Food Chemistry: X 20 (2023) 101026

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x

Influence of electrohydrodynamics on the drying characteristics and volatile components of iron stick yam

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ARTICLE INFO

Keywords:
Electrohydrodynamics
Drying
Iron stick yam
Volatile components

Chemical compounds used in the study:
Dodecane, PubChem CID: 112-40-3
Undecane, PubChem CID: 1120-21-4
Pentadecane, PubChem CID: 629-62-9
2-Propenoic acid, butyl ester, PubChem CID: 141-32-2
Hexanal, PubChem CID: 66-25-1
Nonanal, PubChem CID: 124-19-6
Heptanal, PubChem CID: 111-71-7
Decanal, PubChem CID: 112-31-2
1-Octen-3-ol, PubChem CID: 3391-86-4
D-Limonene, PubChem CID: 5989-27-5

ABSTRACT

The drying characteristics, rehydration capacity, color, infrared spectra and volatile components of iron stick yam slices were investigated under different alternating current (AC) voltages (13, 17, 21 kV), hot air drying (HAD) (60 °C) and natural drying (AD) by electrohydrodynamic (EHD) drying and HAD experimental devices. The results showed that slices of iron stick yam dried the quickest with HAD, which also had the fastest drying rate; while drying the slices of iron stick yam with EHD led to a better rehydration capacity, higher brightness L* and whiteness, a more stable protein secondary structure, and a greater variety and content of volatile components compared with AD and HAD. These finding indicated that EHD is a more promising method for drying iron stick yam.

1. Introduction

Iron stick yam is the rhizome of *Dioscorea spp*. in the family *Dioscoreaceae* and an excellent yam, with hard flesh, delicate and sweet taste, and rich nutritional and medicinal value. The yam is rich in protein, allantoin, polysaccharides, total phenols and other nutrients and can be used to treat asthma and autoimmune diseases and relieve diarrhea (Kamal et al., 2020). Regular consumption of iron stick yam is conducive to digestion and absorption in the spleen and stomach, helps tonify the lungs, and treats dryness; in addition, regular consumption can lower blood glucose, prevent cardiovascular and cerebrovascular diseases, improve the will to calm the mind and prolong the lifespan.

Drying fresh iron stick yam is beneficial for its storage due to its high moisture content; yams are difficult to store and prone to mold and decay, and because of its brittle texture, the yam cannot be easily transported for long periods of time. When iron stick yams are dried, their shelf life can be extended, and mold damage can be avoided (Gu et al., 2022). Dried foods have many advantages over fresh foods, as storage and transport are easier and nutrients and bioactive compounds are better preserved (Kudra and Martynenko, 2023). Currently, the common drying methods are natural drying and hot air drying. Natural drying (AD) is inexpensive and simple to operate, but it takes a long time. Hot air drying (HAD) is easy to use, inexpensive, widely applicable and easy to control and is among the most widely used drying techniques at present (Dai et al., 2023); however, the high temperature has a greater impact on the quality and nutrient composition of the dried samples. Heat pump drying consumes low levels of energy and better preserves nutrients and bioactive compounds. Heat pump drying requires low levels of energy but is time-consuming. Vacuum freeze drying and variable temperature differential pressure drying generate high quality results but are expensive. Lastly, far infrared drying is quick but consumes high amounts of energy. These drying techniques used at the

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https://doi.org/10.1016/j.fochx.2023.101026
Received 29 September 2023; Received in revised form 15 November 2023; Accepted 21 November 2023
Available online 23 November 2023

present stage cannot simultaneously meet the requirements of a fast drying rate, low energy consumption and high quality, so it is necessary to adopt more innovative and efficient techniques to improve the process of drying slices of iron stick yam.

Electrohydrodynamic (EHD) drying, also known as high-voltage electric field drying, is a new drying technology that was developed in recent years. The main principle of EHD is the combined action of non-uniform electric field and ionic wind, which belongs to low-temperature drying (Onwude et al., 2021). Therefore, it will not affect the nutritional components of the heat-sensitive materials during drying process. Low-temperature drying makes EHD have lower energy consumption, reduces the occurrence of Maillard reaction during drying, and makes the physical color after drying closer to the color of fresh materials. The blowing of ionic wind can shorten the drying time and improve the drying rate of materials. Ozone, free radicals and active atoms generated in the drying process play a bactericidal role in drying materials (Polat and Izli, 2020). Han et al. (2023) investigated the effect of electrohydrodynamics on the drying characteristics and physicochemical properties of garlic and found that the color, rehydration rate, cell structure, active ingredient content and protein secondary structure of EHD-dried garlic were better than those of HAD-dried garlic. Paul and Martynenko (2022) investigated the effect of electrohydrodynamics on the drying efficiency and quality of apples and found that EHD drying had a significantly lower effect on the product quality, could better preserve the color and phenolics of the dried apple products, and caused less damage to the cells. Meng et al. (2022) investigated the characteristics of combined electrohydrodynamic-hot-air drying of carrot and banana slices and found that adding EHD to hot-air drying could shorten the drying time, reduce energy consumption and improve the rehydration rate, and it was concluded that EHD could inhibit the growth of microorganisms and improve drying quality. Furthermore, compared to solar drying and freeze drying, EHD drying leads to a higher total phenol content, less color degradation and better drying performance (Iranshahi et al., 2023). However, there are few reports on the application of EHD drying technology in iron stick yam.

Yu et al. (2022) investigated the effects of different varieties and drying methods on the volatile components of citrus peels and found that there were significant differences in volatile components between different varieties and drying methods and that freeze-drying is more favorable for the preservation of esters and phenols in citrus peel; hot-air drying is unfavorable for the preservation of ketones. Hou et al. (2021) investigated the volatile flavor of hot air drying with vacuum freeze drying and combined drying. Chen et al. (2020) identified 84 volatile compounds in 11 varieties of yam by the headspace solid phase micro extraction-gas chromatographymass spectrometry (HS-SPME-GC–MS) method. The volatile compounds in yam can be mainly classified into alcohols, aldehydes, ketones, ethers, esters, phenols, etc. Among them, alcohols and ethers such as 1-octen-3-ol and anthole are the volatile compounds present in most varieties of yam. Twenty volatile compounds were identified by Guo et al. (2022) using an HS-GC-IMS technique in different yellowing phases in slices of different varieties of fresh yam. The most volatile substances were alcohols and aldehydes, and the concentrations of most volatile compounds tended increase and then decrease with time. In recent years, increasing attention has been focused on the volatile compounds in yam; however, the changes in volatile compounds in iron stick yam under electrohydrodynamic drying have not yet been reported.

Therefore, the main research objective of this paper is to dry iron stick yam slices by three methods, namely, EHD, HAD and AD, to determine the drying characteristics, rehydration capacity and changes in surface color difference of iron stick yam slices under different drying methods and different drying voltages of EHD. The effects of different drying methods and different drying voltages of EHD on the secondary structure of proteins and volatile components in the slices of iron stick yam were investigated by infrared spectroscopy and HS-SPME-GC–MS.

2. Materials and methods

2.1. Experimental materials

Fresh, undamaged, uniformly shaped iron stick yam with the same maturity level was obtained from a supermarket near the Inner Mongolia University of Technology in Hohhot, Inner Mongolia, and the fresh samples were stored in a refrigerator at −4 °C for no more than 7 days before the experiment.

2.2. Experimental equipment

A schematic diagram of the high-voltage electric field drying device is shown in Scheme 1, which mainly includes a high-voltage power supply (YD(JZ)-1.5/50, Wuhan, China), adjustable AC voltage range of 0 ~ 50 kV controller (KZX-1.5KVA, Wuhan, China), needle plate electrodes (The upper plate is a needle plate electrode of 400 mm × 240 mm with a needle spacing of 40 mm × 40 mm, the lower plate is a 1000 mm × 450 mm grounded flat plate electrode. The gap between the discharge electrode and the grounding electrode is 60 mm.), and the length and diameter of each needle are 20 mm and 1 mm, respectively. Hot air drying oven with adjustable temperature range from 10 °C to 250 °C (Shanghai, China), temperature and humidity meter (GJWS-A2,Tianjin, China), thermal anemometer (testo 4050i, Shenzhen, China). 3nh colorimeter (3nh-NR60CP, Shenzhen,China), electronic balance (BS124S, Shanghai, China) constant-temperature water bath (DK-600BS, Jiangsu, China).

2.3. Experimental methods

The surface stains of iron stick yam were cleaned, the outer skin was peeled off, and the slices were cut into thin slices of 3 mm thickness with a fixed cross-sectional area. The initial moisture content of iron stick yam was detected to be 77.61 ± 0.88 % by using a rapid moisture detector (SH10A, Shanghai, China). Measurement of ion velocity on the surface of materials during EHD drying process using a thermal anemometer. The experiment was carried out in a drying environment with a drying temperature of 20 ± 2 °C, a relative humidity of 39 ± 1 %, and a wind speed of 0 m/s until the moisture content of the dry base of the samples reached 10 % when the experiment was terminated. The specific experimental method is shown in scheme 1. Drying characteristics, physical properties, rehydration rate, infrared spectroscopy and volatile components were analyzed for the dried samples of iron stick yam.

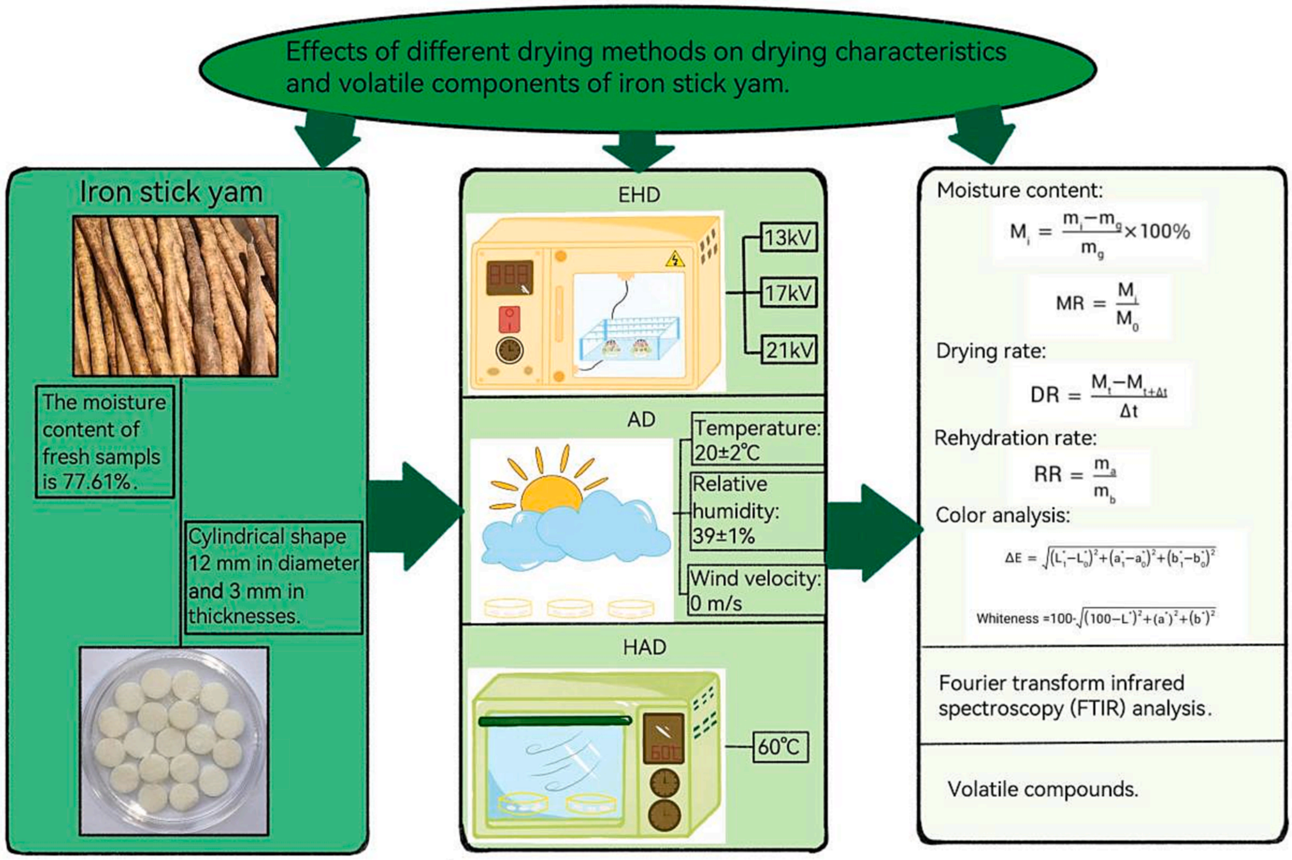
2.4. Moisture content

The dry basis moisture content and water content ratio of the iron stick yam samples during drying were calculated using the following formula (Ni et al., 2020):

$$M_i = \frac{m_i - m_g}{m_g} \times 100\% \tag{1}$$

$$MR = \frac{M_i - M_e}{M_0 - M_e} \tag{2}$$

where M_i is the dry basis moisture content of the iron stick yam dried to t_i time (unit: g water/g solid), m_i is the mass of the iron stick yam dried to t_i time (unit: g), m_g is the dry mass of the iron stick yam (unit: g), MR is the moisture ratio of the iron stick yam, M_e is the equilibrium moisture content of the iron stick yam, and M_0 is the moisture content of the iron stick yam at t_0 time. Usually, the equilibrium moisture content of food ingredients is so small that it is negligible (Chauhan et al., 2021). Therefore, the water content equation can be simplified as:



Scheme 1. Schematic diagram of the experimental procedure and drying model.

$$MR = \frac{M_i}{M_0} \quad (3)$$

2.5. Drying rate

The drying rate of the iron stick yam was calculated using the following formula (Taghian Dinani et al., 2014):

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (4)$$

where DR is the drying rate(unit: g water/g solid·h^{-1}), M_t is the moisture content of iron stick yam at time t, and $M_{t+\Delta t}$ is the moisture content of iron stick yam at time t+Δ t, T is the drying time of iron stick yam.

2.6. Rehydration rate

The rehydration rate is an important parameter for testing the quality of dried products. The dried iron stick yam was soaked in a beaker containing 60 ml of deionized water, and then the beaker was placed into a constant-temperature water bath at 37 °C until the change in mass of the yam samples was less than 0.001 g in 0.5 h. The water on the surface of the iron stick yam was completely absorbed by the filter paper after the samples were removed. An electronic balance was used to measure the mass of the iron stick yam before and after rehydration. The rehydration rate of the iron stick yam was calculated using the following formula (Taghian Dinani et al., 2014):

$$RR = \frac{m_a}{m_b} \quad (5)$$

where RR is the rehydration rate of the iron stick yam, m_a is the mass of the sample after rehydration, and m_b is the mass of the sample before rehydration.

2.7. Color

The brightness value L*, redness value a* and yellowness value b* of fresh and dried samples of iron-stick yam were measured using a 3 nh colorimeter, and the experimental results were taken as the average of five different positions of the color of the same sample. The total color difference and whiteness of iron stick yam were calculated as follows (Jalaee et al., 2011; Kamal et al., 2020):

$$\Delta E = \sqrt{(L_1^* - L_0^*)^2 + (a_1^* - a_0^*)^2 + (b_1^* - b_0^*)^2} \quad (6)$$

$$Whiteness = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2} \quad (7)$$

where ΔE is the total color difference of the iron stick yam samples before and after drying, L_0^*, a_0^*, b_0^* are the brightness, redness and yellowness values of the fresh iron stick yam samples, respectively, and L_1^*, a_1^*, b_1^* are the brightness, redness and yellowness values of the dried iron stick yam products, respectively.

2.8. Infrared spectral analysis

The infrared spectra of the dried iron stick yam products were measured using the attenuated total reflection (ATR) method. The test samples were taken, and the infrared spectra of the dried iron stick yam products were obtained directly after the air background was measured in the ATR mode. After the air background was subtracted, the samples were scanned 32 times with an fourier transform infrared spectroscopy (FTIR) spectrometer with a wavenumber range of 400–4000 cm^{-1}, a resolution of 4 cm^{-1}, and a signal-to-maneuver ratio of 50,000:1. The amide I spectra were analyzed in the range of 1600–1700 cm^{-1} in the IR spectra by smoothing, baseline calibration, Gaussian inverse convolution, second-order derivatives and curve fitting. The percentages of α-helix, β-sheet, β-turn, β-antiparallel and random coil protein secondary structure compositions were calculated.

2.9. Volatile component

Headspace solid-phase microextraction coupled with gas chromatography (HS-SPME-GC–MS) was used to measure the volatile components of the dried products of iron stick yam. The dried products of iron stick yam were ground to powder, and 3 g of sample (accurate to 0.0001 g, and the mass difference between samples was not more than 3 %) was weighed into a headspace vial. Solid-phase microextraction (SPME) was carried out at 50 °C for an adsorption time of 50 min and then tested after desorption at 250 °C for 5 min.

The gas analysis method was selected as a column DB-5MS (Agilent, J&W Scientific, 30 m*0.25 mm*0.25 μm) with an inlet port of 250 °C, a shunt ratio of 10:1, a carrier gas of high purity helium at a flow rate of 1.00 ml/min, and a warming process of holding at 50 °C for 2 min, rising to 200 °C at 10 °C/min, and rising to 250 °C at 2 °C/min. The temperature of the ion source was 220 °C, the temperature of the interface was 280 °C, and the scanning m/z was 30–500.

2.10. Statistical analysis

All experiments were repeated three times, and the experimental results were taken as the mean ± standard deviation of the data of the three experiments. The differences in the data of drying rate, moisture content, rehydration rate and color of the iron stick yam were determined by one-way analysis of variance (ANOVA), and $p < 0.05$ was considered a significant difference. The infrared spectra, principal component analysis (PCA) and correlation thermograms were also performed using relevant software.

3. Results and analysis

3.1. Moisture content ratio

Fig. 1a shows curves for the moisture content ratio of the dried products of iron stick yam over time under different drying methods. As seen in Fig. 1a, the influence of different voltages on the rate by which moisture content decreased inside the samples as the iron stick yam was dried in the EHD treatment group was different. The slowest decrease of

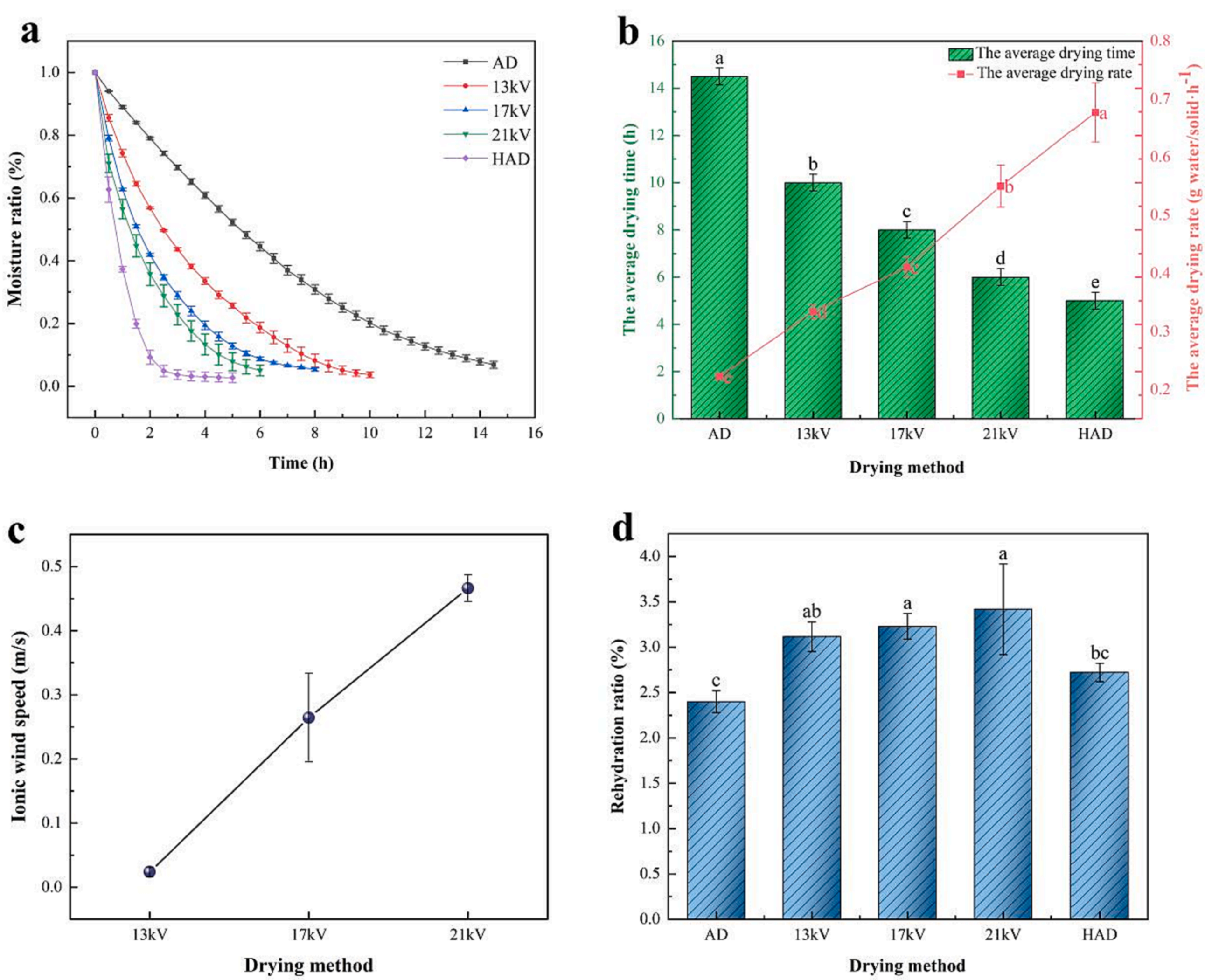


Fig 1. Drying characteristics of dried iron stick yam products under different drying conditions. a: Curve of the water content ratio with time of dried iron stick yam under different drying conditions. b: Average drying time and average drying rate of dried iron stick yam under different drying conditions. c: Surface ionic wind speed of iron stick yam under different drying voltages. d: Rehydration rate of dried iron stick yams under different drying conditions. Note: Different letters indicate significant differences in the results ($P < 0.05$).

moisture content was observed in the AD treatment group, and the rate of water decrease in the EHD treatment group was significantly higher than that in the AD treatment group. The rate by which the dried products of iron stick yam dried increased with increasing voltage, but the increment decreased with increasing time, which corresponds with the results obtained by Xiao and Ding (2022). The fastest decrease in moisture content was found in the HAD treatment group. HAD mainly uses hot air as the drying medium, and the moisture on the material surface diffuses outward through the air film on the material surface through convective heat transfer, which results in a moisture difference between the inside of the material and the surface of the material; therefore, the moisture in the inside of the material diffuses to the surface of the material. Thus, high temperature and fast airflow lead to a fast drying rate of HAD (Han et al., 2023).

3.2. Drying rate

Fig. 1b shows the average drying time and average drying rate of the dried iron stick yam under different drying methods. The drying rate mainly depends on the electric field strength and the nature of the drying material, especially the amount of free moisture initially available on the surface of the drying material (Martynenko and Zheng, 2016). The average drying rates of the 13 kV, 17 kV, 21 kV and HAD treatment groups were 1.50, 1.84, 2.46 and 2.53 times higher than those of the AD treatment group, respectively. The drying rate of the samples increased with increasing voltage. The drying process involves the evaporation of water inside the samples, and the drying rate depends on the evaporation rate of water. During the electrohydrodynamic drying process, the movement of electrons and positive ions towards the two opposite electrodes accelerates the movement of air molecules, forming an ionic wind. Ionic wind will accelerate the evaporation of water on the surface of the iron stick yam. Thus, the migration of water molecules from the inside to the surface of the samples is accelerated. The higher the voltage is, the more obvious the promotion effect of ionic wind on the drying rate. With increasing drying time, the internal moisture of the samples gradually decreased, and the drying rate gradually slowed down. In this way, the drying process was a deceleration period. This result corresponds with the conclusion of Anukiruthika et al. (2021). The drying rate of the EHD treatment group of iron stick yam increased with increasing applied voltage, mainly because with increasing voltage, the intensity of the needle tip discharging of the upper electrode plate increased, and the speed of the ionic wind increased (Fig. 1c), which accelerated the rate by which the material dried. The average drying time of the AD treatment group was significantly longer than that of the EHD and HAD treatment groups ($p < 0.05$), and the average drying time was 1.45, 1.81, 2.42, and 2.42 times longer than that of the 13 kV, 17 kV, and 21 kV treatment groups and the HAD treatment group, respectively.

3.3. Rehydration rate

The rehydration rate refers to the ratio of dried sample mass that absorbs water and returns to the predrying state to the mass of the dried sample. The strength of the rehydration ability of a substance depends on the degree by which the cells and structures are destroyed by the drying method (Contreras et al., 2012). When the rehydration rate of a sample is lower, the sample's internal organization structure are more greatly destroyed and the quality of the sample obtained by the drying method is improved. Fig. 1d shows the rehydration rate of the dried products of iron stick yam under different drying conditions. Fig. 1d shows that the rehydration rates from high to low were 3.4177, 3.2300, 3.1149, 2.7210 and 2.3993 for 21 kV, 17 kV, 13 kV, and HAD, respectively. The rehydration rates of the EHD treatment group dried iron stick yam were significantly better than those of the HAD and AD treatment groups because EHD drying is nonthermal drying, and the ionic wind only acts on the surface of the substance and does not damage the internal organizational structure of the substance. Compared to HAD drying under high temperature conditions, the process by which the internal moisture diffuses to the substance surface causes the substance surface to intensely contract and crack, damaging and rupturing the organizational internal capillary structure of the substance; as a result, the rehydration capacity of the dried products is affected (Maskan, 2001).

3.4. Color

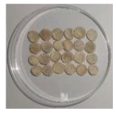
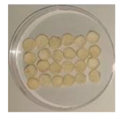
Color is closely related to food quality and a key factor that affects first impressions and consumer recognition (Argaw et al., 2023). Table 1 shows the changes in surface color parameters before and after iron stick yam was dried under different drying methods, and the effects of different drying methods on the surface color of iron stick yam were significantly different ($p < 0.05$). As seen from Table 1, the values of each color difference were significantly different in the dried products of iron stick yam after drying compared to the fresh yam slices.

The brightness value (L^*) and whiteness value of the dried iron stick yam products in the EHD were higher than those of the HAD and AD and increased with increasing voltage. The redness values (a^*) of the dried products of iron stick yam under different drying conditions were significantly increased, and the largest value of a^* was in the AD, which was 4.44 ± 0.06. This phenomenon may occur because iron stick yam is rich in ferrous iron, vitamin C, and phenolics, which chemically react with the substances in the air after prolonged exposure to the air and thus lead to an increase in the a^* value (Zhang et al., 2023). The a^* values of the EHD were not significantly different from those of the HAD, and the b^* values were lower than those of the HAD; in addition, b^* values the decreased with increasing voltage because EHD is nonthermal drying and HAD is thermal drying. This change mainly results from the production of enzymatic browning, which is often found in low-temperature drying, and nonenzymatic browning, which is often found in thermal drying (Manzocco et al., 2001). Higher drying temperatures promote browning and yellowing due to the Maillard reaction, ascorbic acid, and phenolic degradation, suggesting that EHD drying is effective in reducing browning in the dried iron stick yam. The 21 kV had the highest L^*, the highest whiteness, and lower b^*. The higher L^* value indicates that less browning reaction occurs during the drying process (Wang et al., 2018), which further demonstrates that EHD drying can better protect the color of the dried materials.

3.5. Infrared spectral analysis

FTIR exhibits unique robustness and sensitivity and thus has become a very popular technique in food science in recent years. Fig. 2a shows the infrared spectra for the dried products of iron stick yam under different drying conditions. From Fig. 2a, it can be seen that different functional groups correspond to different characteristic absorption peaks in the infrared spectra. The peaks near 3288 cm^{-1} are wider and mainly attributed to the N—H of proteins and the O—H telescopic vibration peaks of polysaccharides. The energy band intensity (transmittance %, T) was significantly lower in AD and EHD-dried iron stick yam than in HAD-dried yam. Broad bands of —OH stretching on starch due to hydrogen bonding were also observed near this band by Falade and Ayetigbo (2021), who investigated the effect of physicochemical modification on the FTIR spectral lines of yam starch. A methylene —CH2 antisymmetric stretching vibrational absorption peak was observed near 2929 cm^{-1}, and the transmittance of the dried iron stick yam increased with increasing voltage. The carbonyl C═O telescopic vibration of cholesteryl ester and triglyceride is mainly near 1745 cm^{-1}, and the carbonyl C═O telescopic vibration of the protein amide I group is mainly near 1645 cm^{-1}, which may also contain N—H bending vibration absorption peaks and C—N telescopic vibration peaks. The transmittance of the dried products of iron stick yam under different drying conditions showed a decreasing trend in the wavelength range, which indicates that the condition is unfavorable for the preservation of

Table 1
Color changes in iron stick yam samples before and after drying under different drying conditions.

	Fresh	AD	13 kV	17 kV	21 kV	HAD
Sample						
L*	61.52 ± 0.3[d]	47.37 ± 0.49[f]	63.40 ± 0.13[c]	66.14 ± 0.22[b]	69.52 ± 0.16[a]	60.24 ± 0.51[e]
a*	1.28 ± 0.04[d]	4.44 ± 0.06[a]	2.61 ± 0.15[bc]	2.62 ± 0.07[bc]	2.54 ± 0.17[c]	2.73 ± 0.11[b]
b*	9.79 ± 0.02[f]	10.34 ± 0.06[b]	14.81 ± 0.05[c]	14.04 ± 0.05[d]	13.09 ± 0.03[e]	15.79 ± 0.01[a]
ΔE	/	15.84 ± 0.64[a]	5.50 ± 0.04[d]	6.35 ± 0.15[c]	8.52 ± 0.22[b]	6.35 ± 0.15[c]
Whiteness	60.37 ± 0.23[c]	44.97 ± 0.47[e]	60.42 ± 0.12[c]	63.25 ± 0.21[b]	66.72 ± 0.16[a]	57.13 ± 0.47[d]

Note: Different letters indicate significant differences ($p < 0.05$) between sample means. L*: brightness value; a*: redness value; b*: yellowness value; ΔE: total color difference; whiteness: whiteness value. Note: Different letters indicate significant differences in the results ($P < 0.05$).

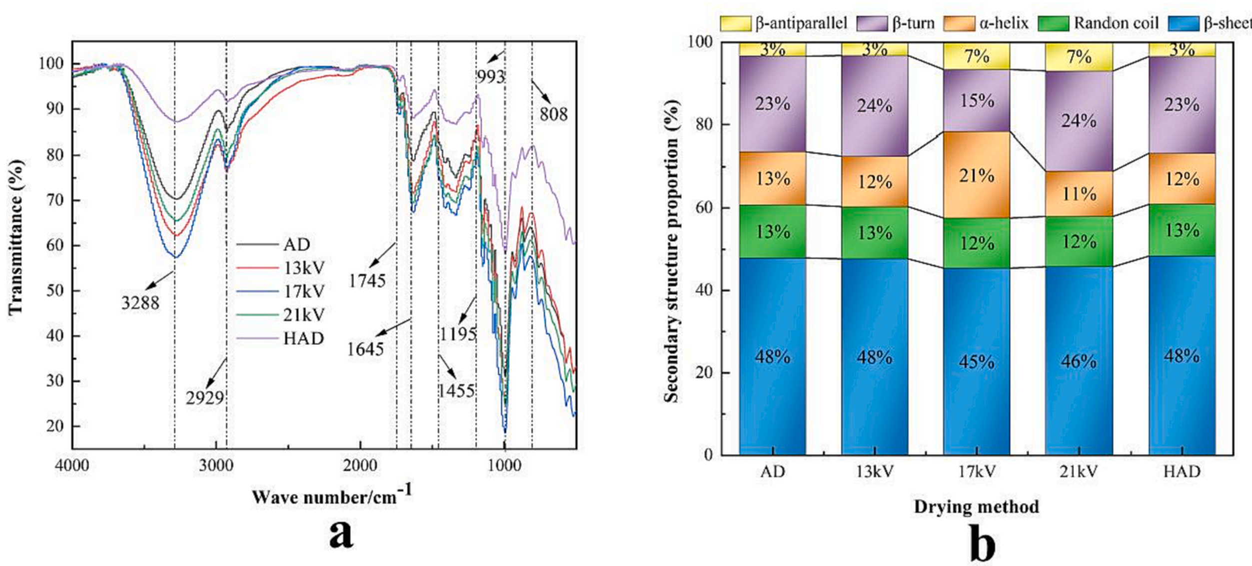


Fig 2. Infrared spectra and protein secondary structure of dried iron stick yam under different drying conditions. a: Infrared spectra of dried iron stick yam under different drying conditions. b: Proportion of protein secondary structure of dried iron stick yam under different drying conditions.

active components, such as amide bands of amino acids and proteins, alkaloids, and unsaturated esters. This result was similarly found by Ni et al. (2020), who believed that the different pretreatment methods had some effects on the internal structure and active ingredients of Chinese wolfberry. The C—O—H and methyl bending modes of proteins and lipids were predominantly observed near 1455 cm$^{-1,}$ C—O telescopic vibrations were predominantly observed near 1195 cm^{-1} (Candoğan et al., 2020), and the energy band intensities of the dried products of iron stick yam were significantly reduced in the wavenumber range near 1000 cm^{-1} for different drying conditions. This indicates that the increase in voltage is not favorable for the preservation of carbohydrates such as polysaccharides and glycosides. Below 950 cm^{-1} is the characteristic peak of fingerprints, and Candoğan et al. (2020) concluded that this region mainly contains characteristic bands of proteins, lipids, phospholipids, and nucleic acids produced by a variety of biological molecules. From Fig. 2a, it can be seen that the positions of the infrared spectral peaks for the dried iron stick yam under different drying voltage treatment conditions were basically similar, but the intensities of the characteristic peaks of the dried iron stick yam under different treatment conditions were obviously different; the intensity of the absorption peaks from the strongest to the weakest was as follows: 17 kV > 13 kV > 21 kV > AD > HAD. In conclusion, suitable EHD voltage treatment conditions are more favorable for retaining nutrients in the dried products of iron stick yam.

Fig. 2b shows the protein secondary structure of the dried products of iron stick yam under different drying conditions. Through baseline adjustment, Gaussian inverse convolution, second-order derivatives and curve fitting, the shapes located in the amide I band 1600–1700 cm^{-1} in the FTIR spectra could be used to determine the protein secondary structure of the dried products of iron stick yam. The secondary structure corresponded to the different peak positions, with the β-sheet appearing at 1600–1642 cm^{-1}, the random coil at 1642–1650 cm^{-1}, α-helix at 1650–1660 cm$^{-1,}$ β-turn at 1660–1680 cm^{-1}, and β-antiparallel at 1680–1700 cm^{-1} (He et al., 2015). The α-helix and β-sheet belonged to the ordered structure. β-turn and random coil belonged to the disordered structure (Qian et al., 2019). As shown in Fig. 2b, β-sheets and β-turns are the main forms of protein secondary structure in dried iron stick yam, and it has been found that β-sheets provide the most significant contribution to the amide I band in plant foods with high protein content (Carbonaro and Nucara, 2009). The difference in the content of β-sheets and random coils under different drying conditions was not significant, and the content of α-helices was significantly higher and that of β-turns was significantly lower in the 17 kV-treated group; thus, the protein secondary structure of the EHD dried products of iron stick yam at the appropriate voltage may be higher, as similarly found by Han et al. (2023). This was attributed to the destruction of the protein secondary structure by high temperature and prolonged drying. In conclusion, compared to HAD drying, EHD drying retains more nutrients in dried iron stick yam.

3.6. Volatile component

To study the volatile compounds in the dried products of iron stick yam under different drying conditions, the volatile compounds and their relative contents in the iron stick yam under different drying conditions were analyzed and identified using the HS-SPME-GC–MS method. A total of 82 volatile organic compounds were identified in the dried products of iron stick yam, but the number of volatile compounds in the iron stick yam dried by different drying methods was different, and 43, 42, 46, 46 and 43 volatile compounds were identified in the AD, 13 kV, 17 kV, 21 kV and HAD treatment groups, respectively. All these volatile compounds belonged to eight classes, namely, 35 alkanes, 15 esters, 12 aldehydes, 8 alcohols, 8 terpenes, 4 ketones, 2 acids and 5 others. Fig. 3 shows the number and proportion of volatile compound classes in the dried products of iron stick yam under different drying conditions. The categories and contents of volatile components can be used as important indicators to differentiate iron stick yam dried by different drying methods. The above results indicated that the process of drying iron stick yam under different drying conditions was accompanied by a loss of certain volatile components and the generation of new volatile components, which might be related to the generation of chemical reactions such as the Maillard reaction the degradation reaction of macromolecules, and the interaction of different molecules in different drying methods (Guo et al., 2018).

For a more convenient and intuitive observation, 28 alkanes, 9 esters, 12 aldehydes, 8 alcohols, 8 terpenes, 3 ketones, 2 acids and 5 others were identified based on the NIST library combined with retention index (RI) and retention time. Using the shared volatile compounds as the dependent variable and different drying conditions as the independent variables, effective differentiation of the iron stick yam under different drying conditions could be achieved by orthogonal partial least squares discriminant analysis OPLS-DA (Fig. 4a), which showed that the HAD was located at the positive half-axis of the longitudinal axis, and the AD and EHD were located at the lower half-axis of the longitudinal axis. The fit index (R_x^2) for the independent variable in this analysis was 0.99, the fit index (R_y^2) for the dependent variable was 0.999, and the model prediction index (Q^2) was 0.998; R^2 and Q^2 exceeded 0.5, indicating acceptable model fit results (Yun et al., 2021). After 200 substitution tests, as shown in Fig. 4b, the intersection of the Q^2 regression line with the vertical axis was less than 0, indicating that there was no overfitting of the model, and the model was validated. The results were useful for the identification and analysis of the volatile compounds in the iron stick yam under different drying methods. Fig. 4c shows the fingerprints of the volatile compounds in the iron stick yam under different drying methods, which were established according to the peak retention time, peak area and other parameters of these volatile compounds, and the fingerprints of the volatile compounds in the iron stick yam under different drying methods were significantly different from each other. The volatile compounds in the iron stick yam were similar under different drying methods, but the total content of each type of volatile compound was different. The contents in descending order were aldehydes > alkanes > esters > alcohols > terpenes > others > ketones > acids.

Aldehydes are the main volatile constituents in the process of drying iron stick yam, with higher levels in each drying method. It must be emphasized that aldehyde volatiles play a very important role in the overall volatile composition of dried iron stick yam due to their low odor threshold (Ni et al., 2023). A total of 12 aldehydes were identified in different drying conditions, among which the most important volatile components were hexanal, nonanal and decanal; all these components were in the form of colorless and transparent liquids, and since aldehydes were mostly produced by lipid oxidation and amino acid catabolism, they possessed fruity and oily aromas. The contents of total aldehydes were higher in the EHD group than in the AD and HAD groups. This indicates that aldehydes are more volatile under low-temperature and high-pressure conditions, while high-temperature conditions are unfavorable for the formation of aldehyde volatiles. Among the 12 detected aldehydes, the highest content of 7 was found in the 21 kV treatment group, and interestingly, 21 kV also possessed the highest amount of aldehydes. The results showed that EHD drying was more favorable for the volatilization of aldehyde volatiles than AD and HAD.

Alkanes were the second most abundant compounds after aldehydes in the dried iron stick yam under different drying conditions. At the same time, alkanes were the most abundant types of volatile compounds detected in the dried iron stick yam under different drying conditions in GC–MS, and a total of 28 volatile compounds of alkanes were detected. The more volatile alkanes in dried iron stick yam under different drying

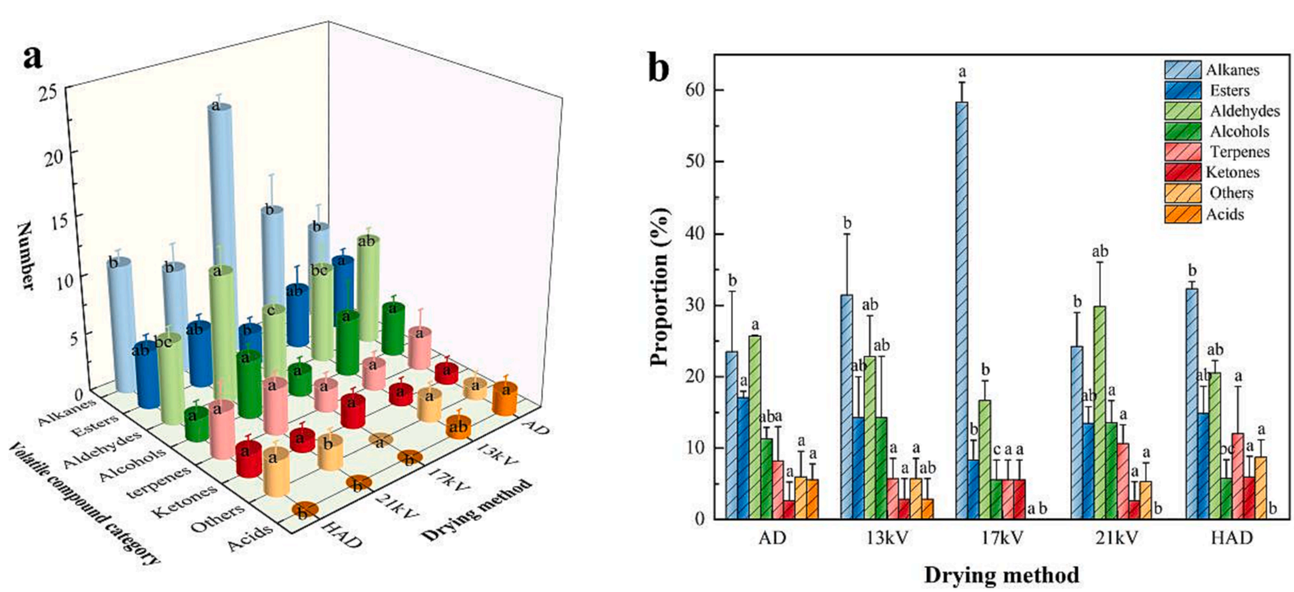


Fig 3. Quantity and proportion of volatile compound classes in dried iron stick yam under different drying conditions. a: Quantity of volatile compound classes in dried iron stick yam under different drying conditions. b: Proportion of volatile compound classes in dried iron stick yam under different drying conditions. Note: Different letters indicate significant differences in the results ($P < 0.05$).

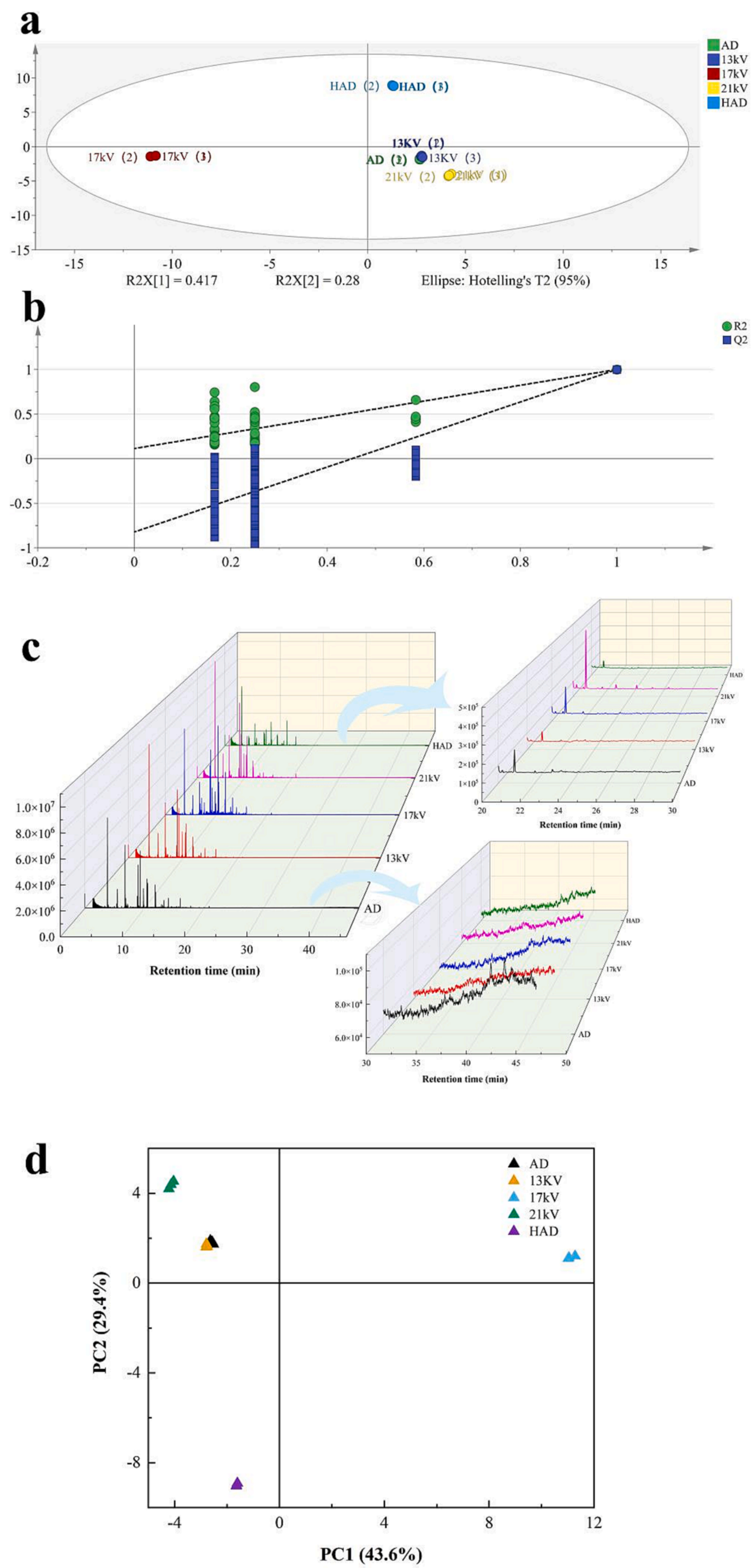


Fig 4. a: OPLS-DA of dried iron stick yam under different drying conditions. b: Model cross-validation results. c: Fingerprints of volatile compounds in dried iron stick yam under different drying conditions. d: PCA plots of the intensity of VOCs detected by HS-SPME-GC–MS for the dried products of iron stick yam under different drying conditions.

conditions were dodecane. The 17 kV treatment group contained the most volatile aldehydes in terms of type and content, twelve of which appeared only in the products of iron stick yam after drying in the 17 kV treatment group (EHD). This result indicates that proper voltage parameters are more favorable for the formation of volatile alkane compounds in the dried products of iron stick yam.

A total of nine ester volatiles were identified in the dried iron stick yam under different drying conditions. The esters generally originate from esterification reactions between alcohols and acids caused by the degradation of fats or proteins or from alcoholysis reactions between triglycerides, fatty acids and esters in ethanol (Yun et al., 2021). Most of the esters have a fruity fragrance. Acetic acid, butyl ester and 2-propenoic acid, butyl ester were the volatiles of esters that were more abundant in the dried iron stick yam under different drying conditions. Both were colorless and transparent liquids with fruity fragrances. The content of total esters in the dried iron stick yam in the HAD was significantly higher than that in the EHD. This result indicates that the ester volatiles were destabilized and became volatile under high temperature conditions. This finding validates the conclusion of Ni et al. (2023).

Alcohols usually carry special floral and fruity aromas (Yun et al., 2021) and are mainly produced by the reduction of the corresponding aldehydes (Bi et al., 2023). The content of volatile alcohols detected using GC–MS decreased with increasing voltage. 1-Octen-3-ol was the volatile alcohol with the highest content in the dried iron stick yam under different drying conditions, and 1-octen-3-ol was a colorless oily liquid. The compound has a strong acrid, herbal aroma and a clear but weak aroma with a sweet lavender scent; due to its low odor threshold, 1-octen-3-ol contributes more to the volatile odor of iron stick yam (Zhang et al., 2023). The content of 1-octen-3-ol decreased significantly with increasing voltage, but interestingly, the content of 1-octen-3-ol in the 21 kV sample was still 55.06 % higher than that in the HAD sample despite decreasing by 29.58 % compared with that in the 13 kV iron stick yam. This result indicates that volatile alcohols in the dried iron stick yam are affected by the voltage parameter in the EHD drying influence and that the high temperature conditions make it more stable and unfavorable to volatilization.

A total of eight terpene volatiles were detected by GC–MS in the dried iron stick yam under different drying conditions. D-Limonene, a monocyclic monoterpene, is a colorless oily liquid with a pleasant citrus aroma that is irritating and sensitizing to the skin and is a natural constituent present in a wide range of fruits (mainly citrus), vegetables and spices. In citrus fruits (especially its peel), spices and herbs in the essential oil content are higher. D-Limonene is easily oxidized and deteriorated to parsley oil terpene ketone and parsley oil terpene alcohol in the air. The content of D-limonene at 17 kV was significantly higher than that in the other groups and was 9.81, 5.68, 10.8, and 5.27 times higher than that in the AD, 13 kV, 21 kV, and HAD treatment groups, respectively. The volatilization of D-limonene is affected not only by the drying temperature but also by the voltage parameters.

A total of three ketone volatile compounds were detected in the 13 kV, 17 kV and HAD treatment groups. Ketone volatiles are generally derived from lipid oxidation, alkane degradation, and the Maillard reaction,. Even though the content of ketone volatiles in the dried iron stick yam under the different drying methods was lower, it still generated a butter and blue cheese flavor in the dried iron stick yam (Bi et al., 2023). The highest content was 5-hepten-2-one, 6-methyl-, which is a colorless or pale yellow liquid with a fruity aroma. The content of 5-hepten-2-one and 6-methyl- at 17 kV was significantly higher than that of the other 2 groups. This result indicates that suitable EHD voltage drying is favorable for the volatilization of ketones in the dried iron stick yam. 5,9-Undecadien-2-one, 6,10-dimethyl-, (E)- is a ketone volatile specific to the HAD treatment group. This substance is mostly found in smoke or in tea, mint, and tomatoes and has a penetrating clear, sweet, slightly rosy aroma. This compound mainly resulted from the higher temperatures in the HAD-treated group leading to the production of 5,9-undecadien-2-one, 6,10-dimethyl-, (E)-. Acids were the least volatile compounds in the iron stick yam under different drying conditions, and only two acids were detected in the AD and in the 13 kV, 3-Hydroxymandelic acid, 3TMS derivative, and dl-Leucine, N-[(phenylmethoxy)carbon-yl]-. dl-Leucine, N-[(phenylmethoxy)carbonyl]- is an acid volatile specific to AD, which is commonly found in the form of white, slightly bitter crystals or crystalline powder. In addition, GC–MS also detected some other volatile components in the dried iron stick yam under different drying conditions, in which furan, 2-pentyl-, formed from linoleic acid and other n-6 fatty acids with a low-threshold and phytoaromatic aroma, was detected in the AD, 13 kV, and 21 kV treatment groups (Wall et al., 2019). It has been found that furan, 2-pentyl, exhibits various beneficial effects, such as antimicrobial, analgesic, antimutagenic, antiplatelet, antiallergic, antitussive, anti-inflammatory and antioxidant properties (Sun et al.,2023). Decane, 1,1′-oxybis-, butylated hydroxytoluene and *n*-butyl ether were found to be present only in the HAD-treated group. *n*-Butyl ether and Decane, 1,1′-oxybis- were both colorless, odorless and clear liquids. Butylated Hydroxytoluene. On the other hand, it is a colorless crystal or white crystalline powder, which can cause dermatitis and allergy formation on contact with the skin, suggesting that the main cause of the tingling and itching of the skin after contact with yam in some people is most likely due to the presence of butylated hydroxytoluene in yam.

Principal component analysis (PCA) has been widely used as a multivariate statistical analysis technique for sample variation analysis, which can simplify the data and reveal the interrelationships among different samples; this analysis involves describing the unsupervised classification trends among samples (Yu et al., 2022). Fig. 4d shows the principal component analysis (PCA) based on the signal intensities of the volatile compounds identified by GC–MS in the dried iron stick yam on the basis of the above results, and the cumulative variance contributions of PC1 (43.6 %) and PC2 (29.4 %) were 73 %. Different drying conditions had a significant effect on the volatile constituents of iron stick yam. From Fig. 4d, it can be clearly seen that the samples from the EHD treatment group were in the first and second quadrants, and the samples from the HAD treatment group were in the third quadrant, which may be attributed to the difference between low-temperature drying and high-temperature drying. PCA was effective in distinguishing between EHD and HAD.

3.7. Statistical analysis

The drying characteristics data (average drying rate, average drying time, rehydration rate, color difference value) of the dried iron stick yam under different drying conditions were normalized, and then correlation analysis was carried out. Fig. 5a shows a correlation heatmap for the effects of different drying methods on the drying indices of the dried iron stick yam. In terms of average drying rate and average drying time, HAD was superior to EHD. However, the results of other parameters showed that the EHD was superior to the HAD, in which the correlation coefficient between the L* value and the whiteness value of the dried iron stick yam after drying at 21 kV was the largest, the negative correlation coefficient of the a* value was the largest and the correlation coefficient of the rehydration capacity was the largest; thus, it can be concluded that the color at 21 kV was the best preserved and the rehydration ability of the dried iron stick yam after drying was the strongest. Fig. 5b shows the cluster heatmap of differential volatile screening in iron stick yam under different drying conditions. A better stability prediction model was established by OPLS-DA, and 13 differential volatile volatiles were screened ($VIP > 1$, $P < 0.05$), which were 5-undecene, 9-methyl-, (Z)-; dibutyl phthalate; decanal; benzaldehyde; butanal, 2-ethyl-3-methyl-; dodecane, 2-methyl-6-propyl-; 2-Octenal, 2-butyl-; 3-Decen-1-ol, (E)-; hexanal; nonanal; heptanal; acetic acid, butyl ester; 1-Hexanol. From Fig. 5b, it can be seen that the 13 different volatile volatiles can achieve a better distinction between the dried products of iron stick yam under different drying conditions. At 21 kV, 5-undecene, 9-methyl-, (Z)-; 2-octenal, 2-butyl-; dibutyl phthalate; decanal; hexanal; butanal, 2-ethyl-

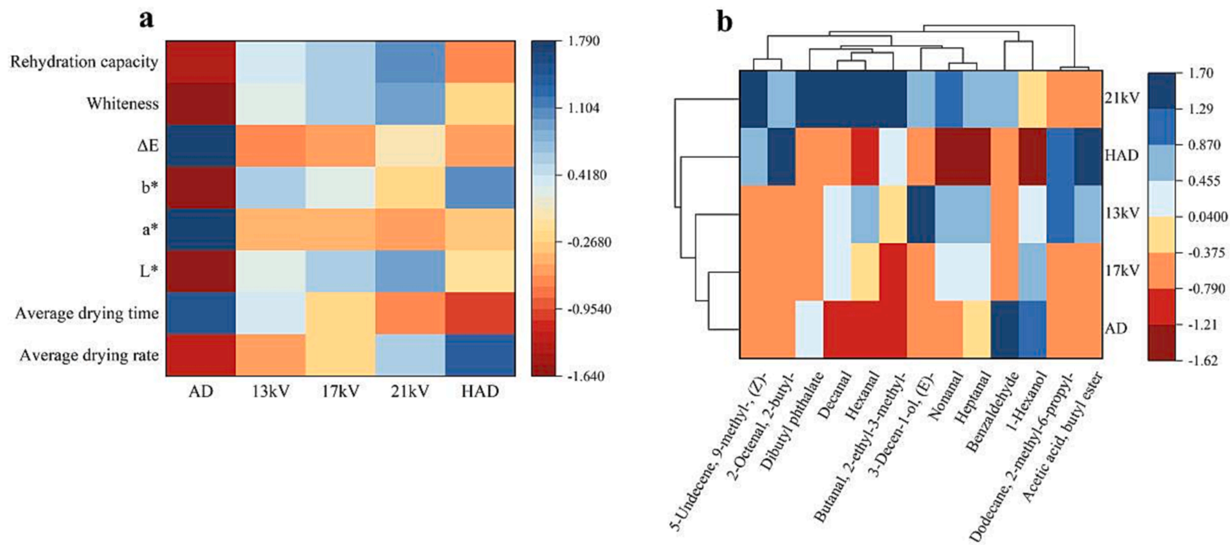


Fig 5. Statistical analyses. a: Correlation heatmap between different drying methods and drying indices. b: Heatmap of differential volatile screening clustering in iron stick yam under different drying conditions.

3-methyl-; 3-Decen-1-ol, (E)-; nonanal; heptanal and benzaldehyde were higher, and the above compounds might be positively correlated with the relevant aroma attributes at 21 kV. The contents of 5-undecene, 9-methyl-, (Z)-; 2-octenal, 2-butyl- in the dried products of iron stick yam after drying were lower in the AD, 13 kV and 17 kV treatment groups than in the 21 kV and HAD treatment groups. These two compounds were negatively correlated with the aroma attributes associated with the AD, 13 kV, and 17 kV treatment groups.

4. Conclusions

Comprehensively, the results of the above studies and analyses showed that different drying methods exhibited significant effects on the drying characteristics and volatile components of iron stick yam. Compared with EHD and AD, the drying time of HAD was shortened by 20 %-65.51 %, and the drying rate was increased by 18.74 %-67.10 %. On the contrary, after EHD drying, the color, rehydration ability, and secondary structure of the protein of dried iron stick yam products are significantly better than HAD drying and AD drying. The rehydration capacity of iron stick yam dried at 21 kV(EHD) is 1.26 and 1.42 times that of HAD and AD. 82 volatile organic compounds were identified by GC–MS. The types of volatile compounds in dried iron stick yam products were similar under different drying methods, but the contents of aldehydes, alkanes, alcohols, alkenes and ketones in iron stick yam after EHD drying were higher. Hexanal, Nonanal and Dodecane are the most abundant compounds in dried iron stick yam products. Provide fruit and oil aroma for iron stick yam dry products. Therefore, the current research provides a more favorable drying method for iron stick yam, but the mechanism underlying the production of various volatile substances has not been uncovered, and further research is needed.

CRediT authorship contribution statement

Jie Zhang: Conceptualization, Investigation, Methodology, Writing – original draft. **Changjiang Ding:** Conceptualization, Project administration, Resources, Supervision, Writing – review & editing. **Jingli Lu:** Conceptualization, Project administration, Resources, Supervision, Writing – review & editing. **Huixin Wang:** Data curation, Visualization, Validation. **Yuting Bao:** Data curation, Visualization, Validation. **Bingyang Han:** Data curation, Visualization, Validation. **Shanshan Duan:** Data curation, Visualization, Validation. **Zhiqing Song:** Conceptualization, Methodology. **Hao Chen:** Conceptualization, Methodology.

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.

Acknowledgements

The authors are grateful for the support provided by National Natural Science Foundations of China (Nos. 12365023, 52067017 and 12265021), Program for Young Talents of Science and Technology in Universities of Inner Mongolia Autonomous Region (No. NJYT23020), Natural Science Foundation of Inner Mongolia Autonomous Region (Nos. 2022LHMS01002 and 2023LHMS05019), The basic scientific research business project of the universities directly of the Inner Mongolia Autonomous Region (Nos. JY20220066 and JY20220232).

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