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Metabolomics approach to exploring the effects of changes in substance composition induced by different irradiation doses on the sensory quality of saozi

Xue Li [a], Ling Zhang [a], Yexing Liang [a,*], Shixiong Yang [a], Jiaying Peng [c], Fanyi Gong [b], Buzhou Xu [b], Dong Zhang [b,*]

[a] *Agricultural Product Processing Institute, Chongqing Academy of Agricultural Science, Chongqing 401329, China*
[b] *College of Food and Bioengineering, Xihua University, Chengdu 610039, China*
[c] *Chongqing Jingguyuan Food Technology Co., Ltd., Chongqing 400084, China*

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ABSTRACT

In order to ensure the quality of saozi and expand its usage scenarios, it is necessary to determine the appropriate dose of irradiation. Non-targeted metabonomics method was used to explore the influence of changes in composition induced by different irradiation doses on the sensory characteristics of saozi. With increased irradiation dose (0, 2, 5, and 8 kGy), the TBARS value of saozi increased, whereas aroma, taste, and overall acceptability scores of saozi significantly decreased ($p < 0.05$). A total of 147 differential components including amino acids, organic acids, fatty acids, purines, and pyrimidines were screened from different irradiation doses of saozi. Twenty significant change pathways were identified in the KEGG enrichment results, most of which involve amino acids, nucleotide substances, acidic substances, among others, indicating that radiation-induced changes in these substances were one of the main reasons affecting the sensory scores of saozi. Considering the sensory scores and changes in the composition of saozi, when using cobalt 60 for the irradiation treatment of saozi, the optimal irradiation dose should be less than 5 kGy.

1. Introduction

In recent years, with the rapid development of cold chain logistics and the increase in resident income, prefabricated food has become increasingly popular among young consumers due to its convenience, safety, and market share (Ying et al., 2024). Saozi is a type of food processed from diced meat. As a pre-prepared food, it is often used to eat noodles or paired with pastries, and it has a good flavor and taste (Bai et al., 2021). Its production method involves dicing the meat and stir-frying it with various seasonings, vinegar, chili peppers, *etc.* However, saozi on the current market is mostly made and sold on the spot. If it cannot be sold promptly and exposed to the air for a long time, its flavor and safety are affected. Therefore, to ensure the quality of saozi, expand its usage scenarios, and further extend its shelf life, identifying new and suitable sterilization treatments has great significance.

As a cold sterilization technology, irradiation sterilization can kill various microorganisms such as bacteria, viruses, fungi, and parasites (Berni & Brutti, 2023). It can also maintain the nutritional composition, taste, and quality of food with the appropriate dose, as well as prolong the shelf life of food (Asghar et al., 2023). However, too high a radiation dose influences the quality and safety of food. Too high a radiation dose may destroy some food ingredients, such as vitamins and amino acids, thereby affecting the nutritional value (Jia et al., 2023). Thus, when using irradiation sterilization technology, the irradiation dose requires strict control. Researchers have explored the effects of irradiation treatment on the nutritional value, tenderness, color, and flavor of meat products (Jia et al., 2023). Wang et al. (2022) investigated the effect of irradiation treatment on the flavor characteristics of fresh yak meat. They found that irradiation can accelerate lipid oxidation and hydrolysis, thereby exacerbating the irradiation odor of meat. Jia et al. (2021) found that different irradiation doses lead to significant differences in the flavor of fresh goat meat. The protein of 26 differences involved seven functional enrichment items, which were related to odor, particularly those participated in protein oxidation, as well as cysteine and methionine metabolism, leading to the formation of irradiation flavor. Yao et al. (2024) found that the color and texture scores of pork increase

* Corresponding authors.
E-mail addresses: 18983692739@163.com (Y. Liang), dongzhang@mail.xhu.edu.cn (D. Zhang).

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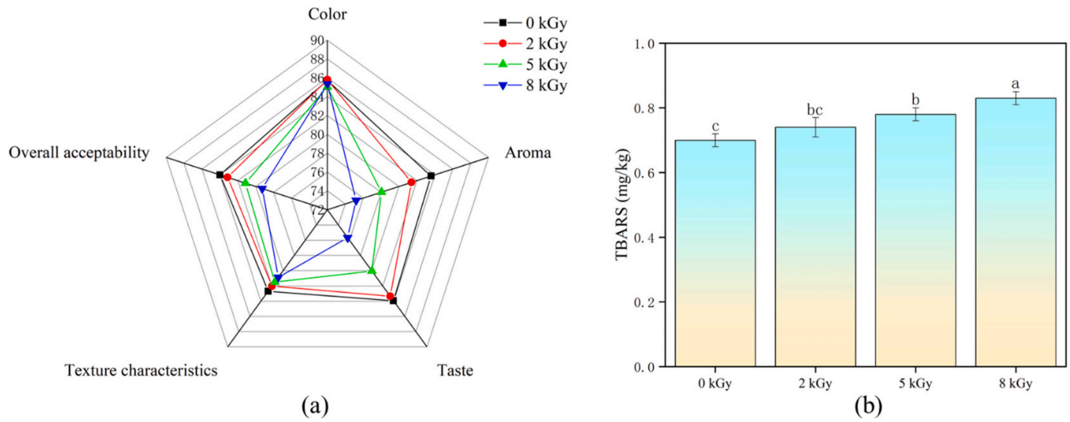


Fig. 1. Effects of different irradiation doses on saozi sensory evaluation (a) and TBARS value (b).
Note: The superscripts (a-c) of different lowercase letters in the same index indicate significant differences ($p < 0.05$).

with increased irradiation dose, but the flavor score decreases. However, in-depth explorations on the impact of different radiation doses on saozi substance composition are lacking. Whether different radiation doses affect the taste of saozi, as well as the interrelationships between various substances, are also unclear. New detection techniques are needed to further clarify the mechanism of the impact of different radiation doses on the composition of saozi substances and thus determine the optimal radiation dose. Metabolomics technology has the advantages of a wide analysis range, strong separation ability, reliable qualitative analysis results, low detection limit, and a high degree of automation (Ribbenstedt et al., 2018). This technique can be used to compare experimental and control groups, identify substances with significant changes, and construct pathways to explain the interrelationships among substance transformations.

The present study focused on saozi and explored the effects of different radiation doses on its sensory characteristics. A nontargeted metabolomics method was used to systematically analyze the composition of saozi substances at different irradiation doses. Significant differences in substances caused by different irradiation doses. The effects of these substances on the sensory quality of saozi were elucidated, and the optimal irradiation dose for saozi was identified. This work can provide an experimental basis for the further application of irradiation technology in meat products such as saozi.

2. Materials and methods

2.1. Materials

Fresh 5-month-old female fragrant pork was purchased from Century Parkson Supermarket and transported to the laboratory in a refrigerated box (approximately 6 °C). The rest of the ingredients required for processing, such as cooking wine, soy sauce, vinegar, sugar, *etc.*, were also purchased from Century Parkson Supermarket.

2.2. Methods

2.2.1. Preparation of samples

Saozi was prepared to refer to the method of Bai et al. (2022) with some modifications. We washed the pork and cut it into long strips with a length, width, and height of 2, 1, and 1 cm, respectively. The sliced meat was placed into a pot filled with cold water, to which 5 % cooking wine was added. The water was brought to a boil and the foam was removed. The cooked meat strips were placed into the pot, to which we added water that was 50 % of the meat weight. After boiling, turn to low heat (LA-BQ2, AUX Group Co., Ltd., China). When the water boiled dry and the meat shrank to half, we took it out and poured the oil into a clean container. After adding a little water, we poured the meat strips into the pot and heated them at low heat until the meat strips shrank again. Then, the prepared whistle juice (10 % sweet rice wine, 1.5 % soy sauce, 1 % vinegar, and 0.5 % sugar, all calculated by meat weight) was poured and stir-fried until the juice was almost dry. Stop heating and the samples were taken out.

2.2.2. Irradiation treatment

The irradiation treatment of saozi was performed based on the method of Wang et al. (2022) with slight modifications. The prepared saozi was randomly grouped, vacuum packaged, and then packed into a refrigerated box and transported to Sichuan Atomic Energy Research Center (^{60}Co irradiation source, FJX-432G2 mode), where it was finally sterilized by ^{60}Co irradiation. The irradiation doses were 0 (control group), 2, 5, and 8 kGy, respectively. After irradiation was completed, we placed the sample in a cooler and immediately returned it to the laboratory for index measurement.

2.2.3. Sensory evaluation

Sensory evaluation was conducted based on the method of Lynch et al. (2024) with slight modifications. We selected 5 males and 5 females to participate in sensory training and conducted a sensory evaluation on different irradiation treatments of saozi in the sensory-evaluation laboratory. Sensory evaluation was used on a 100-point scale. This laboratory had a bright and non-glaring light, with a stable temperature of 25 °C. The sensory evaluation method was approved by the Institutional Review Committee (School of Food and Biotechnology, Xihua University). Every participant in sensory experiments was aware of the experimental method and voluntarily participated. Relevant information on the personnel participating in sensory experiments was protected. They all agreed for their information and sensory experiment data to be collected and used for scientific research.

2.2.4. Thiobarbital acid reactants (TBARS)

For TBARS analysis, we referred to the method of Liu et al. (2024) and made slight modifications. About 10 g of crushed saozi was mixed with 50 mL of 7.5 % trichloroacetic acid (containing 0.1 % disodium oxalate). After shaking at 200 r/min for 0.5 h, fast filter paper was used for filtration. We mixed 5 mL of filtrate with 5 mL of thiobarbituric acid solution (0.02 mol/L), boiled it in water for 40 min, and removed and cooled the resulting solution. It was then centrifuged at 4000 r/min for 20 min (Avanti J-30I, Beckman Coulter, Inc., USA). Then, 5 mL of chloroform was added, and the solution was thoroughly shook and allowed to stand for layering. The supernatant was collected and subjected to absorbance measurements (UV-16001, Shimadzu Corp, Kyoto, Japan), and the TBARS value was calculated.

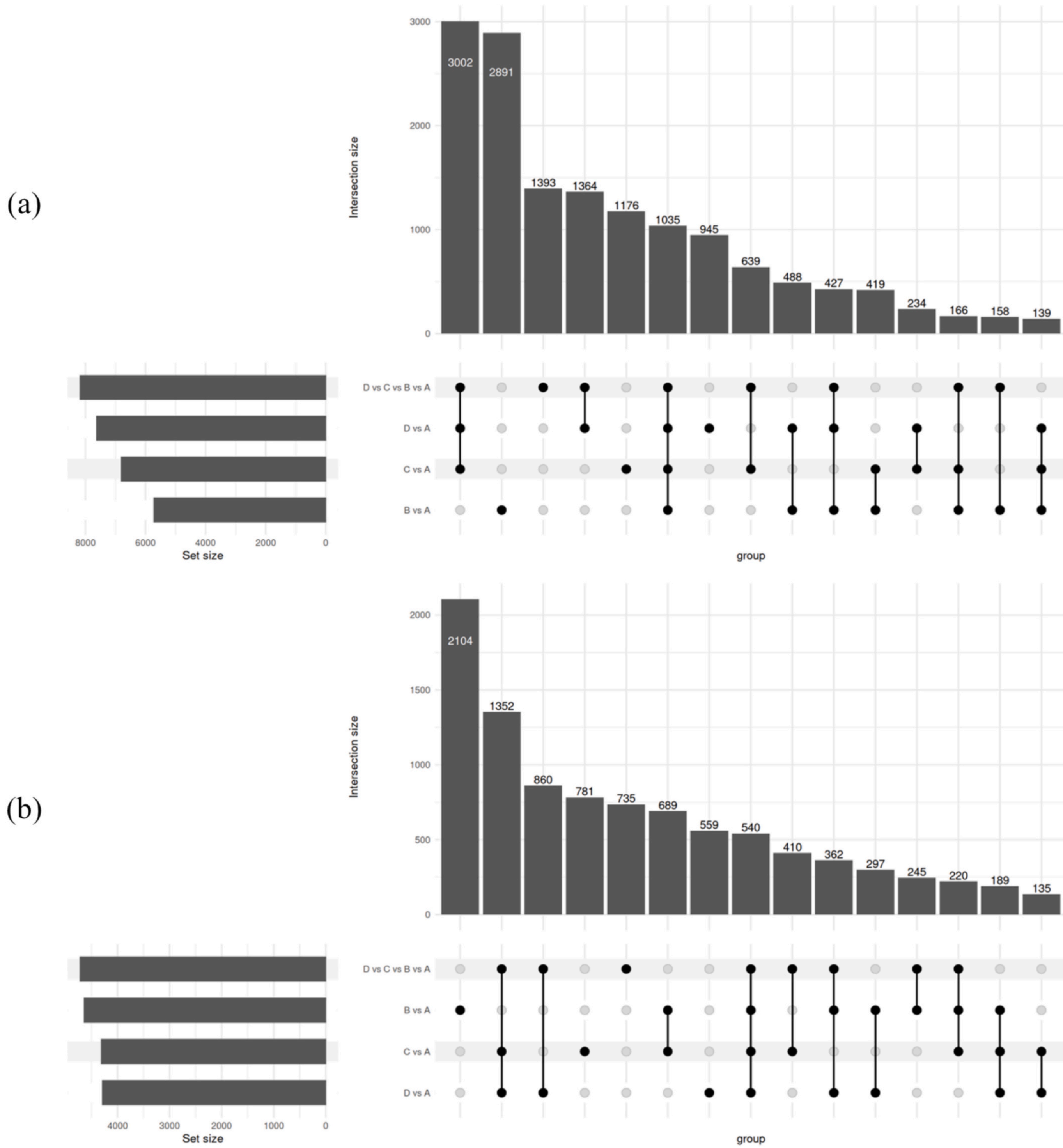


Fig. 2. Differential component statistical histograms (below) based on positive ion (a, c) and negative ion modes (b, d) at different radiation doses and venn diagram of primary differential components (upper).
Note: A, B, C, and D represent irradiation doses of 0 kGy, 2 kGy, 5 kGy, and 8 kGy, respectively.

2.2.5. Liquid chromatography/tandem mass spectrometry (LC-MS/MS) analysis

The samples of saozi were analyzed by non-target metabolomics after pretreatment, and the chromatographic and MS conditions were consistent with previous reports (Zhang et al., 2023).

2.2.6. Statistical analysis

SPSS 26 software was used for statistical analysis of the data, and the raw data was converted to mzXML file format (v3.0.8789) by using the MSConvert tool in Proteo Wizard. The chemical composition was identified through public databases such as HMDB, Massbank, LipidMaps, mzcloud, and KEGG. Only ion peaks with a relative standard deviation of less than 30 % were retained in QC to ensure the normal identification

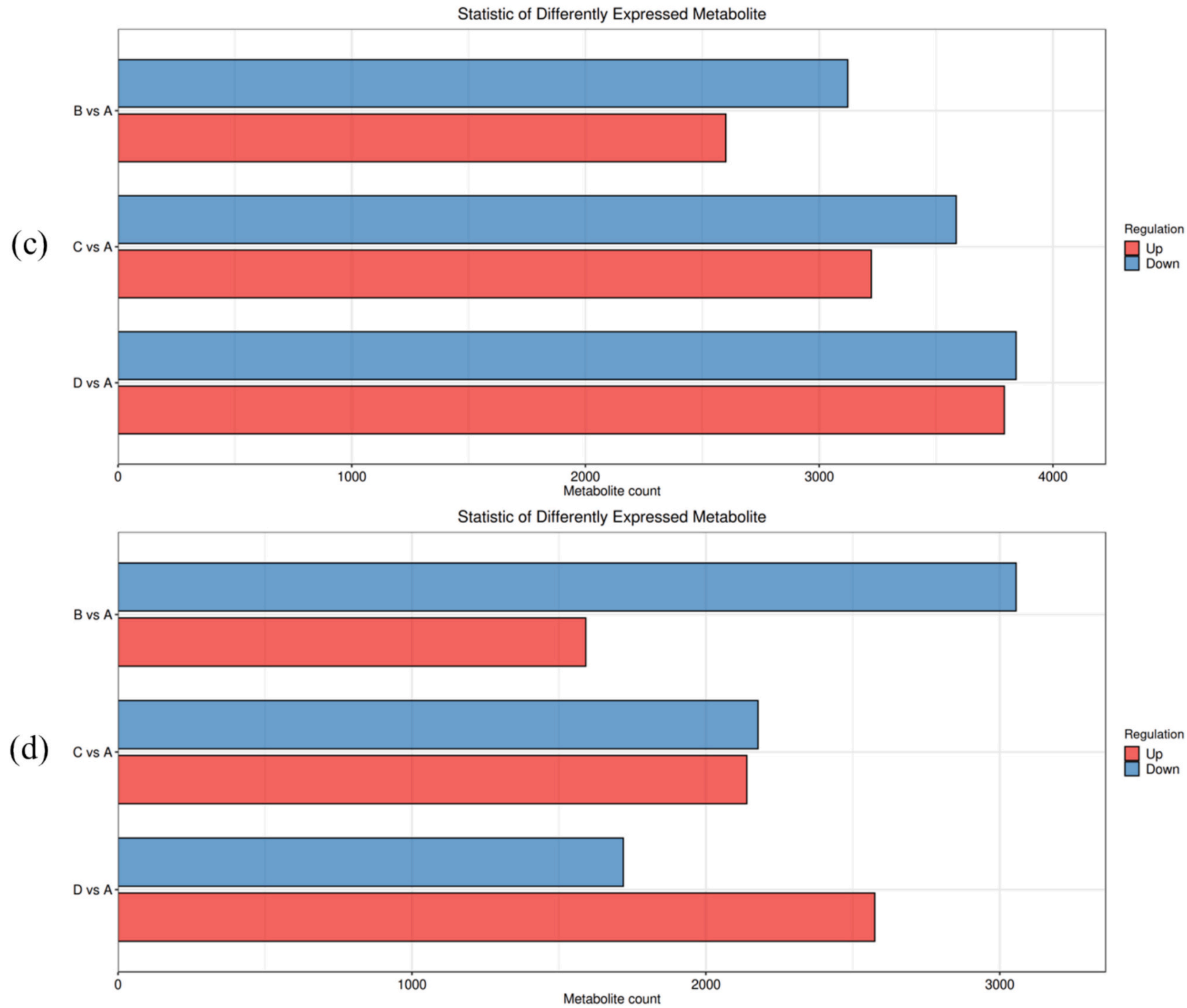


Fig. 2. (*continued*).

of chemical components. We performed PCA, PLS-DA, and OPLS-DA dimensionality-reduction analysis on the sample data by using the R software package (Ruan et al., 2023).

3. Results and discussion

3.1. Sensory evaluation

We compared the sensory differences of different irradiation doses of saozi by analyzing color, aroma, taste, texture characteristics, and overall acceptability scores. As shown in Fig. 1(a), different irradiation doses had a certain impact on the sensory characteristics of saozi. No significant difference ($p > 0.05$) in the color score of saozi existed among different irradiation doses. This may be due to the addition of soy sauce during saozi production, which can give the saozi a slightly black color. However, the irradiation treatment had no significant effect on the color components given by the soy sauce, so no significant difference in color scores existed among different saozi samples. With increased irradiation dose, the overall aroma score of saozi decreased ($p < 0.05$). This may be due to high-dose irradiation treatment leading to an increase in aldehydes and sulfides with unpleasant odors in saozi (Yao et al., 2024), which in turn affected its aroma score. With increased irradiation dose, the overall taste score of saozi also decreased ($p < 0.05$). This may be due to the fact that high-dose irradiation accelerated the degradation of nucleotides in saozi (Feng et al., 2016), thereby affecting its taste score. With increased irradiation dose, the texture-characteristic score of saozi relatively decreased, but the difference was not significant ($p > 0.05$). This may be due to the severe structural denaturation of the saozi after being fried, whereas the degradation of components induced by irradiation had a smaller impact on the texture characteristics, resulting in a smaller difference in texture-characteristic scores. With increased irradiation dose, the overall acceptability score of saozi decreased primarily due to the induction of degradation of volatile flavor and non-volatile flavor components by high-dose irradiation, which in turn affected the overall score of saozi. Li et al. (2022) also found that sauced duck samples irradiated with 0, 2, 4, and 6 kGy had acceptable sensory quality, but those irradiated with 6 kGy exhibited a more pronounced radiolytic off-flavor, which was associated with the formation of volatile sulfur compounds. Considering the inhibitory effect on microbial growth and the limited impact on physicochemical properties, 4 kGy is the optimal irradiation dose. Therefore, when using irradiation to treat saozi, the irradiation dose was necessary to control within a certain range.

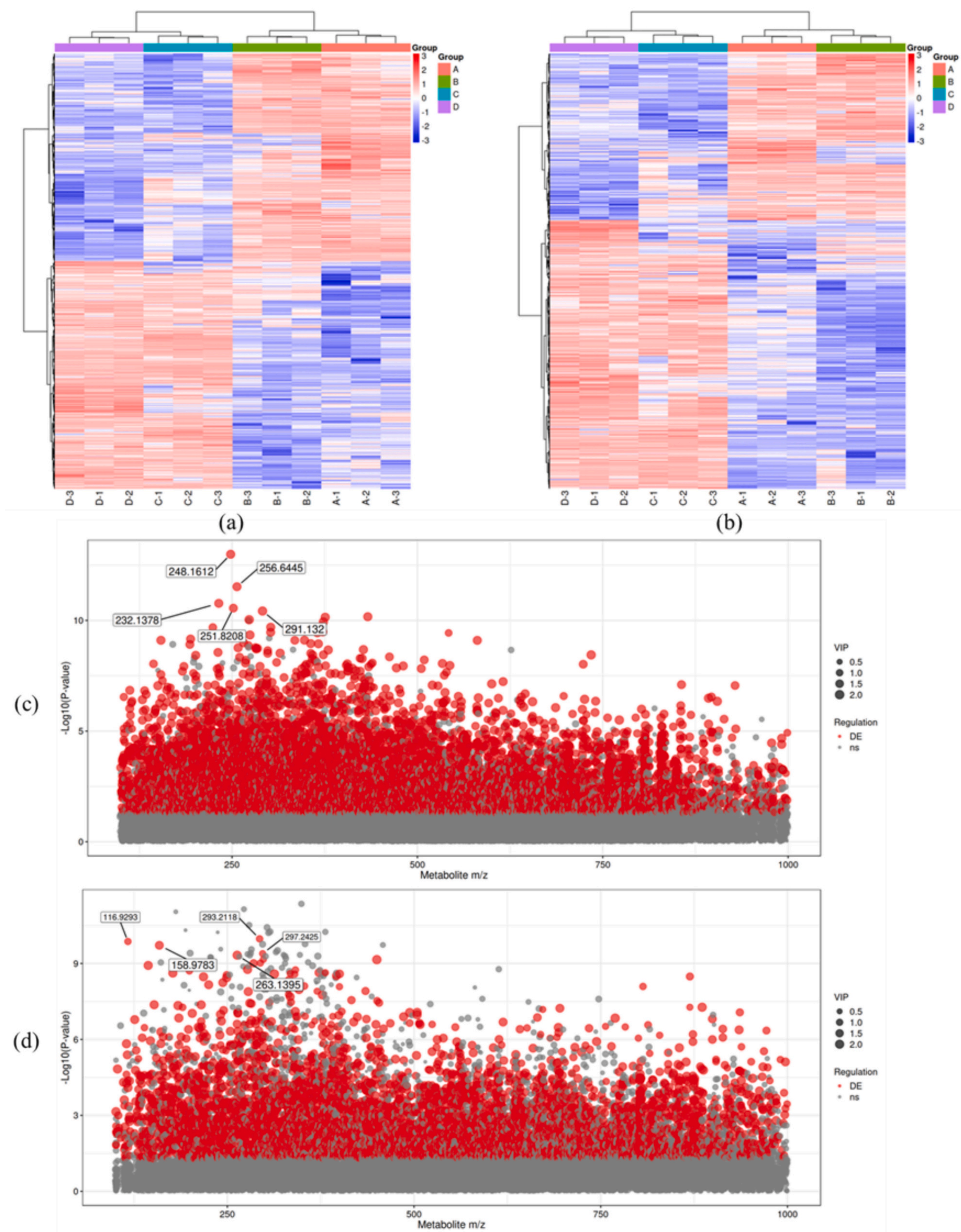


Fig. 3. Primary differential components heatmaps (upper) based on positive ion (a, c) and negative ion modes (b, d) at different irradiation doses and scatter plots of differential component mass-to-charge ratio and *p*-value ((below)).
Note: A, B, C, and D represent irradiation doses of 0 kGy, 2 kGy, 5 kGy, and 8 kGy, respectively. 1, 2, and 3 at each irradiation dose represent three repeated experiments.

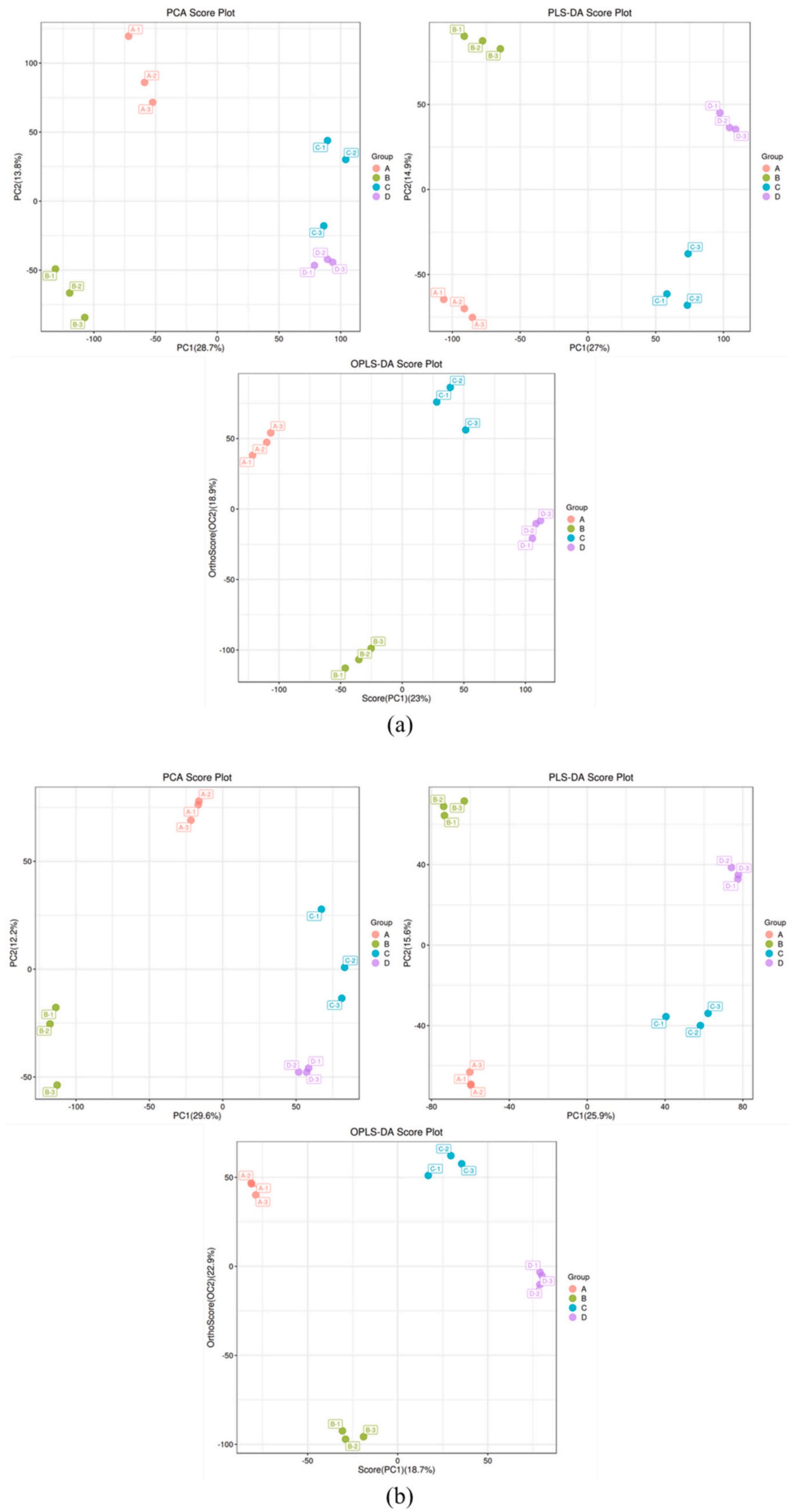
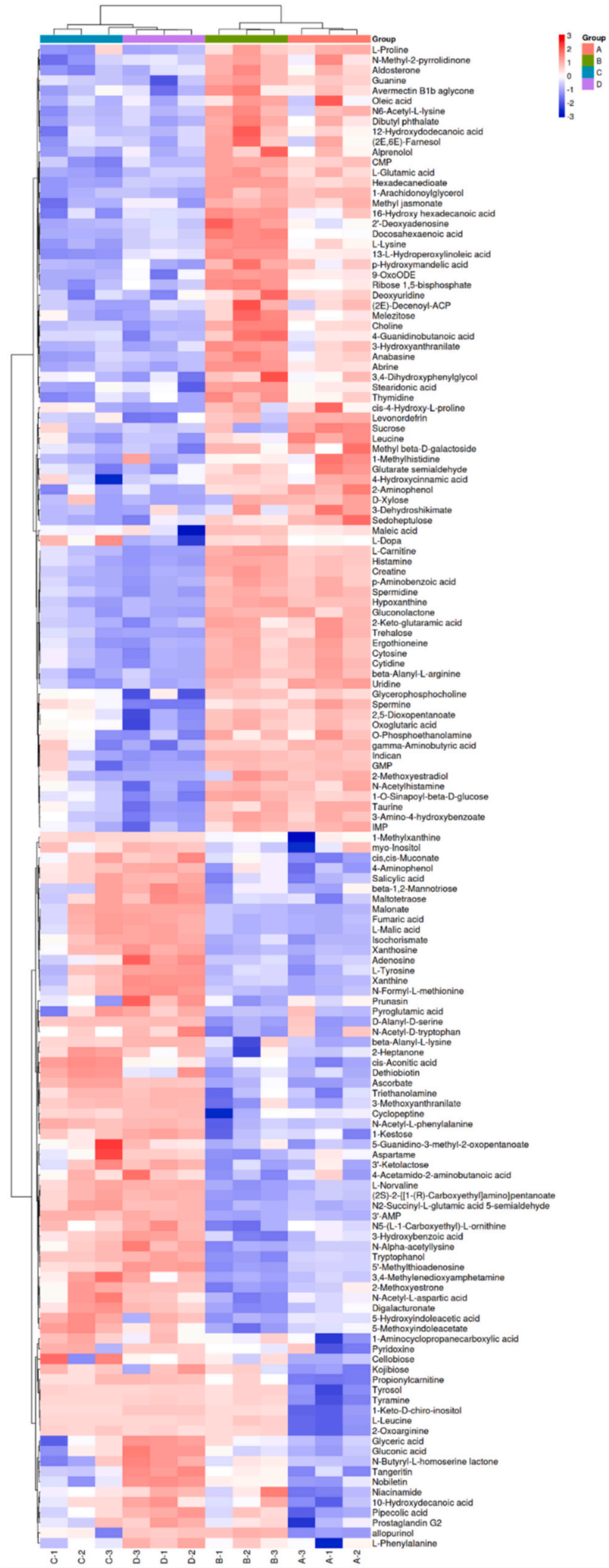


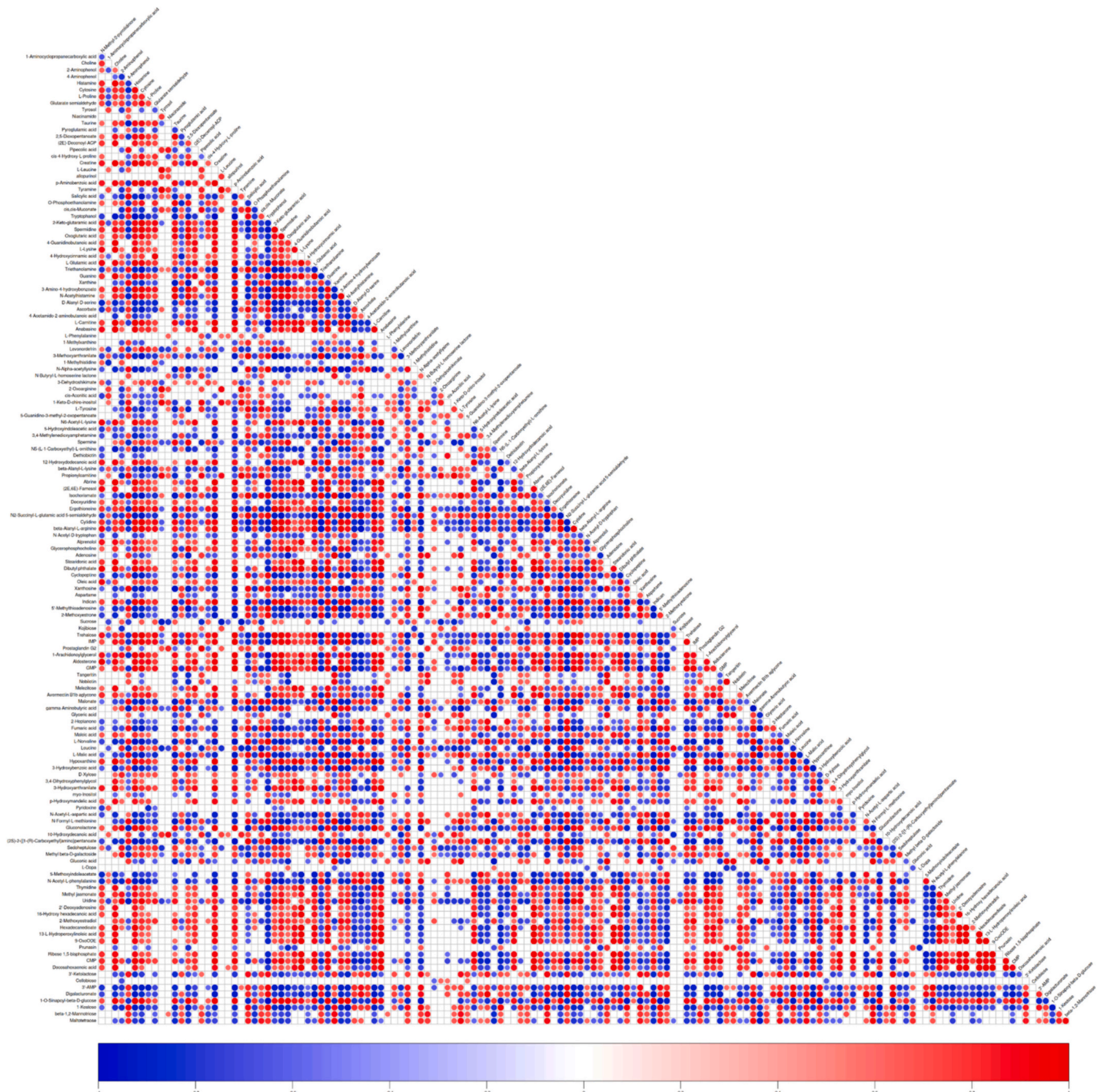
Fig. 4. Multivariate statistical analysis chart based on positive ion (a) and negative ion mode (b) under different irradiation doses (PCA score chart, PLS-DA score chart, OPLS-DA score chart).
Note: A, B, C, and D represent irradiation doses of 0 kGy, 2 kGy, 5 kGy, and 8 kGy, respectively.



(a)

Fig. 5. Identification of differential components under different irradiation doses - MS/MS plot (a - hierarchical clustering heatmap of differential components, b - correlation heatmap of differential components).

Note: A, B, C, and D represent irradiation doses of 0 kGy, 2 kGy, 5 kGy, and 8 kGy, respectively.



(b)

Fig. 5. (*continued*).

3.2. TBARS

The TBARS value can be used to reflect the degree of lipid oxidation in meat products (Ruan et al., 2024). Fig. 1(b) shows that when the irradiation dose was 0 kGy, the TBARS value of saozi was 0.70 mg/kg. With increased irradiation dose, the TBARS value of saozi increased overall. When the irradiation dose reached 8 kGy, the TBARS value of saozi significantly increased to 0.83 mg/kg ($p < 0.05$). These results indicated that high-dose irradiation can significantly increase the degree of lipid oxidation in saozi because the radiation generated by irradiation had high energy. When these rays penetrated food, they can cause molecules in the food to produce free radicals (Li et al., 2022). These free radicals had high reactivity and can react with hydrogen atoms in lipid molecules to generate lipid free radicals, thereby initiating lipid-oxidation chain reactions. Irradiation may also cause local slight heating effects, which can accelerate the automatic oxidation reaction of lipids (Zhang et al., 2024). The main component of saozi is fatty meat, and lipids themselves are prone to oxidation. Unsaturated fatty acids in fatty meat contain double bonds that are easily oxidized. Under the action of free radicals and reactive oxygen species generated by irradiation, the double bonds of unsaturated fatty acids are easily attacked, leading to oxidation and the generation of various oxidation products (Sadiq et al., 2023). Huang et al. (2023) also found that, compared with the control group, the TBARS value of smoked chicken breast increased significantly as radiation dose increased. However, when the irradiation dose was 3 kGy and 4 kGy, the difference was not significant, while at 6 kGy, the TBARS value showed a significant increase.

3.3. Statistics of substances with differences in different groups

Fig. 2 shows the statistical difference chart. In the positive-ion mode, 2601, 3223 and 3792 components in 2 kGy *vs.* 0 kGy, 5 kGy *vs.* 0 kGy and 8 kGy *vs.* 0 kGy were upregulated, whereas 3122, 3587, and 3842 components were downregulated. Among them were 1035 common components in 0 kGy *vs.* 2 kGy *vs.* 5 kGy *vs.* 8 kGy, such as the advanced venn diagram (Fig. 2). In the negative-ion mode, 1591, 2139, and 2575 components in 2 kGy *vs.* 0 kGy, 5 kGy *vs.* 0 kGy and 8 kGy *vs.* 0 kGy were upregulated, whereas 3055, 2177, and 1719 components were downregulated. Among them were 540 common components in 0 kGy *vs.* 2 kGy *vs.* 5 kGy *vs.* 8 kGy. These data showed that the number of differential components increased with increased irradiation dose. Radiation, as an external stimulus, can affect the component change processes inside cells and tissues. The size of the radiation dose directly determines the degree of damage to cells (Fan et al., 2024). Many studies have confirmed the relationship between radiation and component changes. Xiang et al. (2023) found that 10 kGy has a greater impact on compound content than 0 and 5 kGy treatments and primarily targets esters, acids, *etc.* Huang et al. (2023) showed that irradiation doses greater than 3 kGy can effectively kill microorganisms, reduce protein oxidation, and promote lipid oxidation. These studies demonstrate a significant correlation between radiation dose and the number of differential components in cells or tissues.

3.4. Differential analysis of primary metabolic components

Cluster analysis is an effective statistical method that can classify substances based on their similar characteristics and identify differences among groups. The clustering analysis results of substances in four groups of samples are shown in Fig. 3. The three repeated experiments of each group of samples showed similar color-distribution patterns, fully demonstrating the high reproducibility of the experiment. Significant differences in the expression levels of most substances also existed among the four groups of samples. This result revealed the variations in the main substances' composition among the different groups of samples. It also suggested that different radiation doses had varying degrees of impact on the content of components in meat products. Notably, the results obtained in the positive and negative-ion modes were consistent, further confirming the reliability and stability of our experimental results. Notably, the control group treated with 0 kGy and the experimental group treated with 2 kGy showed similar classification patterns in cluster analysis, whereas the experimental groups treated with 5 and 8 kGy were also classified as one group. This indicated that the composition and differences of components in the non-irradiated saozi were relatively similar to those in saozi treated with 2 kGy irradiation. After irradiation with 5 and 8 kGy, the component composition and differences between the two groups of samples were also relatively similar. When the irradiation dose exceeded 5 kGy, a significant clustering difference existed between the experimental and control groups of saozi, indicating that high-dose irradiation had a significant impact on the component of saozi.

3.5. Multivariable statistics

To analyze the changes in total components more intuitively, a classification heatmap of all components was created (Fig. 3). Results showed that the difference of overall components showed increased with increased irradiation dose. To better analyze and screen data and obtain detailed information on the differences in components between different irradiation doses of saozi. Using multivariate data analysis (PCA, PLS-DA, OPLS-DA). Multivariate statistical analysis can enable the observation of the degree of clustering and dispersion of samples. A greater dispersity among each sample in the graph corresponds with a more significant difference in chemical composition (Ruan et al., 2023).

Results showed (Fig. 4) that in positive-ion mode, for PCA, cross-validation was performed with $R2X = 0.529$, PLS-DA ($Q2 = 0.928$), OPLS-DA ($Q2 = 0.839$). In negative-ion mode, for PCA, cross-validation was performed with $R2X = 0.519$, PLS-DA ($Q2 = 0.931$), and OPLS-DA ($Q2 = 0.787$). Twelve samples were clustered into four types. Among them, the control group dosed with 0 kGy and those dosed with 2, 5, and 8 kGy had far distribution points on the score plot, indicating significant differences in the composition and concentration of components among these groups. The composition and concentration of components in the samples irradiated with 5 and 8 kGy were similar, with the closest similarity observed between these two irradiation doses. The above results can well reflect the differences between different irradiation doses, thereby effectively distinguishing them.

As shown in Table S1, a total of 147 differential components were screened. The types of differential components included amino acids, such as L-proline, L-tyrosine, L-lysine, *L*-phenylalanine, and leucine. Except for L-tyrosine, L-leucine, and *L*-phenylalanine, all other amino acids decreased with increased irradiation dose. Nucleotides such as guanosine monophosphate (GMP), and cytidine monophosphate (CMP) had their maximum values at an irradiation dose of 2 kGy, higher than 0, 5, and 8 kGy. Purines such as guanine and hypoxanthine had their maximum values at 2 kGy, whereas xanthine had its maximum value at 8 kGy. Fatty acids and organic acids such as stearidonic acid, oleic acid, salicylic acid, oxoglutaric acid, L-malic acid, *etc.* Most of the fatty acids remained at their maximum value at 2 kGy, while most of the organic acids remained at their maximum value at 8 kGy. Components such as amino acids and fatty acids have unique physicochemical properties and important physiological functions. However, high-dose irradiation treatment can lead to their loss or damage (such as the oxidation). Therefore, during the processing, excessive irradiation must be avoided to maintain the stability and activity of these substances.

3.6. Differential analysis of secondary metabolic components

As shown in Fig. 5(a), the relative content is displayed in different colors. According to the clustering heatmap, significant differences existed between the groups compared with the control group. With increased irradiation dose, a significant difference in the content of components existed. According to Table S1, a total of 147 differential secondary metabolic components were screened, including 31 amino acids (21.09 %), 11 fatty acids (7.48 %), 25 organic acids (17.01 %), 12 purines and pyrimidines (8.16 %), 2 vitamins, 9 neurotransmitters and related substances (6.12 %), 12 nucleosides and nucleotides (8.16 %), 1 enzyme inhibitor (0.68 %), 2 hormones and their derivatives (1.36 %), 1 sweetener and food additive (0.68 %), 13 sugars and their derivatives (8.84 %), and 33 other organic compounds (22.45 %).

Amino acids generally produce volatile flavor substances through the Maillard reaction and Strecker degradation, thereby affecting the flavor of meat. In terms of amino acids, a significant difference in overall signal intensity existed between irradiated and non-irradiated saozi in amino acid classification. Compared with other irradiation doses, the signal intensity of 2 kGy was the highest, reaching 14,664.81 million ($p < 0.05$). Unirradiated, irradiated doses of 5 and 8 kGy were 10,593.14 million, 13,525.16 million, and 14,179.83 million, respectively. Among them, the relative content of phenylalanine was the highest, and the detected relative contents in the four groups were 57.22 %, 46.65 %, 47.07 %, and 51.95 %, respectively. As a bitter amino acid, phenylpropanoid amino acid had a certain impact on the flavor of the sample due to its relatively rich content. After different irradiation treatments, its content initially decreased and then increased. Next is taurine, with relative contents detected in the four groups of 22.64 %, 15.42 %, 11.68 %, and 7.46 %, respectively. The relative contents of L-leucine (Leu) detected in the four groups were 0.96 %, 23.68 %, 23.15 %, and 23.18

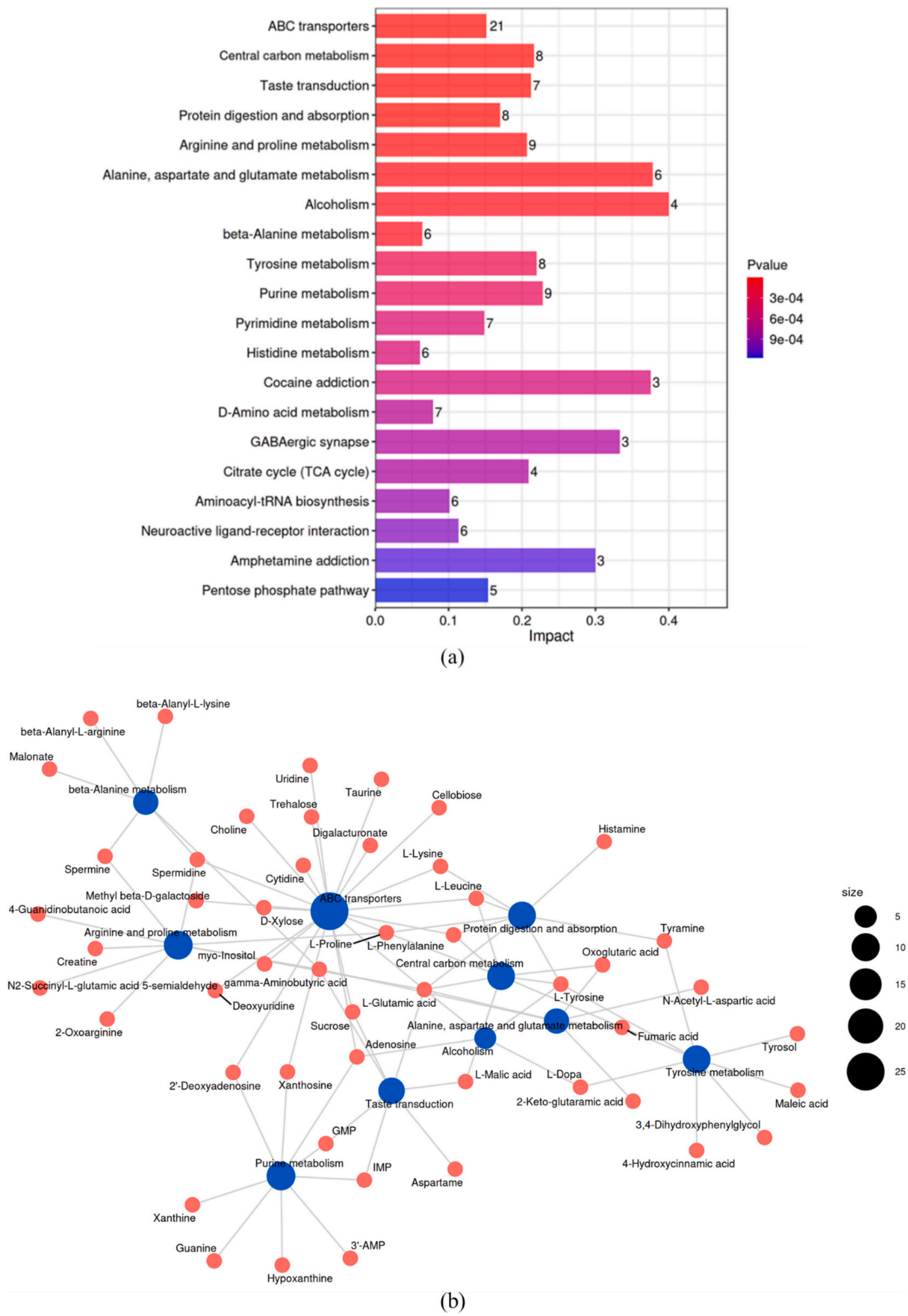


Fig. 6. Analysis of different change pathways under different irradiation doses (a- change pathway influencing factor histogram, b- change pathway network diagram).

%, respectively. The levels of creatine, L-leucine, and L-lysine significantly increased ($p < 0.05$) in saozi with an irradiation dose of 2 kGy. These results indicated that high dose irradiation treatment accelerated the decomposition of amino acids. Under similar irradiation doses, amino acids in sea bream also exhibit the same trend (Erkan & Özden, 2007). Creatine is a nitrogen-containing organic acid (Yang et al., 2018), the amount of it can affect muscle metabolism, which can reduce the softening, exudation, and color fading of meat products (Reig et al., 2013). Therefore, the higher the creatine content, the better the final quality of the product may be. Mora et al.'s (2010) research indicates that creatine has sensory properties that contribute to the development of meat extracts and the complete flavor of meat. L-lysine can effectively scavenge free radicals and chelate Fe^{2+}, thereby inhibiting the oxidation of meat proteins (Bao et al., 2022). Additionally, L-lysine can effectively improve the water-holding capacity, texture, and color of meat (Bao et al., 2021). According to Fig. 5(b), a significant positive correlation ($p < 0.05$) existed between L-lysine and creatine. Due to the characteristics of L-lysine, irradiation sterilization had a significant impact on L-lysine. Therefore, a reasonable irradiation dose should be selected. Wang et al. (2022) pointed out that when the irradiation dose was 7 kGy, the contents of some amino acids were significantly reduced, because high-dose irradiation can lead to the oxidation of amino acid residues, thus affecting flavor. For example, the oxidation of sulfur-containing amino acids (cysteine and methionine) can lead to the production of sulfur-containing volatile flavor substances with a radiation-induced odor.

Nucleotides play a crucial role in the freshness of food (Zhou et al., 2016). IMP is the main flavor component of meat, but it is unstable and can be further degraded into inosine and hypoxanthine (Liu et al., 2022). After our irradiation treatment, the relative content of IMP and hypoxanthine gradually decreased with increased irradiation dose, and a significant positive correlation existed between the two ($p < 0.05$). The content of hypoxanthine is used as one of the indicators to evaluate the freshness of the product (Mooltongchun & Teepoo, 2019), reaching its maximum value at 2 kGy treatment, which can serve as a reference irradiation dose for subsequent irradiation sterilization to maintain sample. As fresh taste nucleotides, IMP and GMP were significantly positively correlated ($p < 0.05$) in the sample, which improved the freshness and endowed the sample with good sensory characteristics (Wu et al., 2024). Some nucleotide substances decreased with increased irradiation dose, indicating that high-dose irradiation treatment had a significant impact on these substances. Feng et al. (2016) also found that compared with the control group, when the irradiation dose was 1.5 kGy, the contents of inosine, hypoxanthine, and adenosine monophosphate in cooked turkey meat were significantly increased. However, as the irradiation dose increased to 4.5 kGy, the contents of these substances decreased significantly. The levels of nucleotides in meat products vary with different irradiation doses.

Organic acids, fatty acids, and sugars also account for a large proportion of the sample. The quality characteristics of meat were greatly influenced by its fatty acid composition, such as flavor, texture, and aroma characteristics. Under irradiation conditions, the double-bond structure of fatty acids was disrupted, leading to a decrease in the detection rate of oxidized or free fatty acids. Free fatty acids to some extent can reflect the degree of lipid oxidation and decomposition in meat (Wu et al., 2021). A significant difference existed in the overall signal intensity between irradiated and non-irradiated saozi in fatty acid classification. Compared with other irradiation doses, the signal intensity of 2 kGy was the highest, reaching 456,859,804 ($p < 0.05$). Unirradiated, 5 kGy, and 8 kGy were 274,046,904, 208,793,438, and 246,021,161, respectively. These results indicate that different irradiation doses can lead to changes in the levels of fatty acids in meat and may lead to the formation of new fatty acid components. The levels of some unsaturated fatty acids, such as 12-hydroxydodecanoic acid, oleic acid, and docosahexaenoic acid, decreased at high-dose irradiation conditions ($\geq$5 kGy), indicating that oxidation was intensified. Li et al. (2020) also found that the number of fatty acids in fish samples increased after irradiation. At an irradiation dose of 6 kGy, the acid value, peroxide value, and TBARS value were the largest. Free radicals generated by high-energy radiation can attack unsaturated fatty acids and directly act on unstable fatty acids, thereby generating other compounds.

3.7. Analysis of component change pathways

As shown in Fig. 6, the changes in ABC transporters, central carbon metabolism, taste transduction, protein digestion and absorption, arginine and proline metabolism, alanine, aspartate and glutamate metabolism were important conversion pathways. Twenty significant change pathways were identified in the KEGG enrichment results. Most of the substances associated with these pathways involve amino acids, nucleotide substances, acidic substances, and others. This shows that these substances may be the main reason for the differences in composition and sensory scores of saozi under different irradiation doses.

4. Conclusion

This study investigated the effects of changes in substance composition caused by different radiation doses on the sensory characteristics of saozi. With increased irradiation dose, the degree of lipid oxidation of saozi significantly increased. The effect of different irradiation doses on the color and texture characteristics of saozi was not significant, but high-dose irradiation can lead to a significant decrease in the aroma, taste, and overall acceptability score of saozi. A total of 147 differential secondary metabolic components including 31 amino acids, 11 fatty acids, 25 organic acids, and 12 purines and pyrimidines were screened from Saozi treated with different radiation doses. High-dose irradiation treatment can lead to a decrease in the content of substances such as creatine, L-lysine, and some nucleotides that contribute significantly to the sensory quality of saozi. The KEGG enrichment results identified 20 significantly enriched change pathways. Most of the substances associated with these pathways involve amino acids, nucleotide substances, acidic substances, and so on. Considering the sensory scores and changes in material composition of saozi, when using cobalt 60 for irradiation sterilization of saozi, the optimal irradiation dose should be less than 5 kGy. It is worth noting that this study did not explore changes in the microbial community structure (including bacteria and fungus) in saozi after different irradiation doses treatments, as well as changes in microbial indicators during storage, which need to be explored in future studies.

Statement

All subjects have obtained informed consent for the sensory evaluation experiment in the article. We promise that all sensory experiments related to humans were carried out in accordance with the Code of ethics of the World Medical Association (Declaration of Helsinki), and always abide by the privacy right of human subjects.

CRediT authorship contribution statement

Xue Li: Writing – original draft, Methodology, Investigation. **Yexing Liang:** Formal analysis. **Shixiong Yang:** Formal analysis. **Jiaying Peng:** Formal analysis. **Fanyi Gong:** Formal analysis. **Buzhou Xu:** Formal analysis. **Dong Zhang:** Formal analysis.

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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