Food Research 9 (4) : 286 - 293 (August 2025)
Journal homepage: https://www.myfoodresearch.com

FOOD RESEARCH

RESEARCH PAPER

Effects of hot air drying on the kinetics and characteristics of pregelatinized corn grits

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Article history:
Received: 3 April 2024
Received in revised form: 3 May 2024
Accepted: 11 April 2025
Available Online: 17 August 2025

Keywords:
Convenient food,
Corn grits,
Drying kinetics,
Food structure

DOI:
https://doi.org/10.26656/fr.2017.9(4).121

Abstract

The sun drying of partially gelatinized corn grits can take 1-3 days and result in an unfavorable odor and inconsistent quality of the final products. This research aimed to investigate the effect of hot-air drying (HAD) temperature on the drying kinetics and characteristics of pregelatinized corn grits. The effect of various HAD temperatures (50-70°C) on the characteristics of pregelatinized corn grits, such as microstructure, water absorption index (WAI), water solubility index (WSI), and yellowness index (YI), as well as the textural properties of rehydrated pregelatinized corn grits, was analyzed. Results showed that temperature was a significant factor ($p<0.05$) affecting the drying kinetics of pregelatinized corn grits. A high drying temperature increased the drying rate, homogeneity of surface pores, and WAI of dried pregelatinized corn grits, as well as reduced the hardness and increased the adhesiveness of rehydrated pregelatinized corn grits.

1. Introduction

Steamed corn grits, locally called nasi jagung, are an indigenous corn-based product consumed by a part of society in the central part of Java and the Madura Region, Indonesia. The appearance of steamed corn grits is similar to that of couscous from North Africa (Serna-Saldivar, 2014). Steamed corn grits are used as a substitute carbohydrate source for rice and can be served with vegetables, salted fish, soup, sauce, sambal (chili sauce), and other condiments. The preparation of corn into steamed corn grits takes approximately 4 days and includes milling, soaking, mixing to form agglomerates and two rounds of steaming (Sari *et al*., 2019). Since steamed corn grits are time-consuming, local farmers prepare steamed corn grits in large quantities and dry steamed corn grits or pregelatinized corn grits for their stock during the harvest season. Drying pregelatinized corn grits can take 1-3 days because it still uses sun drying, which depends on sun intensity. Moreover, given its duration, pregelatinized corn grits drying often produces final dried products with an unfavorable odor and inconsistent quality.

Drying in the field of food preparation, a water removal process involving simultaneous heat and mass transfer is performed to improve shelf life or create a new unique structure for functional aims (Dehnad *et al*., 2016; Onwude *et al*., 2016). The functional characteristics of a product during manufacturing determine its desirability of the product. Drying, practiced by ancient people since prehistoric times, can prolong the food shelf life compared to the unprocessed raw material. The primary purpose of drying is to reduce the water activity (aw) of food to prevent degradation during the distribution of products over longer distances and long-term storage at room temperature. Moreover, drying improves physical, organoleptic, and rehydration properties and nutritional value to obtain convenient and novel products. Drying conditions and techniques can create diverse food structures and affect operation costs (Malafronte *et al*., 2012). Hot-air drying (HAD) has been widely used to process agricultural products given its simple technology and operation, low cost, and high efficiency (Khraisheh *et al*., 2004; Pei *et al*., 2022; Wen *et al*., 2022). However, there is limited information

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eISSN: 2550-2166 /
Published by Rynnye Lyan Resources

regarding the HAD process of preparing dried pregelatinized corn grits. In addition to drying kinetics, products' rehydration and quality characteristics are very important drying parameters because they indicate the extent of damage caused by the drying medium (Ceclu *et al.*, 2016). The mathematical modelling of the drying process is an important component of drying improvement because it is useful for designing new or improved systems or even for controlling the drying of agricultural products (Ojediran *et al.*, 2021). Therefore, this study investigated the effect of HAD temperature on the drying kinetics and characteristics of pregelatinized corn grits to provide a convenient and high-quality product. The HAD is proposed because the process can be applied on a commercial scale.

2. Materials and methods

2.1 Materials

Milled yellow corn (*Zea mays* var. indurate 'Sturt') with a size of 1.6±0.2 mm and moisture content of 9.6±0.65% wb. Impurities were sorted manually prior to further processing, and the remaining were stored in polypropylene vacuum bags at 12±2°C before use.

2.2 Methods

Pregelatinized corn grits were prepared in accordance with Sari *et al.* (2019), which provides a shorter preparation time, which was 4-6 h and double resistant starch, as compared to the conventional process that needs 3-4 days of preparation. Milled yellow corn was ground into grits with a size of 0.30±0.05 mm by using a two-speed Waring blender (Waring Products Inc., USA) and conditioned with a certain amount of water until it reached 52.33% moisture content. Subsequently, the mixture was placed in a glass jar and steamed in a 1941X stovetop autoclave (Red Hill General Store Inc, USA). The mixture was retained at the processing temperature of 123.67°C for 5 min to pregelatinized the grits. Afterwards, the pregelatinized corn grits were placed in an aluminum tray with a size of 20 cm × 28 cm and a thickness of 1 cm.

Subsequently, the pregelatinized corn grits were dried in a hot-air oven (Memmert UF110, Memmert GmbH + Co, Schwabach, Germany) at 50°C, 60°C, and 70°C and a 1.5 m/s airflow rate. The pregelatinized corn grits were weighed by using a digital balance (Scaltec SPO 61, Denver Instrument, USA) every 30 min until their moisture content reached equilibrium for the drying kinetic study. Then, the dried pregelatinized corn grits were kept in vacuum plastic bags. The water absorption index (WAI), water solubility index (WSI), yellowness index (YI), and microstructure of dried pregelatinized corn grits with the final moisture content reaching 8±2%, as well as textural properties of rehydrated pregelatinized corn grits, were used as the responses of pregelatinized corn grits to HAD.

The drying curves of HAD at various temperatures provide information regarding the mechanisms of water transportation. The reduction in moisture ratio during drying was used to evaluate the experimental data. The moisture ratio is defined as the remaining amount of moisture in pregelatinized corn grits as a function of drying time per the initial moisture content of pregelatinized corn grits (Equation 1) (Ceclu *et al.*, 2016). The drying rates of pregelatinized corn grits were calculated by using Equation 2.

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

Where MR represents the dimensionless moisture ratio; M_e represents equilibrium moisture content wherein no further change in pregelatinized corn grits weight is observed under each drying condition (g water/g dry matter); M_t represents the moisture content at each time (g water/g dry matter) and M_0 represents the initial moisture content (g water/g dry matter).

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (2)$$

Where DR represents the drying rate (g water/g solid.min), M_t represents the moisture content at a specific time (g water/g solid), M_{t+dt} represents the moisture content at t + dt (g water/g solid), and *t* represents the interval drying time between M_t and M_{t+dt} (min).

The moisture ratios were fitted with the empirical thin-layer drying model to determine the moisture content of pregelatinized corn grits as a function of drying time. The empirical Page model (Equation 3) and logarithmic model (Equation 4) were used to fit the drying curves of pregelatinized corn grits.

$$MR = \exp -kt^n \quad (3)$$

$$MR = A\exp(-kt) + b \quad (4)$$

where *k* represents the drying constant in min^{-1}; *t* represents the time in min; *n*, *A*, and *b* are the dimensionless empirical coefficients.

Linear and nonlinear regressions were performed by using Minitab 16.0 (Minitab Inc., USA) software.

2.3 Analysis

2.3.1 Water absorption index and water solubility index

The WAI and WSI of pregelatinized corn grits were determined in accordance with the method described by

https://doi.org/10.26656/fr.2017.9(4).121

Contreras-Jiménez *et al*. (2014). Each sample was weighed with distilled water at a ratio of 1:10. The dispersion was stirred gently for 10 min at 200 rpm. Subsequently, the dispersion was incubated in a shaking waterbath (WNB 14, Memmert GmbH + Co, Germany) for 30 min at 30±2°C and then subjected to centrifugation (EBA 20, Hettich Instrument, Massachusetts, US) at 3000 rpm for 15 min. The pellet was placed in a crucible of known weight, dried at 105°C by using a hot-air oven (Memmert UF110, Memmert GmbH + Co, Schwabach, Germany), and weighed until it reached constant weight. The WAI was calculated as the weight of the sediment obtained after separating the supernatant (Equation 5). WSI was calculated as the percentage of dry solid weight in the supernatant per the original dry weight of the sample (Equation 6).

$$\text{WAI (g/g)} = \frac{\text{Weight gain by sediment}}{\text{Dry weight of sample}} \quad (5)$$

$$\text{WSI (\%)} = \frac{\text{Weight of dry solids in supernatant}}{\text{Dry weight of sample}} \times 100\% \quad (6)$$

2.3.2 Color

The surface color of dried pregelatinized corn grits was measured by using a Hunter Lab JUKI colorimeter (JP7100P, Hunter Association Laboratory Inc., USA). The color of dried pregelatinized corn grits was expressed in CIE tristimulus values as XYZ to acquire YI. YI was calculated in accordance with ASTM E313 (Laboratory, 2008) (Equation 7).

$$\text{YI E313} = \frac{100(C_X X - C_Z Z)}{Y} \quad (7)$$

where C_x(D65/10°) = 1.30 and C_z(D65/10°) = 1.15.

2.3.3 Microstructure observation

Following the technique of Bahrani *et al*. (2012), the surface morphology of the dried PCCG surface was scanned using a scanning electron microscope (SEM) (JSM6400, JEOL Ltd, Japan) at 15 kV of acceleration voltage. An aluminum SEM stub was used to mount the dry PCCG using double-backed carbon tape. Under vacuum conditions, the sample was coated with gold using a sputter coater (SCD 005, Bal-Tec, Balzers, Liechtenstein). Using JEOL SemAfore digital image acquisition software (JEOL Ltd, Tokyo, Japan) at 500× and 1000× magnifications, the picture was taken, and the pores were measured.

2.3.4 Texture profile analysis

A texture analyzer (TA-XT.plus, Stable Micro System, UK) was used to determine the textural properties of rehydrated pregelatinized corn grits by following the method of Le and Jittanit (2015). A cylindrical probe with a diameter of 36 mm was used to compress the rehydrated pregelatinized corn grits to 85% deformation of the original sample height. The test used the pretest speed of 1 mm/s, the test speed of 5 mm/s, and the post-test speed of 10 mm/s. Hardness, adhesiveness, cohesiveness, chewiness, and resilience were determined in triplicate.

2.4 Statistical analysis

The completely randomized design was used in this experiment, with the independent factor being the HAD temperature (50°C, 60°C and 70°C). Each temperature was done in triplicate. Statistical analyses were performed by using Minitab 16.0 (Minitab Inc., State College, PA, USA) software. Analysis of variance with a 95% confidence level was then carried out on each response variable to test significant differences amongst individual means. The differences amongst mean values were considered significant at $p < 0.05$.

3. Results and discussion

Drying is an important unit operation in food processing that preserves food by reducing the amount of water in the food matrix to a level that decelerates/ inhibits active enzymes, microorganisms, and degradative biochemical reactions (Sabarez, 2016). This process has advantages in reducing food weight and transport costs (Oikonomopoulou *et al*., 2011; Sharma *et al*., 2021).

3.1 Drying kinetics of hot air drying of pregelatinized corn grits

HAD temperature had a significant effect ($p<0.05$) on the reduction in the moisture ratio and drying rate of pregelatinized corn grits. The interaction of drying temperature and drying time had a significant effect ($p<0.05$) on the reduction in the moisture ratio and drying rate of pregelatinized corn grits. The moisture ratio of pregelatinized corn grits versus drying time at various drying temperatures is shown in Figure 1-A. The drying temperature and drying time of pregelatinized corn grits significantly affected ($p<0.05$) the reduction in moisture ratio. The moisture ratio of pregelatinized corn grits reduced quickly at high drying temperatures. The time needed to reach the moisture content of 8±2% d.b in pregelatinized corn grits was 300 min at 50°C, 210 min at 60°C and 150 min at 70°C (Figure 1-A). Increasing the HAD temperature of pregelatinized corn grits from 50°C to 70°C reduced the total drying time by 50% (300 min to 150 min). Several researchers obtained comparable results for the HAD of various agricultural products (Luangmalawat and Prachayawarakorn, 2008; Scariot *et al*., 2020; Muthukumar *et al*., 2022). High drying temperatures shortened the drying time needed to

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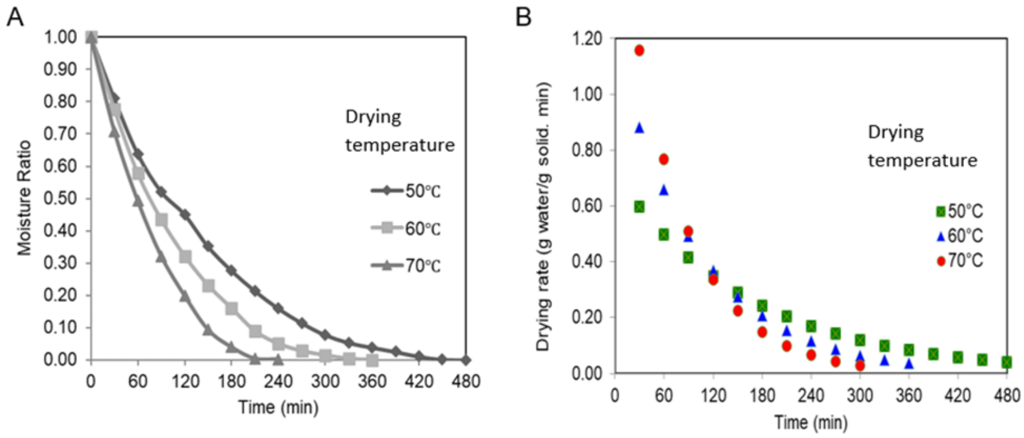

Figure 1. Drying parameter of pregelatinized corn grits as a function of drying time at various drying temperatures. (A) Moisture ratios. (B) Drying rates.

achieve the target moisture content of the final products due to the increase in the temperature gap between the surface of pregelatinized corn grits and the evaporation front. Consequently, the moisture content of the product is easily diffused outward (Kahyaoglu *et al*., 2011).

Drying rate is calculated on the basis of the amount of removed water per unit dry solid per unit time (g water/g solid·min). The drying rate of pregelatinized corn grits versus drying time at various drying temperatures is shown in Figure 1-B. During drying, the pregelatinized corn grits showed no constant drying rate at various drying temperatures. All the drying conditions occurred during the decline period, indicating that moisture diffusion was the dominant mechanism of the drying of pregelatinized corn grits. The slow reduction in drying rate during the decline period resulted from the reduction in the moisture content of pregelatinized corn grits (Ayadi *et al*., 2014). The decline phase was characterized by a decrease in the migration of humidity from the inside to the outside of the product when the moisture was no longer sufficient. The initial drying rate of pregelatinized corn grits significantly increased ($p<0.05$) from 0.5 water/g solid·min to 1.04 g water/g solid·min at the drying temperatures of 50-70°C (Figure 1-B).

High drying temperature increased the evaporation rate and promoted effective mass diffusivity in pregelatinized corn grits, resulting in high drying rates at high moisture contents (Hashim *et al*., 2014; Zielinska and Markowski, 2016). However, the effect of temperature became insignificant ($p \geq 0.05$) when the moisture content reached low levels. This phenomenon could be observed in pregelatinized corn grits with a moisture ratio of less than 20% d.b., wherein the drying rates did not significantly differ ($p\geq0.05$) amongst various drying temperatures.

Thin-layer drying models, such as the Page and logarithmic models, were used to describe the drying characteristics of pregelatinized corn grits. The best model to illustrate the drying behavior of pregelatinized corn grits was selected on the basis of the lowest RMSE and SSE. Table 1 shows the *n* parameter of the Page model and the *b* value of the logarithmic model. The model parameters decreased as the drying temperature increased. Jiao *et al*. (2013) reported that the different *n* values of the Page model and the *b* values of the logarithmic model indicated that the drying processes of pregelatinized corn grits differed with drying temperatures. The lowest RMSE and SSE values of the models indicated the suitability of the empirical relationship for describing the variation in moisture ratio with drying time. Thus, the logarithmic model could be assumed to illustrate the thin-layer drying of pregelatinized corn grits under HAD for the simulation and scale-up of the process. Artificial neural networks (ANNs) and multiple linear regression (MLR) could be used in further mathematical modeling study to forecast moisture content (MR) and drying rate (DR) in the upcoming drying investigation (Meerasri and Sothornvit, 2022).

Table 1. Model parameters of moisture ratios and drying time of pregelatinized corn grits.

T (°C)	Page model				Logarithmic model				
	n	k (min^{-1})	RMSE	SSE	A	k (min^{-1})	b	RMSE	SSE
50	0.6368	0.0119	0.31	10.06	1.0860	0.0060	-0.0760	0.0002	0.0064
60	0.2834	0.0142	0.26	8.21	1.0472	0.0097	-0.0263	0.0002	0.0071
70	-0.6699	0.0137	1.16	37.17	1.0293	0.0137	-0.0150	0.0006	0.0174

T: temperature, t: time, k: drying constant, RMSE: root mean square error, SSE: sum square error, n, A and b: dimensionless empirical coefficients.

https://doi.org/10.26656/fr.2017.9(4).121

3.2 Effect of hot air drying on the characteristics of pregelatinized corn grits

3.2.1 Water adsorption index and water solubility index of pregelatinized corn grits

The WAI and WSI of pregelatinized corn grits were affected by the drying condition and sample composition and preparation, as well as the degree of physical and chemical disruptions stimulated by drying (Jogihalli *et al*., 2017). The WAI of pregelatinized corn grits was significantly affected ($p<0.05$) by HAD temperature and increased from 3.24 to 3.81 as the drying temperature was increased from 50°C to 70°C. Pregelatinized corn grits showed higher WAI than instant rice. As reported by Prasert and Suwannaporn (2009), water absorption by instant rice after rehydration was 1.5–3 times that of dried instant rice.

The WAI of pregelatinized corn grits increased with the increase in temperature (Table 2). The high WAI value of pregelatinized corn grits at high temperature could be attributed to the large water vapor pressure difference between the partial pressure of water vapor in air at a specified temperature and the saturated water vapor pressure. The pressure difference is one of the driving forces of moisture diffusion from the inside to the surface of a sample. Given that the final moisture ratios of all of the samples of pregelatinized corn grits were the same, the increase in effective diffusivity as a function of temperature could be attributed to the alteration in the physical structure of the pregelatinized corn grits. As reported by Priyadarshini *et al*. (2013), the basic factor that influences drying depends on temperature, moisture content, and the physical structure of the drying material.

The WSI of pregelatinized corn grits significantly increased ($p<0.05$) from 1.60% to 1.70% as the drying temperature was increased from 50°C to 70°C. Jaiboon *et al*. (2011) reported that high drying temperatures increased the solubility of solid components during rehydration due to the increased porosity of the material. Joardder *et al*. (2016) also added that at high drying rates, the low moisture content of the material surface promoted the transition of rubber-glassy states that created a rigid crust on the material surface. Subsequently, moisture on the surface decreased rapidly, and the development of internal pressure inside the material resulted in a porous interior texture. Similar to previous findings, high porosity was highly correlated with solubility (Michalska *et al*., 2017).

3.2.2 Effect of drying on the yellowness index of pregelatinized corn grits

Color can be used as an indicator of dried food quality because it is an important part of visual appearance. The carotenoids in pregelatinized corn grits (yellow corn grits) not only attract consumers but also provide antioxidant activities and other health benefits. Color alterations can occur during drying because of chemical and biochemical reactions. Reaction rates are affected by processing and drying methods (Pei *et al*., 2022; Sahoo *et al*., 2022). Additionally, the product's ability to retain color is greatly influenced by the methods of drying and dryer types. The YI of pregelatinized corn grits was not significantly affected ($p < 0.05$) by the increase in HAD temperature.

3.2.3 Effect of drying on the texture profile of rehydrated pregelatinized corn grits

Textural properties are related to the viscoelastic behavior of a product. The hardness, adhesiveness, and cohesiveness of rehydrated pregelatinized corn grits were significantly affected ($p<0.05$) by the HAD temperature (Table 2). The hardness of the rehydrated pregelatinized corn grits decreased from 28.04 kg to 26.79 kg as the HAD temperature increased from 50°C to 70°C. HAD temperature also significantly affected ($p<0.05$) the

Table 2. Characteristics of pregelatinized corn grits as a function of drying temperature.

Characteristics	Drying temperature		
	50°C	60°C	70°C
WAI	3.24±0.03^{C}	3.68±0.03^{B}	3.81±0.12^{A}
WSI	1.50±0.04^{C}	1.64±0.03^{B}	1.70±0.03^{A}
YI	98.60±1.63^{A}	99.62±2.40^{A}	99.51±0.98^{A}
Texture profile of rehydrated pregelatinized corn grits			
Hardness (kg)	28.04±0.12^{A}	27.19±0.48^{AB}	26.79±0.51B
Adhesiveness (-g.s)	91.27±6.82^{B}	97.11±1.44^{AB}	103.23±3.65^{A}
Cohesiveness (%)	0.65±0.03^{A}	0.67±0.01^{A}	0.67±0.01^{A}
Chewiness (kg)	11.96±0.47^{A}	11.28±0.70^{A}	11.33±0.50^{A}
Resilience (%)	0.54±0.03^{A}	0.52±0.01^{A}	0.53±0.00^{A}

Values are presented as mean±SD. Values with different superscripts in the same row are statistically significantly different ($p<0.05$).

adhesiveness of rehydrated pregelatinized corn grits. The adhesiveness of rehydrated pregelatinized corn grits significantly increased ($p<0.05$) with the increase in drying temperature. Jaiboon *et al*. (2011) reported that high drying temperatures created numerous porous structures in the final dried product. As the porosity of the structure of pregelatinized corn grits increased, the values of water absorption and solid solubility increased, resulting in reduced hardness and increased adhesiveness of the rehydrated pregelatinized corn grits. Le and Jittanit (2015) reported similar trends in their studies on instant rice development. The drying temperature of 70° C was more suitable than other temperatures for the production of dried pregelatinized corn grits given that cooked pregelatinized corn grits with low hardness and high adhesiveness are preferred.

3.2.4 Effect of drying on the microstructure of pregelatinized corn grits

SEM provided interesting information regarding the surface morphology of the dried pregelatinized corn grits in response to HAD. SEM is suitable for observing morphological differences due to variations in process conditions (Önal *et al*., 2019). The SEM images showed that drying temperature influenced the surface structure of the dried pregelatinized corn grits (Figures 2-A, B, C). The pregelatinized corn grits dried at high drying temperatures had higher surface porosity than the pregelatinized corn grits dried at low drying temperatures. The porous structure of pregelatinized corn grits improved water absorption. This result can also be seen in Figure 2-D, which shows that high drying temperatures and rates increased the homogeneity of the pore sizes of pregelatinized corn grits. In rice kernels subjected to HAD, high drying rates could result in the formation of sponge-like structures in dried rice kernels, whereas low drying rates resulted in the formation of a dense structure (Le and Jittanit, 2015). Joardder *et al*. (2016) reported that, in general, drying rates strongly affected the inner and outer parts and porosities of food.

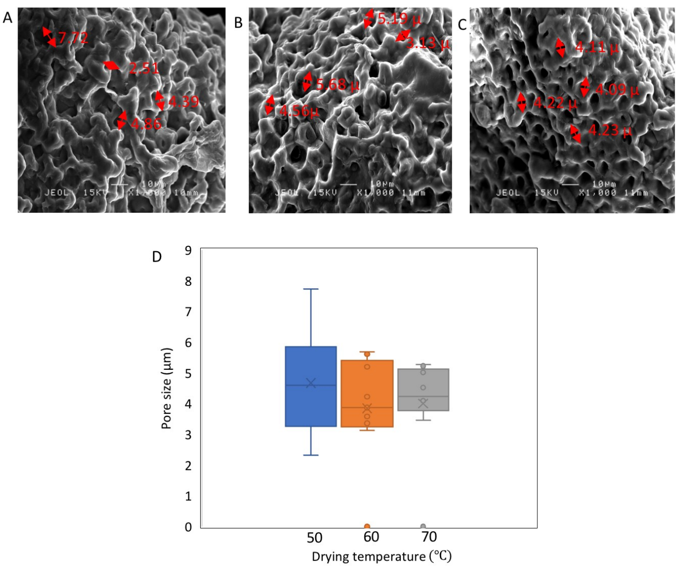

Figure 2. Microstructure of pregelatinized corn grits dried at various HAD temperatures: (A) 50°C, B) 60°C and C) 70°C. (D) Pore size distribution of pregelatinized corn grits as a function of drying temperature.

At low drying rates, moisture diffusion from the interior to the exterior was almost equal to surface evaporation, resulting in the absence of a significant moisture gradient within products with low internal pressure. Accordingly, the food samples shrank into solid cores. However, high drying rates resulted in a highly porous structure. The shrinkage of foodstuffs during drying may affect drying rates because of the changes in drying surface area and the establishment of pressure gradients within the solid material.

4. Conclusion

HAD temperature significantly affected ($p<0.05$) the drying kinetics of pregelatinized corn grits. Moisture removal during the drying of pregelatinized corn grits occurred during the decline period. The logarithmic model could be used to simulate the thin-layer HAD of pregelatinized corn grits. Compared with 50°C and 60°C temperatures, HAD at 70°C resulted in higher reductions in moisture ratios and drying rates and increased water absorption and the homogeneity of pores in dried pregelatinized corn grits, as well as resulted in lower hardness and higher adhesiveness of rehydrated pregelatinized corn grits. In conclusion, HAD at 70°C yielded pregelatinized corn grits with optimal quality over the studied range. In order to verify the differences in the end product, additional research comparing the characteristics of dried pregelatinized corn grits produced using HAD toward dried pregelatinized corn grits produced using traditional sun drying is required.

Conflict of interest

The author declares no conflict of interest.

Acknowledgments

Special thanks to the Southeast Asia Regional Centre for Postgraduate Studies and Agricultural Research (SEARCA) for financial support for this work.

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