Effects of drying methods on the drying kinetics and quality of maize

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Abstract: At present, maize is mostly dried by hot air, and the quality of maize after drying in this way is poor. So it is particularly important to explore the influence of new drying methods on the drying characteristics and quality of maize. Five drying methods, including hot air drying (HAD), vacuum drying (VD), infrared drying (IRD), variable temperature drying (VTD), and vacuum IR drying (VID), were used to analyze the drying rate (DR), moisture ratio (MR), effective moisture diffusion coefficient (D_{eff}), hardness, nutrient composition, color, and microstructure of maize to investigate the effects of different drying methods on the drying kinetics and quality of maize kernels. The results showed that among the five drying methods, the Modified Page drying model could most reflect moisture changes. VTD was better than the other methods in terms of DR, cracking rate, hardness, and crude fat. The highest lysine content in maize was obtained using HAD. The protein content was higher in IRD (p<0.05). The dough characteristics were better in VID and VTD than in IRD. The IRD, VTD, and VID-treated maize had a better color appearance. Microstructure analysis showed that the starch granules of VID, IRD, and VD-treated maize were oval, but large gaps could be found between the granules. The granules were also densely stacked, with most of them relatively intact. Correlation and clustering analysis showed different degrees of correlation between the physicochemical indicators. The overall quality in VTD was the best, followed by VID, whereas HAD and VD showed poorer quality. In terms of economic value and product quality, VTD was the most suitable drying method for maize. This study can provide a theoretical basis for the application of maize drying in the processing industry.

Keywords: maize, drying method, drying kinetics, quality, microstructure

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1 Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops in the world[1] and is usually harvested in the fall and winter. The climate is rainy during these periods and drying maize quickly with machinery to facilitate storage is important[2,3]. In recent years, with the development of agricultural technology, the total production of maize in the world has been increasing year by year, along with the total amount of harvest and storage[4]. At present, the drying methods for maize include hot air drying (HAD), vacuum drying (VD), variable temperature drying (VTD), infrared drying (IRD), and vacuum IR drying (VID)[5-7]. The drying tower technology is the best method to dry a large volume of maize. It can process a large volume of high-moisture maize in a short period of time so that it quickly reaches safe storage moisture[8]. These drying methods have been gradually applied to maize drying towers to change the original single HAD. Although these drying technologies have started to be applied to drying towers, they still lack some theoretical support.

HAD is the most commonly used drying method for preserving food and agricultural products[9]. It is easy to use, technically mature, and widely used for post-harvest processing of agricultural grains[10]. Vacuum can achieve fast drying at low temperatures by reducing the atmospheric pressure of the environment around the material[11,12]. IR radiation can rapidly inactivate the enzymes without destroying the quality of maize and effectively reduce its internal moisture gradient[8,13]. In addition, the combination drying technology can not only improve the drying rate (DR) and reduce energy consumption but also reduce the quality loss of materials[14]. The VTD technology has been in development to eliminate the effect of constant-temperature HAD on maize cracking rate and other related qualities. This technology sets different drying temperatures for different drying stages of the material. Simultaneous improvement of material drying efficiency and quality was achieved[15]. VTD can reduce the quality degradation and the drying time of rice compared with constant-temperature HAD[16]. Bertotto et al. found that process parameters, such as temperature, time of temperature change, and duration of temperature change, were effective in improving the whole grain rate of fine rice and the DR of rice[17].

In this study, five drying methods suitable for combination with drying towers were selected. The effects of each drying method on the drying characteristics (DR, moisture ratio (MR), effective moisture diffusion coefficient (D_{eff}), and drying time) and physicochemical indices (cracking rate, hardness, protein, crude fat, lysine, color difference, viscosity, and microstructure) of maize were investigated using one-way ANOVA. Finally, the optimal

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drying mode suitable for drying maize was selected to provide some theoretical basis for the combination of different drying methods and drying towers.

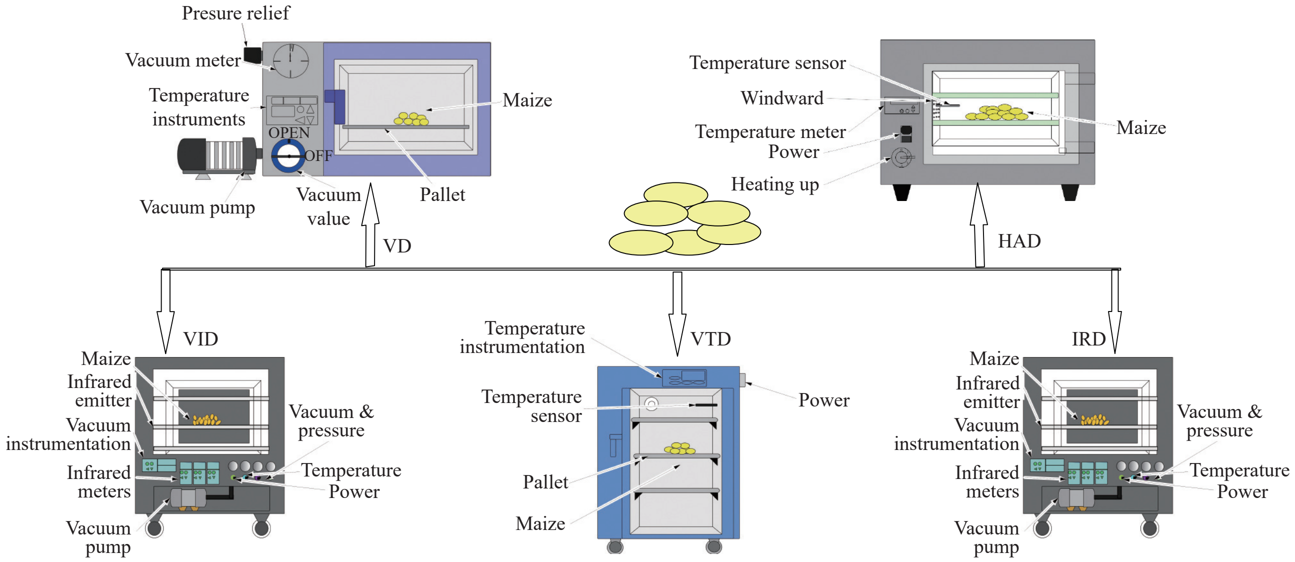
2 Materials and methods

2.1 Preparation of sample

Fresh maize was purchased from a local farm near Zhengzhou, China. The husked maize was stripped of all foreign materials, such as stones, broken kernels, and mold seeds, to prevent the development of mold. The maize kernels were carefully selected to ensure that the most uniformly shaped maize was collected. Samples were stored in individual plastic bags in a refrigerator at 4.0°C±0.5°C to avoid loss of moisture.

2.2 Drying procedure

The drying method is shown in Figure 1. In which hot air drying (HAD) temperature is 50°C, the air speed is 1 m/s; vacuum drying (VD) temperature is 50°C, the vacuum degree is 50 kPa; infrared drying (IRD) temperature is 50°C; variable temperature drying (VTD) pre-temperature is 50°C, when the moisture content of maize is reduced to 22%, the drying temperature is increased to 60°C, the air speed is 1 m/s; vacuum infrared combination drying (VID) temperature is 50°C, the vacuum degree is 50 kPa.



Note: VD: vacuum drying; HAD: hot air drying; VID: vacuum IR drying; VTD: variable temperature drying; IRD: infrared drying. Same below.

Figure 1 Processing of maize by different drying methods

2.3 Measurement of indicators

2.3.1 Moisture content

The initial moisture content of the maize samples was determined gravimetrically in triplicate by using HAD, as described in AOAC[1]. The measured wet basis moisture content was 28.34%±0.30%.

2.3.2 MR

Moisture ratio (MR) is the residual moisture content of the material under certain conditions. The dimensionless MR formula used to obtain the drying kinetics of maize is as follows[4,18]:

$$\mathrm{MR} = \frac{M_t - M_e}{M_i - M_e} \tag{1}$$

where, M_t is the moisture content at time t (decimal dry basis), M_i is the initial moisture content (decimal dry basis), and M_e is the equilibrium moisture content (decimal dry basis) obtained from the Chung-Pfost equation as follows:

$$M_e = E - F\ln[-(T + C)\ln(\mathrm{RH})] \tag{2}$$

where, T is the temperature, °C; C, E, and F are 30.20, 0.34, and 0.06 for shelled maize, respectively; RH is the relative humidity (decimal).

Drying rate (DR) refers to the amount of water evaporated from the maize per unit time in the unit drying area (the contact area between the material and the hot air). Since maize is an irregular material, determination of the size of its contact area with the hot air is more difficult. The drying rate formula is as follows[19]:

$$\mathrm{DR} = \frac{\mathrm{d}M_t}{\mathrm{d}t} = \frac{M_{t+\mathrm{d}t} - M_t}{t_{i+1} - t_i} \tag{3}$$

Where: DR is the drying rate, %/min; M_t is the dry basis moisture content of the maize at the moment of t_i, %; t_i is the maize drying time, h.

2.3.3 Drying kinetics model

Five drying kinetics models were used to fit the drying characteristic curves of maize under the five drying methods. The most appropriate drying kinetics model was selected[20]. The drying kinetics models and their equations are listed in Table 1.

Table 1 Drying kinetics models and equations

Model[21]	Equation
Page	$\mathrm{MR} = \exp(-kt^n)$
Two-term	$\mathrm{MR} = a\exp(-kt) + b\exp(-nt)$
Midilli et al.	$\mathrm{MR} = a\exp(-kt^n) + bt$
Wang and Singh	$\mathrm{MR} = 1 + at + bt^2$
Modified Page	$\mathrm{MR} = a\exp(-kt^n)$

Note: a, b, and k are equation constants, t is the drying time, and n is the number of tests.

The correlation coefficient (R^2), the Chi-square test coefficient (χ^2), and the root mean square error (RMSE) were used to determine the degree of model fit. The closer the R^2 value is to 1, the higher the degree of fit. Likewise, the closer the values of χ^2 and RMSE are to 0, the higher the degree of fit. R^2, χ^2, and RMSE were calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2}{\sum_{i=1}^{N}\left(\overline{\mathrm{MR}_{\exp}} - \mathrm{MR}_{\exp,i}\right)^2} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2}{N - Z} \tag{5}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\exp,i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2}{N}} \tag{6}$$

where, $\mathrm{MR}_{\exp,i}$ is the ith experimental MR value, $\mathrm{MR}_{\mathrm{pre},i}$ is the MR value predicted by the ith drying model, $\mathrm{MR}_{\exp}$ is the mean value of the MR experiment, N is the number of experimental data, and Z is the number of parameters in the model equation.

2.3.4 Moisture effective diffusion coefficient (D_{eff})

D_{eff} determines the mass transfer capacity of moisture within the material. It depends not only on the material composition, moisture content, porosity, and other physical parameters, but also on the drying conditions and methods[22]. Therefore, the values are measured by drying experiments and calculated by substituting them into a mathematical model to obtain a more accurate D_{eff}. The control mechanism of the second unsteady Fick's law for drying is the case of moisture diffusion control. The diffusion coefficient is assumed constant and material shrinkage is ignored during drying[23]. The effective diffusion coefficient of moisture at this temperature is calculated by plotting the drying curve of a drying experiment based on the principle of the inverse method[24].

$$\mathrm{MR} = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2 D_{\mathrm{eff}}t}{4L^2}\right) \tag{7}$$

In this experiment, the drying time is longer, which can be simplified to

$$\mathrm{MR} = \frac{M_t}{M_0} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{\mathrm{eff}}t}{4L^2}\right) \tag{8}$$

The logarithmic transformation on both ends of the above formula was calculated to obtain the following equation:

$$\ln\mathrm{MR} = \ln\frac{8}{\pi^2} - \frac{D_{\mathrm{eff}}\pi^2 t}{4L^2} \tag{9}$$

2.3.5 Cracking rate

Dried maize kernels were examined in a lightbox. The type (single, double, and multiple cracks) and number of stress cracks were determined. The stress cracking index (SCI) of the maize kernels was calculated using the following equation[24,25]:

$$\mathrm{SCI} = \frac{M_1}{M}\times 100\% \tag{10}$$

where M represents the number of kernels tested (M=100) and M_1 represents the number of cracked kernels (one crack, two cracks, and three or more cracks are all considered as cracked kernels). Only one crack and less than half the kernel length were excluded.

2.3.6 Hardness

A physical property analyzer (TPA, Baosheng Technology Co., Ltd., Shanghai, China) was used to determine the hardness of maize for different drying methods. The samples were crushed with a probe made of PA/36 column at a speed of 0.5 mm/s. The speed was set to 2 mm/s before the test, 0.5 mm/s during the test, and 5 mm/s after the test, with a compression distance of 10%. Three measurements were taken for each specimen set[26].

2.3.7 Crude fat, protein, lysine (lys), and total starch

The protein, crude fat, and lysine content were determined using the following method. The Foss Infratec 1241 grain analyzer NIR (Shanghai Laboratory Equipment Co., China) was preheated for more than 30 min, and the sample was loaded into the cuvette. The sample must cover the bottom of the cuvette, the thickness should not be less than 0.5 cm, and no light leakage must be present to obtain the IR absorption spectrum. After the analysis was completed, the data were automatically read and recorded. The total starch content of maize was determined by the Chinese national standard (GB 5009.9-2016)[27].

2.3.8 Color analysis

The color differences were determined using a CR-400 colorimeter (Konica Minolta, Inc., Tokyo, Japan). Maize treated with different drying methods was ground and passed through a 60-mesh sieve. Its color was measured separately with a calibrated colorimeter. ΔE represents the combined amount of color difference deviation, which indicates the value of the color difference between the L^*, a^*, and b^* values of the sample tested and the standard white ceramic plate[28].

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{11}$$

where, ΔL^*, Δa^*, and Δb^* are the differences of L^*, a^*, and b^* between the sample and the calibration white plate, respectively. Among them, the initial values of L^*, a^*, and b^* are 71.87±1.53, 21.18±6.61, and 51.57±8.88, respectively.

2.3.9 Pasting properties

The pasting properties of samples were evaluated using an RVA-TecMaster viscosity analyzer [Icy Technology (Beijing) Co., Ltd.] by following the method of Sandhu and Singh[29], with some modifications. The viscosity distribution of the maize flour samples was determined using starch (on a moisture basis of 14%, w/w; 3.63 g total weight) and certain procedures. The samples were accurately weighed with 25.03 g water, placed in aluminum boxes, mixed up and down several times with a rotating slurry, and placed on RVA for testing using a specific heating and cooling cycle procedure. The test procedure was as follows: 60 s at 50°C, 0.2°C/s uniform temperature increase, 150 s at 95°C, followed by 0.2°C/s uniform temperature decrease, and then 90 s at 50°C. The speed was 960 r/min for the first 10 s of the test and then 160 r/min. The peak viscosity, trough viscosity decay, final viscosity, regeneration, pasting time, and pasting temperature were obtained using the analysis software included in RVA.

2.3.10 Cryo-scanning electron microscopy (Cryo-SEM) system

Cryo-SEM (JSM-5410, JEOL, Kyoto, Japan) was used to observe the microstructure of the cross-sections of maize from different drying methods. The samples were cryogenically fixed to stabilize the structure and composition of the biological system. They were then placed on the specimen holder of the microscope and transferred to a sub-cooled nitrogen slurry at −210°C, which is close to the freezing point of nitrogen. The nitrogen slurry was used because of its effective refrigeration properties. The frozen specimens were freeze-fractured, etched at −90°C for 15 min at 1395 Pa, coated with gold, and observed in the cold stage of SEM. The fractures on the surfaces were observed directly at 150°C. Micrographs were taken at 3000× magnification to observe the cell structure and its changes. The scan of a maize kernel cross-section is shown in Figure 2.

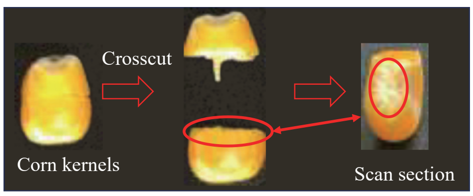


Figure 2 Scan of maize kernel cross-section

2.4 Statistical analysis

Three replications were conducted for each experiment. ANOVA was performed on SPSS software version 20.0. Duncan's multiple range test was used with a 0.05 significance level to determine significant differences between treatments. Graphs were generated using Origin software version 9.0.

3 Results and discussion

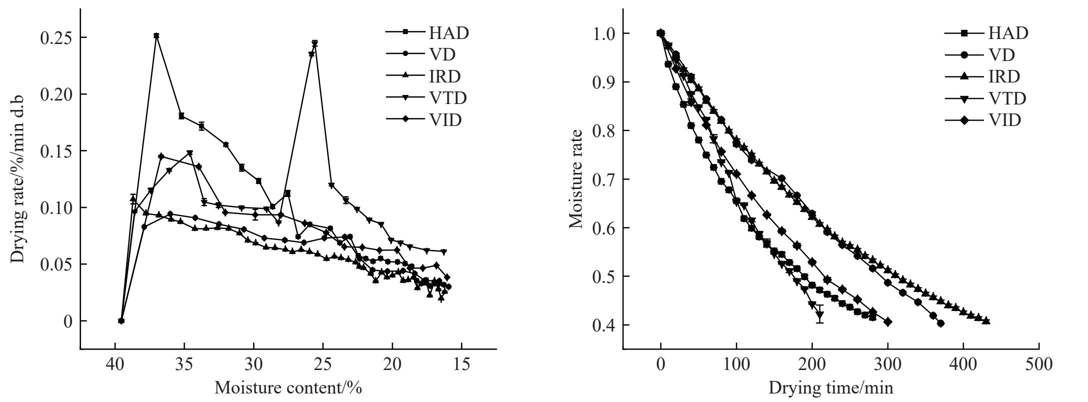
3.1 Effects of different drying methods on the drying characteristics of maize

3.1.1 MR and DR

The variation curve of MR with drying time is shown in Figure 3. With the increase in drying time, the MR of maize under the five drying methods gradually decreased. In the first 100 min of drying, the MRs were HAD>VID>VTD>IRD>VD in descending order. After 100 min, the MRs in VTD decreased faster due to the increase in drying temperature. At the end of drying, the shortest MR was found in VTD (210 min), followed by HAD (280 min), VID (300 min), and VD (370 min), whereas the longest MR was determined to be in IRD (440 min). HAD had a high DR at the beginning of drying, and it decreased as the dry basis moisture content decreased. The DR in VTD increased abruptly after the temperature change (when the wet basis moisture content of maize was 22%) and then started to decrease. The rapid migration of moisture from the interior of the maize to the surface was exacerbated by the increase in temperature. As the moisture gradually decreased, the bound moisture was not easily removed, leading to a decrease in DR[30]. The IR absorption characteristics of the grain skin are somewhat different from those of the internal tissues, although IR radiation heats maize internally and externally. Some of the macromolecules have a certain IR absorption effect, which can weaken the effect of IR radiation on moisture, and the drying time is longer. Combined VID, under the support of a vacuum, further reduced the boiling point of moisture and accelerated DR.

3.1.2 Drying kinetics model-fitting

To investigate the variation of moisture content of maize under different drying methods, five commonly used drying models were used to fit the variation curves of the MR of maize under different drying methods[31,32]. RMSE, R^2, and χ^2 were used to assess the fit of the drying models. As listed in Table 2, the RMSE, R^2, and χ^2 values of the Modified Page model were 0.0026-0.0085, 0.9978-0.9998, and $(0.8381\times10^{-5}) - (1.0091\times10^{-4})$. The R^2 values were greater than those in the other models, whereas the RMSE and χ^2 values were lower, indicating that the Modified Page model not only fitted the drying curve of maize better but also was higher than the other four models. In addition, the model was validated using the data not involved in the fitting (Figure 4). As shown in Figures 3 and 4, the model was found to be a good fit for the MR of maize under the five drying methods and thus could be used as a prediction model. In order to explore the general rules of moisture changes in empirical models under different drying methods, this study aimed to provide a theoretical basis for predicting moisture changes during maize drying and controlling the drying process.



a. Drying rate of the maize under different drying methods b. Trends in moisture ratio of maize under different drying methods

Figure 3 Drying characteristics curve of different drying methods

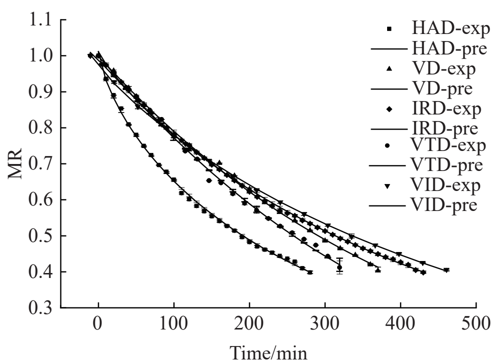


Figure 4 Modified page model verification

3.2 Effect of different drying methods on the physicochemical indices of maize

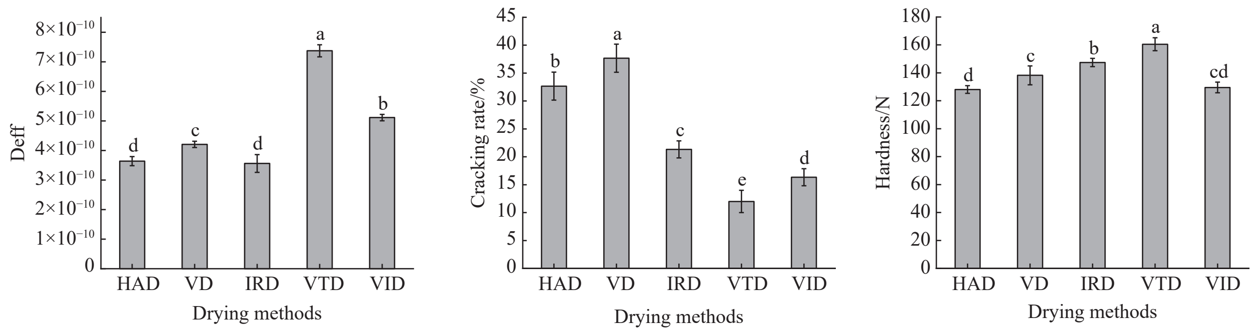
3.2.1 D_{eff}, cracking rate, and hardness

Figure 5a shows the D_{eff} of maize under different drying methods. The results showed that the drying method had a significant effect on D_{eff} (p<0.05). The highest D_{eff} was found in VTD (7.3726×10^{-10}). Increasing the temperature accelerated the diffusion of moisture from the inside to the outside of maize. This finding is consistent with the previous drying study results. In a vacuum, the absorption of IR light from water molecules is accelerated, causing the water to diffuse from the inside to the outside. The rate of water diffusion also affects the stress inside the maize. Meanwhile, the maize cracking rate was not significantly different amongst the five drying methods (Figure 5b). The cracking rates were significantly different (p<0.05) amongst the five drying methods, and the lowest cracking rate was obtained in VTD (12.0%), followed by IRD (21.3%) and VID (16.3%), which had similar cracking rates. This result is similar to the findings of Zhang et al.[33] Increasing the drying temperature can cause the starch in the maize to become rubbery as the moisture content decreases. Acceleration of internal moisture diffusion increases the modulus of

Table 2 Fitting results of the drying dynamic models of maize

Model[21]	Drying methods	Parameter				RMSE	R^2	$\chi^2\times10^{-5}$
		k	n	a	b			
Page	HAD	−0.01 360	0.7481	--	--	0.0076	0.9980	6.2410
	VD	−0.00 228	1.0078	--	--	0.0077	0.9982	6.8709
	IRD	−0.00 387	0.9025	--	--	0.0051	0.9991	2.7356
	VTD	−0.00 223	1.1163	--	--	0.0101	0.9969	1.1256
	VID	−0.00 562	0.8922	--	--	0.0027	0.9998	0.8608
Two-term	HAD	0.00 163	0.0115	0.62 365	0.36 757	0.0043	0.9993	2.1828
	VD	0.00 238	0.0024	0.97 020	0.03 048	0.0079	0.9981	7.8903
	IRD	0.00 308	−2.7421E−4	0.83 490	0.16 478	0.0020	0.9998	4.4564
	VTD	0.00 375	0.0042	0.00	1.02 557	0.0115	0.9959	15.4261
	VID	0.01 060	0.0024	0.16 620	0.83 290	0.0019	0.9999	0.4867
Midilli et al.	HAD	−0.0027	1.5353E−8	0.8616	−0.0018	0.0438	0.9304	222.0000
	VD	−0.0029	2.518E−9	0.9461	−0.0015	0.0211	0.9869	56.2414
	IRD	−0.0027	2.7733E−9	0.9179	−0.0013	0.0311	0.9677	106.0000
	VTD	−0.0028	7.7794E−9	0.9766	−0.0028	0.0205	0.9870	51.6817
	VID	−0.0029	5.7284E−9	0.9066	−0.0018	0.0337	0.9645	152.0000
Wang and Singh	HAD	--	--	−0.0042	8.0339E-6	0.0165	0.9901	29.1512
	VD	--	--	−0.0022	1.7538E-6	0.0085	0.9978	8.1280
	IRD	--	--	−0.0023	2.2713E-6	0.0051	0.9991	2.7125
	VTD	--	--	−0.0035	3.6523E-6	0.0121	0.9955	16.0355
	VID	--	--	−0.0033	4.5352E-6	0.0075	0.9982	6.4874
Modified page	HAD	0.01 542	0.72 763	1.0116	--	0.0072	0.9981	5.7236
	VD	0.00 218	1.01 493	0.9977	--	0.0063	0.9980	7.2414
	IRD	0.00 455	0.87 694	1.0107	--	0.0055	0.9993	2.1496
	VTD	0.00 264	1.08 626	1.0090	--	0.0085	0.9971	10.9910
	VID	0.00 586	0.88 535	1.0029	--	0.0026	0.9998	0.8381

Note: HAD: Hot air drying; VD: Vacuum drying; IRD: Infrared drying; VTD: Variable temperature drying; VID: Vacuum IR drying. Same below.



a. Effect of drying method on the effective moisture diffusion coefficient of maize

b. Effect of drying method on cracking rate of maize

c. Effect of drying method on the hardness of maize kernels

Note: The same letter in the graph indicates no significant difference (p>0.05).

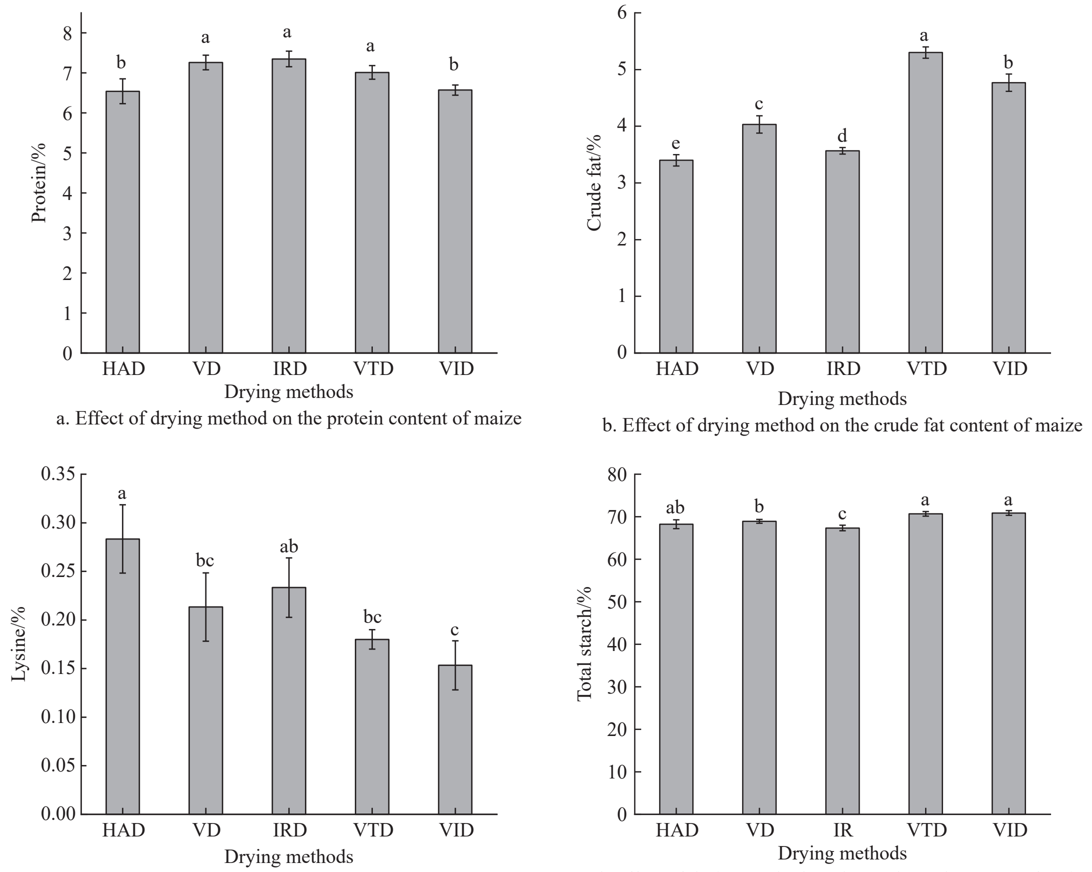
Figure 5 Effect of different drying methods on D_{eff}, cracking rate, and hardness of maize

elasticity of maize and decreases the cracking rate[34]. As a result, the moisture gradients and the cracks caused by starch vitrification are reduced[1].

The hardness of maize affects the cracking rate to some extent. As shown in Figure 5c, the hardness of VTD-treated maize seeds was significantly different from those treated using the other methods (p<0.05), and it was the highest (158.066 N). The variable temperature process is based on the relationship between the state of starch granules (vitrification and rubberization) and moisture content. A temperature above the glass transition temperature was used to dry the material, leaving the starch rubberized and increasing the moisture migration rate. In the later stages of drying, the starch granules shrink and squeeze, making them more compact and increasing their hardness to some extent[35]. The differences in maize hardness amongst VD, HAD, and VID were small (p>0.05). VD and VID caused large voids in starch granules. IRD heats maize internally and externally by IR radiation, which uniformly diffuses moisture and makes maize less susceptible to shrinkage. All three methods reduced the variation in maize hardness.

3.2.2 Crude fat, lysine, protein, and total starch contents

The crude fat content of maize under different drying methods is shown in Figure 6a. The results showed significant differences (p<0.05) in the crude fat content, with VTD having the highest content (5.21%), followed by VID (4.71%), whereas HAD exhibited the lowest (3.31%). The result of VTD was attributed to the accelerated DR, which slows down the oxidation of fatty acids. Meanwhile, VID was less destructive to the structure and composition of the material than VTD. For IRD, some oxidative degradation of crude fat occurs during slow drying. Therefore, a proper drying method can reduce the deterioration of maize quality. In addition, the lysine content (Figure 6b) was affected by different drying methods (p<0.05). The highest content was found in HAD because this method gradually heats from the outside to the inside and it is not damaged by temperature to some extent[36]. VD and VID use the same temperature as HAD, and vacuum has the effect of lowering the water boiling point. Therefore, at a certain vacuum level, the drying temperature can be reduced accordingly to achieve the same effect and save energy. Meanwhile, VTD destroys lysine due to its high temperature. No difference was observed in the protein content among the different drying methods (Figure 6c). The highest protein content was found in IRD (7.15%), followed by VD (7.09%), and the lowest was found in HAD (6.23%). Water molecules absorb some of the IR rays, thus reducing the protein denaturation and losses caused by high local temperature. VTD and HAD increase the local temperature of the maize by heat conduction and the protein structure is damaged. Meanwhile, no difference was found (p>0.05) in the total maize starch content among the drying methods (Figure 6d). The selected drying conditions only change the shape of maize starch granules without denaturing or pasting them[2].



a. Effect of drying method on the protein content of maize

b. Effect of drying method on the crude fat content of maize

c. Effect of drying method on the lysine content of maize

d. Effect of drying method on the total starch content of maize

Figure 6 Effects of different drying methods on protein, crude fat, lysine, and total starch of maize

3.2.3 Color and pasting characteristics

The color of appearance is an important indicator to evaluate the quality of maize after drying. Significant differences were found (p<0.05) in the color of maize under different drying methods. As listed in Table 3, IRD gave the best color with the least color difference (ΔE=6.825) because it reduces the internal moisture gradient, which facilitates the retention of color during water loss. VID and VTD gave better color than HAD (ΔE=12.433) and VD (ΔE=18.613), suggesting that an appropriate drying condition of maize could enhance the preservation of its heat-sensitive components[37,38]. Table 4 lists the effects of different drying methods on the pasting properties of starch. The results showed that VID had the highest pasting index (peak viscosity=2996 mPa·s), followed by VTD, whereas HAD had the lowest[39]. The general trend of the total pasting index values obtained from the different drying methods was HAD<VD<IRD<VTD<VID. On the contrary, the peak time showed an opposite trend. The drying method had no effect on the pasting temperature, whereas VID had less effect on the starch granules due to combined drying, allowing the protein to better coat them. VID had higher peak viscosity and breakdown than the other methods due to combined drying. The lower effect on the starch granules allows the protein to better coat the starch granules and reduces the contact between water molecules and starch. The microstructure of the starch granules can further explain this phenomenon. The low peak viscosity, final viscosity, breakdown, and setback values of HAD, VD, and IRD were attributed to the disruption of the protein-coated starch, bringing the starch in contact with water[40].

Table 3 Effect of different drying methods on color difference indices (L*, a*, b*, ΔE) of maize

Drying methods	L*	a*	b*	ΔE
HAD	67.493±1.207[b]	25.213±1.463[a]	43.626±2.578[c]	12.433±2.771[b]
VD	64.073±1.688[c]	16.286±0.699[b]	37.593±1.117[b]	18.613±1.072[a]
IRD	71.068±1.607[a]	24.070±1.554[a]	45.000±2.003[ab]	6.825±1.626[c]
VTD	70.596±0.949[a]	23.722±1.674[a]	47.718±0.960[a]	7.608±0.651[c]
VID	69.360±0.930[a]	24.918±1.862[a]	46.733±1.173[ab]	7.265±0.551[c]

Note: Values with the same lowercase letter within each column are not significantly different (p>0.05).

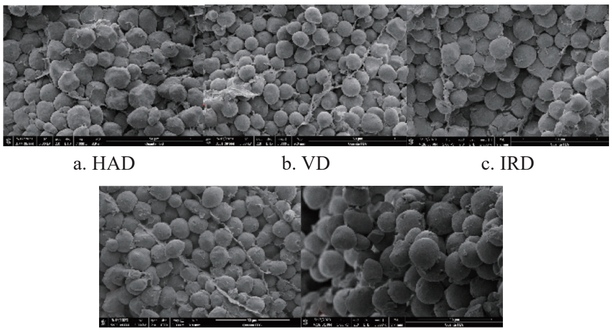
3.2.4 Effects of different drying methods on the microstructure of maize starch

Figure 7 shows the SEM morphology of the internal starch granules of maize seeds after drying under HAD, VD, IRD, VTD, and VID. The results showed that the starch granules under HAD were deformed, with convex and concave surfaces and irregular granule shapes and sizes but relatively dense granules; some of them had depressions. This finding is consistent with the results of Buzera et al.[41] In IRD, all starch granules were dense except for a few irregularly deformed granules. Most of the grains retained their original shape and the surface was smooth, This is similar to the results of Li et al.[42] This result is consistent with previous findings of reduced hardness of maize seeds due to the loosening of soft endosperm starch grains (e.g., Figure 3). In VTD, the volume of starch granules was reduced, small depressions appeared on the surface, and individual granules appeared broken. Using variable temperatures to increase the drying temperature causes the starch to lose water too quickly. In addition, when the temperature is increased, the starch granules interact with each other under the action of water and heat to form a dense structure. This phenomenon accelerates the denaturation and degradation of the surface proteins, resulting in a loose structure. During the VID process, the starch granules generally retain their original shape with large voids between the granules due to the presence of a vacuum. Lower drying temperature also achieves rapid drying, which has a swelling and loosening effect on the starch granules. IR drying provides uniform cob heating and moisture distribution, reducing the risk of excessive cob temperature[36]. In short, VID and IRD had less effect on starch granules than the other methods, and they are suitable for drying maize. VD and VTD were the second most effective, whereas HAD was the least effective.

Table 4 Effects of different drying methods on the pasting properties of maize flour

Drying methods	Peak viscosity/(mPa·s)	Hold through/(mPa·s)	Final viscosity/(mPa·s)	Breakdown/(mPa·s)	Setback/(mPa·s)	Peak time/min	Pasting Temperature/°C
HAD	2296.60±15.35^{d}	1600.60±12.44^{c}	3193.00±18.15^{a}	692.30±5.60^{c}	1558.7±14.43^{c}	4.96±0.18^{b}	76.64±0.48^{a}
VD	2397.30±39.39^{cd}	1641.00±26.90^{c}	3375.30±51.59^{b}	763.00±36.01^{c}	1712.3±36.16^{b}	4.80±0.31^{b}	76.87±0.29^{a}
IRD	2488.00±43.54^{c}	1782.70±37.95^{b}	3409.30±10.65^{b}	760.00±27.68^{c}	1725.3±29.42^{b}	5.19±0.13^{b}	77.58±0.46^{a}
VTD	2803.30±35.80^{b}	1914.30±38.32^{a}	3790.00±28.75^{a}	881.00±55.43^{b}	1895±24.51^{a}	4.77±0.09^{b}	77.68±0.55^{a}
VID	2996.00±40.84^{a}	1974.30±50.38^{a}	3804.70±37.57^{a}	999.70±6.69^{a}	1893±42.47^{a}	4.64±0.63^{a}	77.75±0.65^{a}

Note: Values with the same lowercase letter within each column are not significantly different (p>0.05).



a. HAD b. VD c. IRD

d. VTD e. VID

Figure 7 Effect of the drying method on the microstructure of maize

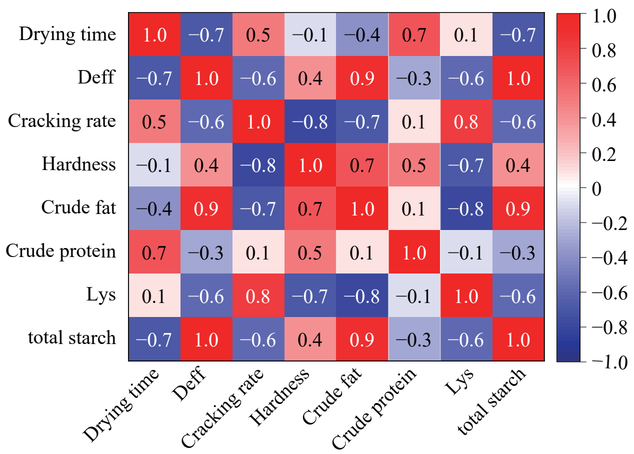
3.3 Correlation and clustering analysis

3.3.1 Correlation analysis

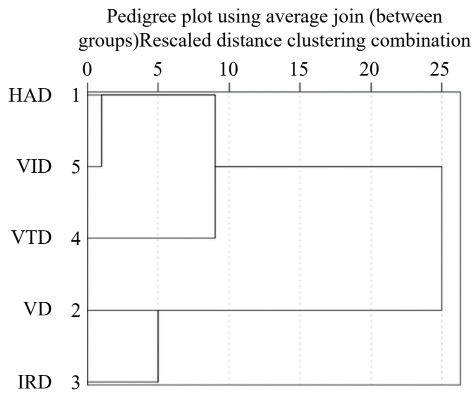
Pearson's two-tailed test was used to analyze the correlation of each index of maize treated with different drying methods. Figure 8a shows two pairs of significant correlations at α=0.01 level: crude fat content, effective water diffusion coefficient, and total starch content. Meanwhile, five pairs of significant correlations were found at α=0.05 level: drying time and cracking rate, protein, hardness and protein, crude fat, and lysine and cracking rate. According to the results of correlation analysis, all eight indicators of maize under the five drying methods had different degrees of correlation. Differences were also observed between the quality indicators, so evaluating the quality of maize under the five treatments by using a certain indicator was not objective. For an objective and accurate evaluation of the overall quality of maize, the quality indices under the five treatments must be simplified and classified.

3.3.2 Cluster analysis

A systematic clustering method was used to classify the maize treated with the five drying methods. The results of the clustering analysis are shown in Figure 8b. By using 5.45 as the threshold, the five drying methods were classified into three categories. The first category included HAD and VID, in which the crude fat, lysine, and total starch contents of maize were higher than in the other methods.



a. Correlation teat map



b. Cluster analysis graph

Figure 8 Correlation analysis and cluster analysis of drying methods on maize quality indicators

The second category included VTD, where maize had the best color, low cracking rate, short drying time, and high hardness. The third category included VD and IRD, which had higher cleavage rates, crude protein content, and longer drying times than the other methods. In a comprehensive analysis, the order of influence on the quality of maize after drying, from the largest to the smallest, was VD, IRD, HAD, VID, and VTD.

4 Conclusions

The effects of drying methods on the color, moisture effective diffusion coefficient (D_{eff}), cracking rate, hardness, pasting, nutrition, and microstructure of maize were investigated. Among them, the Modified Page model can be used to fit the drying curves of maize under the different drying methods. DR was high under temperature drying (VTD), which outperformed this method in terms of cracking rate, protein, crude fat, color, hardness, and drying time. The paste properties and total starch content were best under vacuum infrared drying (VID) and the highest under hot air drying (HAD). VID had the best starch granule integrity. Infrared drying (IRD) was superior to VTD and HAD in producing near-spherical samples with the least damage to the starch granule harvest. The correlation analysis showed varying degrees of correlation between the indicators of the different drying methods. On the basis of the differences in each quality index, the drying methods were divided into three categories: the first category included HAD and VID, which had higher crude fat, lysine, and total starch contents than the other methods. The second category included VTD, which exhibited good maize color, low cracking rate, short drying time, and high hardness. The third category included VD. In terms of economic value and product quality, choosing VTD for drying maize is worth promoting.

This study aimed to explore the differences between different drying methods through maize drying experiments. A comparative analysis of drying efficiency and quality of dried maize was used to derive the advantages and disadvantages of each drying method. This provides a basis for predicting moisture changes in bulk grain dried in a drying tower and for ensuring the quality of the grain after drying. In addition, the drying method used in grain drying towers is still hot air drying. This method can only solve the problem of precipitation and mold prevention of grains, and it is difficult to ensure the quality of grains after drying, such as the rate of cracking and crushing. Therefore, exploring new drying methods applied to drying towers to improve the quality of grains after drying is an urgent problem to be solved.

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