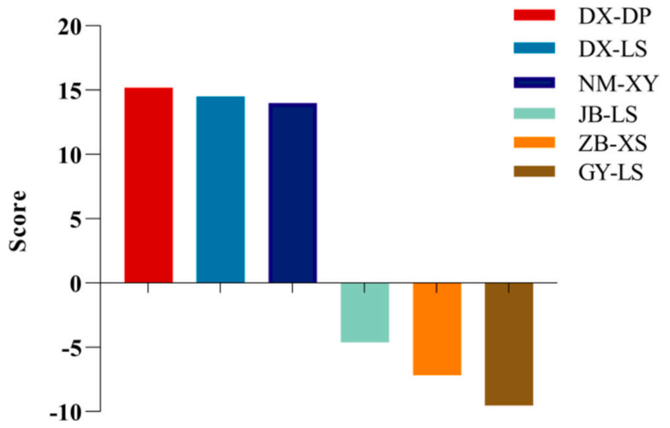

Fig. 3. Potato flavor score chart.

compounds among the potatoes from different varieties and sources. “NM-XY” was mainly located in the first quadrant, “DX-DP” and “DX-LS” were located in the second quadrant, and they were placed close to each other, indicating that they had similar aromatic profiles. In contrast, “ZB-XS”, “JB-LS” and “GY-LS” were mainly located in the third and fourth quadrants, intersecting with each other and distant from the varieties “NM-XY”, “DX-DP” and “DX-LS”. This was also consistent with the scoring results of the comprehensive model above, with “DX-DP”, “DX-LS” and “NM-XS” ranking the top three in the aroma evaluation model score, followed by “JB-LS”, “ZB-XS” and “GY-LS”.

Furthermore, as shown in Fig. 4B, PLS-DA was conducted to obtain the VIP values. Based on *t*-tests ($p < 0.05$), 5 discriminating aromatic compounds were selected with VIP ≥ 1 and $p < 0.05$: 2-pentyl furan, benzeneacet aldehyde, 1-octen-3-ol, geraniol and D-limonene.

3.4. Starch contents of potatoes

For potatoes, the starch content is one of the evaluation criteria of the internal quality of potato tubers and is affected by cultival, location, climatic conditions and fertilization. The value of the starch content is most linked to the influence of the variety with a correlation assessment of up to 66 % (Šimková et al., 2013). For starch used in industry, high starch content is one of the main requirements. As shown in Fig.5A, the differences in starch content in potato tubers were significant, from high to low were “DX-DP”, “DX-LS”, “NM-XY”, “JB-LS”, “ZB-XS”, “GY-LS”. Interestingly, we found that the starch content of potato tubers of the same variety but from different origins varied considerably, with 14.76 % starch content in “DX-LS” and only 11.20 % starch content in “GY-LS”. However, potatoes from the same origin “DX”, had higher starch content in “DX-LS” and “DX-DP”, with “DX-DP” at 15.21 %.

The ratio of AMS to AMP fractions determines not only the properties of starch but also the optimal application of potatoes in food and industry. Potato starch has a semi-crystalline structure and is composed of amylose and amylopectin, which occur roughly in a 3:1 ratio (Alvani et al., 2011; Šimková et al., 2013). The amylopectin component accounts for the crystallinity, while amylose represents the amorphous component. The ratio of these components affects the swelling capacity, water solubility, water absorption capacity, and the barrier and mechanical properties of starch and starch films (Alvani et al., 2011). Amylose is generally slower to digest than amylopectin, resulting in a high amylose content that contributes to a lower glycemic index in potatoes(Ek et al., 2014). In this study, it was found that the amylose/amylopectin ratio in starch was highest in “DX-DP”, followed by “DX-LS”, which may be more suitable for people with hyperglycemia (Fig. 5B).

Overall, we found that the starch content and aroma score of potato varieties from the origin of “DX” were relatively prominent, then we analyzed the soil elements of the potato planting area to explore the influence of different soil elements on the starch content of potato.

3.5. Soil element contents of potato in “DX”

Nitrogen, phosphorus, potassium and other elements are essential nutrients for potato growth that have a great impact on the yield and quality of potatoes. However, different soil elements can be absorbed and utilized by potatoes with different efficiencies. Understanding the correlation between different soil elements and potato starch yield may provide better guidance for potato fertilization.

The soil elements (Table 6) of “DX-DP” and “DX-LS” potatoes were detected, and the correlation between the soil element content and the starch content of potatoes was also assessed. It was found that there was a significant positive correlation between slowly available potassium and starch content. Conversely, total nitrogen content and pH exhibited a significantly negative correlation with starch content, and no correlations were found for other soil elements (Fig. 6).

Up to now, most studies have been focused on the flavor of baked or fried potatoes from different varieties(Starowicz & Zieliński, 2019). However, few studies have monitored the flavor change in steamed

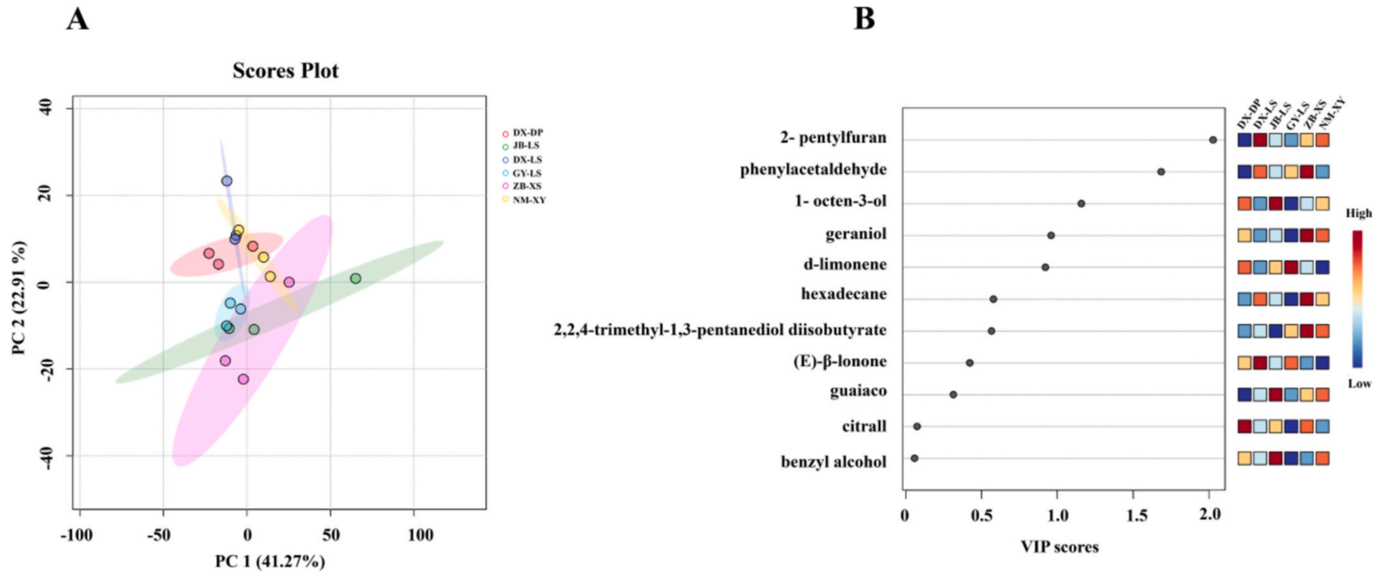

Fig. 4. Statistical analysis of the 11 key compounds. (A) Principal component analysis scores plot. (B) Partial Least Squares Discriminant Analysis (PLS-DA) variable importance in the projection (VIP) scores plot.

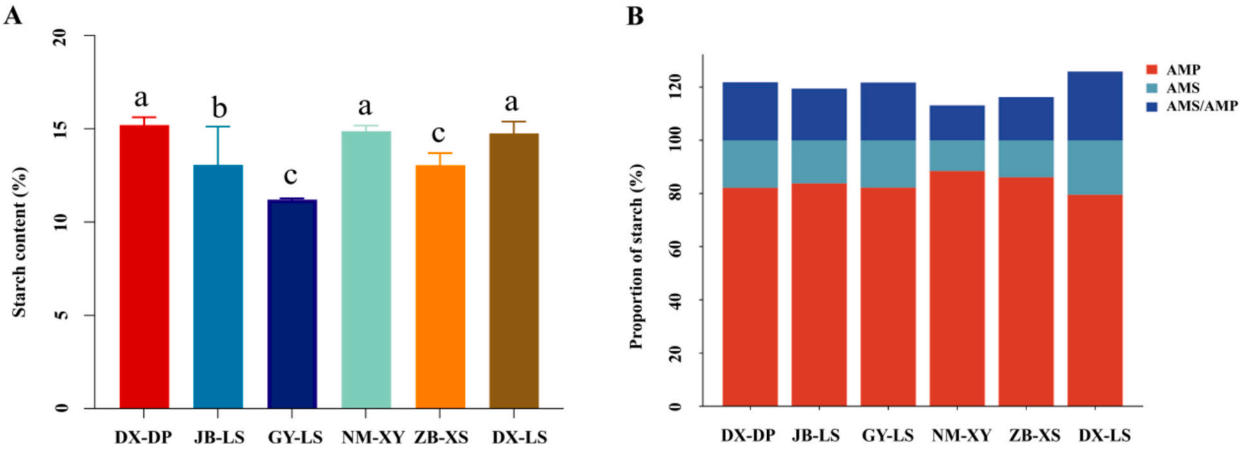

Fig. 5. Starch content in potatoes.

potatoes from domestic self-breeding varieties.

This study collected potato samples from 4 distinct varieties across 5 regions in China. HS-SPME-MS was employed to analyze the volatile compounds in steamed potatoes, facilitating a comparison of flavor differences among the varieties, and analyzing the correlation between starch content and soil elements. A previous study has indicated that the order of aroma release for volatile compounds with similar chain lengths was typically: aldehydes > esters > ketones > alcohols(Descours et al., 2013). In this study, we found that aldehydes had the highest relative abundance among all potato samples, followed closely by alcohols and esters, which is consistent with prior research findings. In addition, studies have shown that aldehydes containing 6 to 10 carbon atoms were typically associated with "green" and "fatty" aroma characteristics(Zhu et al., 2018). In this regard, the "green" aroma characteristics of benzaldehyde, nonanal, and γ-nonalactone detected in this study have also been validated. Research has found that the species and concentrations of volatile compounds are highly dependent on the original nutritional components in potatoes, including carbohydrates, amino acids, fatty acids, and a series of vitamins and minerals. These components can be transformed into multiple flavor compounds through thermal reactions, such as lipid oxidation, the Maillard reaction and Strecker degradation. These precursor substances are believed to be associated with the variety, cultivation conditions, processing methods, exhibiting genotype specificity(Hao et al., 2024a). The results of this study indicated that the "DX-DP" potato has the highest flavor compound score and starch content, while the "DX-LS" exhibited a relatively lower flavor compound score. The VIP analysis revealed that 2-pentyl furan, 1-octen-3-ol and-benzeneacet aldehyde were the primary volatile compounds influencing the model variables, and these compounds rank among the top three in relative abundance in "DX-DP". This may explain the higher score for this variety. Furthermore, 2-pentyl furan, 1-octen-3-ol, andbenzeneacet aldehyde are considered typical aroma substances in steamed potatoes, further supporting our understanding of the flavor characteristics of "DX-DP"(Yahya et al., 2024).

On the other hand, the analysis revealed that the "DX-DP" and "DX-LS" potatoes from the Dingxi region have relatively high starch contents, measuring 15.21 % and 11.20 %, respectively. Correlation analysis between starch content and soil elements in Dingxi indicated that the starch content in potatoes was positively correlated with available potassium levels, while it exhibited a negative correlation with total nitrogen levels and pH. The study indicated that the appropriate application of potassium can significantly enhance leaf photosynthesis and transpiration rates, thereby effectively promoting starch accumulation in potatoes(Moinuddin Singh & Bansal, 2005). It is noteworthy

Table 6
Soil elements of “DX-DP” and “DX-LS” potatoes.

NO	Slowly Available Potassium (mg/kg)	Available Potassium (mg/kg)	Available Manganese (mg/kg)	Available Phosphorus (mg/kg)	Total Nitrogen (mg/kg)	Available Zinc (mg/kg)	pH
1	1020	112	8.28	7.2	0.106	0.67	8.5
2	1245	162	7.73	18.7	0.042	0.61	8.0
3	1133	211	5.50	9.3	0.077	0.39	8.4
4	2064	161	4.00	6.0	0.065	0.24	8.5
5	1244	189	8.05	7.5	0.075	0.57	8.4
6	1406	119	10.17	20.7	0.111	1.34	8.5
7	1111	136	9.97	19.1	0.125	1.94	8.2
8	1012	111	8.08	17.5	0.101	1.18	8.6
9	1114	160	5.58	2.4	0.086	0.33	8.4
10	976	97	6.13	9.1	0.098	0.66	8.6
11	1277	164	13.38	59.6	0.042	1.62	8.4
12	1238	286	11.77	41.3	0.052	1.87	8.8
13	1055	135	9.90	17.9	0.080	1.30	8.2
14	1033	181	13.62	51.8	0.084	1.07	8.5
15	1450	98	5.37	18.7	0.112	0.40	8.3
16	1159	136	6.07	3.8	0.083	0.25	8.8
17	1053	155	5.80	18.2	0.077	0.34	8.9
18	1126	103	6.18	8.0	0.076	0.44	8.7
19	1375	300	6.04	10.3	0.050	0.42	8.4
20	1482	121	9.06	6.6	0.052	0.48	8.0
21	1039	93	8.22	18.2	0.051	0.78	8.7
22	1293	120	11.77	41.4	0.124	0.99	8.5
23	1120	120	21.96	200.5	0.189	4.23	8.4
24	1204	183	12.37	13.8	0.069	0.88	8.7
25	1305	180	14.49	41.3	0.055	1.07	8.3
26	1232	288	9.14	24.2	0.084	0.88	8.7
27	1020	144	10.00	15.8	0.146	0.48	5.8
28	1042	102	9.88	27.3	0.075	0.64	8.6
29	912	100	11.30	26.7	0.096	0.78	8.6
30	1020	222	9.96	22.2	0.123	0.91	8.3

Samples 1 to 15 are DX-LS, and samples 16 to 30 are DX-DP.

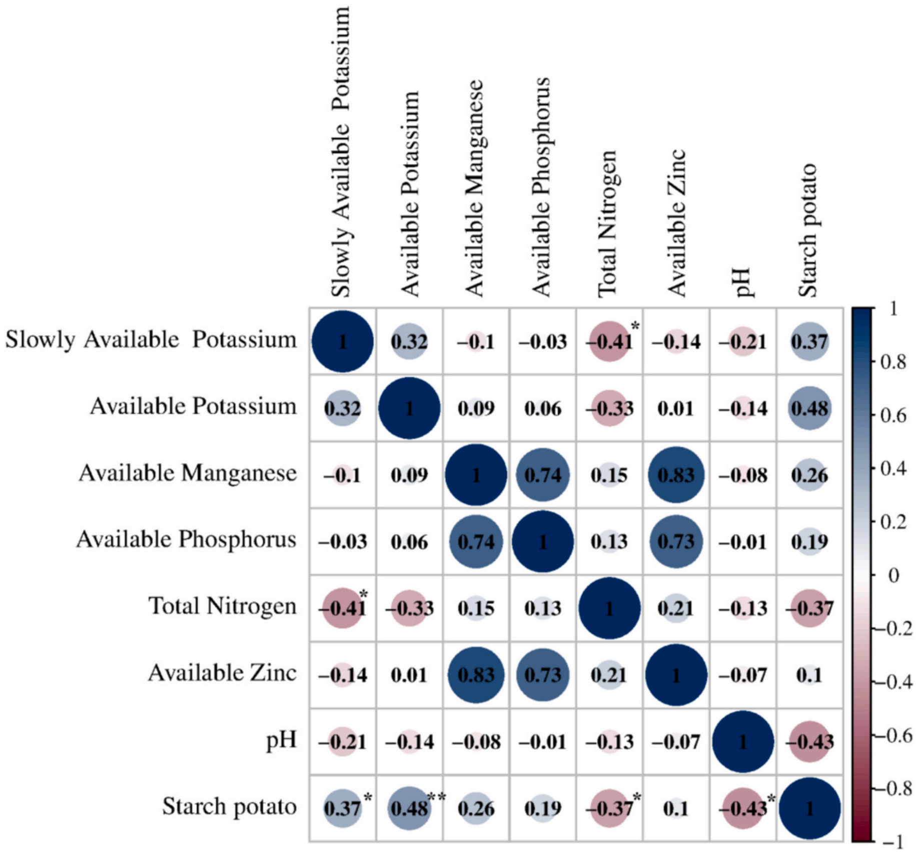

Fig. 6. Correlation analysis of potato starch content and soil elements, “*”: statistically significant at $p \leqq 0.1$, “**”: statistically significant at $p < 0.01$.

that excessive application of nitrogen fertilizer could reduce starch content in potatoes, potentially due to the slow formation of tubers caused by nitrogen surpluses, which diminishes starch production. At the same time, insufficient nitrogen fertilizer may lead to premature tuber formation, subsequently affecting the rate of starch accumulation and contributing to environmental issues such as water eutrophication (Lin, 2019). Therefore, dose-response experiments for nitrogen fertilizer application are still needed to accurately assess the appropriate fertilization rates. Furthermore, the study found that the exclusive application of nitrogen fertilizer significantly decreases soil pH, while the impact of phosphorus and potassium fertilizers on soil pH are relatively minor. However, regardless of the type of fertilizer applied, prolonged use tends to lead to a decline in soil pH(Wang et al., 2020). The results of this study indicated that soil pH was negatively correlated with tuber starch content. However, this did not imply that a decrease in soil pH was beneficial for increasing starch content, as it may also be attributed to the accumulation of organic elements in the soil.

In addition to inorganic fertilizers such as potassium, nitrogen, and phosphorus, organic fertilizers significantly influence the starch content of potatoes. Research conducted by Hou et al. indicated that the application of sheep manure could enhance the diversity and abundance of rhizobacterial communities associated with potatoes(Hou et al., 2024). This enhancement promoted the growth of beneficial microorganisms such as *Streptomyces, Gemmatimonas* and *Lysobacter,* which produced antibiotics and plant growth hormones, ultimately facilitating tuber development and starch accumulation in potatoes. Additionally, various soil amendments have been shown to improve soil quality, providing nutrients for potatoes and inhibite pathogens, which positively impacted the starch content in potatoes(Hao & Ashley, 2021). Additionally, researches have found that fertilizers produced from the decay of potato plants could also effectively promote starch accumulation in potatoes (Majee et al., 2021). Future studies should aim to elucidate the specific mechanisms of these factors on contributing to the enhancement of starch content in potatoes, taking into account the variability of responses across different soil types and environmental conditions.

4. Conclusion

In summary, an effective HS-SPME-MS method has been established in this study for the successful detection of volatile compounds in steamed potatoes and the characterization of aroma profiles across different varieties has been analyzed. The analysis of soil elements in the Dingxi region indicated that the local soil, rich in potassium, can effectively promote the accumulation of starch content in potatoes. These findings have provided important insights for the market application of the locally developed “DX-DP” variety and offer scientific guidance for potato cultivation practices. However, the varieties and regions were limited in the current study. To address these, future research could further explore a diverse range of potato varieties and conduct comprehensive studies on their physicochemical properties. Simultaneously, utilizing techniques such as metagenomics and metabolomics to investigate the release mechanisms of flavor compounds in potatoes, as well as the growth pathways of potatoes under diverse soil environments, will provide new perspectives for enhancing the flavor profile and nutritional content of potatoes, thereby promoting the sustainable development of the potato industry.

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CRediT authorship contribution statement

Luqi Qin: Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Jiahuan Zheng:** Methodology, Data curation. **Bei Fan:** Supervision. **Yixia Zhou:** Data curation. **Rao Diao:** Data curation. **Yufeng Sun:** Supervision. **Jiameng Liu:** Methodology, Funding acquisition. **Fengzhong Wang:** Supervision, Funding acquisition.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.102019.

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