Effect of Drying Methods on the Physical and Mechanical Properties of Dried Sweet Corn

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Abstract: The effect of the different drying processes of sweet corn on color, water activity, rehydration and texture were studied. In the present study, the lyophilization method as control was employed to dry sweet corn in comparison with infrared-freeze drying, hot-air-freeze drying, and vacuum pre- and freeze finish-drying methods. Research has highlighted the changes in physical and mechanical properties during drying. The drying methods were noted to have a statistically significant influence on the color, rehydration and firmness of the seeds. The Hunter color scale parameters redness, yellowness and lightness were used to estimate color changes during drying of sweet corn. Regarding texture, freeze dried samples showed lower firmness than the combined dried samples. The total color difference and rehydration of samples treated by the hybrid drying method were found to be more favorable compared to freeze-dried material. On the other hand, the dehydration had a statistically significant influence on the water activity of the sweet corn. Considering all the properties studied, combined vacuum and infrared freeze-drying is a suitable alternative to lyophilization.

Keywords: sweet corn, hybrid drying, color, texture, rehydration, water activity

1 INTRODUCTION

Zea mays L., also known as maize or sweet corn is a cereal that is one of the most important grains in all of the world. In recent years, an average of 30-34 thousand hectares of sweetcorn has been grown in Hungary, the largest in Europe. Sweet corn is one of the major primary products for human consumption, due to its nutritional value [6].

Drying of foodstuff is indispensable to control and maintain the quality of final products. Dehydration process is one of the thermal processes that are time and energy consuming in the industry. The hot-air drying, is one of the most widely used technique for the conservation of food on a global scale [19]. However, this drying method involves several disadvantages, such as its low energy efficiency and lengthy drying time during the falling rate period [12]. Moreover, unexpected quality degradations including browning and vitamin degradation are easily produced. The degradation of product quality is linked to high temperature and long drying time of hot-air drying [7]. Infrared radiation is able to penetrate into materials and directly transfer thermal energy to a certain depth of the products. The depth to which infrared radiation can penetrate is generally dependent on the absorbance of the products. Finally, it is helps to rapid evaporation of moisture from the samples due to high frequencies of waves [5]. The infrared drying method has many advantages such as high heat transfer coefficient and short drying time [13]. Higher quality products can be obtained using freeze-drying method. Freeze-drying involves crystallization of water in ice crystals, which subsequently sublimate, thus leaving a porous dried product [16]. Lyophilization typically creates a porous microstructure, which results in shorter rehydration process and higher rehydration capacities than in products dried using any other techniques [11]. During the freeze drying, the whole dehydrating process is accomplished in the state of high vacuum and low temperature, which almost retains the original color, shape and chemical components in raw materials [17]. Despite of its capability of providing a very high quality dried product, freeze drying is an expensive method and the high costs of process limit its using in industrial scale [16, 17].

That's why new methods so called *hybrid drying are aimed to decrease working time and energy uptake without reduction in quality [9]. Hybrid drying techniques such as combining infrared radiation or convective drying with methods such as freeze drying or microwave drying can also be used [4, 21].*

The color, rehydration and firmness of a food product is most important quality factors and plays a remarkable role in its appearance and consumer acceptability [10].

The different drying methods is a decisive impact for product quality such as physical, mechanical, chemical and nutritional changes that can affect color, rehydration, texture and nutritional value. However, there are few data about the effects of drying on physical and mechanical properties of sweet corn which is important for consumer.

Therefore, the aim of this work was to investigate the effect of hybrid and freeze drying on physical and mechanical properties in terms of color, rehydration, water activity, and firmness.

2 MATERIALS AND METHODS

2.1 Raw Material

Sweet corn (*Zea mays* L.) was purchased from a local supermarket and stored at 5°C until used. The average moisture content of sweet corn seed prior drying process is 75% (in wet basis) and 3.0 kg H_2O kg dry matter^{-1} (in dry basis). The moisture of corn grain was determined by drying it in an oven at 105 ± 1°C, for a 24 h period. Immediately after washing, the samples were placed in the dryers.

2.2 Drying processes

The corn grain samples had a total weight of 30.0 ±0.1 g for each of the seven samples. Details of each drying experiment are shown in Table 1.

Table 1. Summary of the drying program

Drying methods	*Pre-drying time [min]*	*Pre-drying temperature [°C]*
5min-MIR-FD	*5*	*40*
10min-MIR-FD	*10*	*40*
2h-VD-FD	*120*	*40*
3h-VD-FD	*180*	*40*
2h-HAD-FD	*120*	*40*
3h-HAD-FD	*180*	*40*
FD	-	-

Note: MIR-FD: infrared-freeze drying, VD-FD: vacuum pre- and freeze finish drying, HAD-FD: hot-air-freeze drying, FD: freeze drying

In the drying of sweet corn, it was found that at a drying temperature of 50°C, the surface of the samples was already browned, so only the pre-drying results at 40°C are reported in this study.

Hybrid drying: The drying air temperature (40 °C) and pre-drying time were set in the first stage (VD pre-drying, HAD pre-drying and MIR pre-drying) in the two-stage drying experiment. The first drying stage was followed by the second stage (so called post-drying: FD).

MIR pre-drying: The chamber wall was formed from aluminized steel, with a length of 15 cm, a breadth of 15 cm, and a height of 25 cm, equipped with a single door opening at the top, which allowed insertion and removal of the sample. The wavelength of radiation between 2.4-3.0 μm and the heating intensity were maintained 3 kW m^{-2} (Infrared intensity is usually expressed as radiation power per unit area). The quartz glass emitter (maximum power of per lamp 400 W) is located at a distance of 15 cm from the grain surface. The sample tray was supported on a balance (a precision of ± 0.1 g, model Precisa, Precisa Instruments AG, Dietikon, Switzerland).

VD pre-drying: A lab-scale vacuum dryer (model Kambic VS-50C, Kambic Lab. Eq., Semic, Slovenia) was operated at 4.9-5 kPa was used during the drying processing. For measuring the weight of the sample during experimentation, the tray with sample was taken out of the drying chamber, weighed on the digital balance.

HAD pre-drying: This drying technigue was carried out in a hot-air dryer (model LP306, LaborMIM, Hungary) at 40°C with an air flow rate of 1 m s^{-1}. During the drying process, the temperature (material and air) and air velocity were measured using a Testo 4510 type meter (Testo GmbH, Germany). The mass was measured on an analytical balance (model JKH-500, Jadever Co., Taiwan) with a precision of ±0.1 g.

FD drying: The laboratory freeze-dryer (model Armfield FT-33 freeze-dryer, Armfield Ltd., Ringwood, UK) is composed of a refrigeration system, heater, vacuum pump, working and condenser chamber and data collecting system (Emalog, Budapest, Hungary). The corn samples were frozen at -23°C in a freezing/heating chamber, with an absolute pressure of 80-90 Pa with a chamber temperature of 21°C and a condenser temperature of -49°C. In all experiments, temperature of the condenser and the chamber pressure were maintained at constant parameter.

The corn samples were dried by different drying methods until the final moisture content (3.6-5.8%, in wet basis). The drying process was continued until a constant moisture content was recorded. In all experiments, the sweet corn grain were spread uniformly in a single layer on a stainless steel tray.

2.3 Physical Properties

Color: Instrumental measurements of color characteristic were performed on fresh and dried material. The color of the samples was measured different place corn grain surface. The total color difference (ΔE) were measured with a ColorLite-sph900 spectrophotometer (ColorLite GmbH, Katlenburg-Lindau, Germany). The values were reported in the CIE color profile system as L^* − value (lightness), a^* − value (redness/greenness), and b^* − value (yellowness/blueness). was calculated according to the following equation (1):

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \quad 1$$

Fresh sweet corn grain were used as the reference (0) and a larger *ΔE* denotes greater color change from the control material.

Rehydration: Randomly chosen 5 pieces of the dried samples with different methods were weighed (balance accuracy 0.1 g) and placed in a plastic dish with 80 ml distilled water (20°C) at room temperature (25°C), and allowed to rehydrate. The water immersion time was 60 minutes. After end of process the sample was removed from the bath, the excess water was drained with absorbent paper, then weighed. Rehydration ratio (RR) of dehydrated samples was estimated using the equation given below (2):

$$RR = \frac{W_r}{W_d} \quad 2$$

where W_r is the drained weight of the rehydrated sample (g), and W_d is the weight of the dry sample used for rehydration (g).

Water activity (a_w): Before and after the drying process the water activity in the samples was measured using Novasina Labmaster (model CH-8853, Novasina AG, Switzerland) apparatus at 25±0.5°C with direct reading.

2.4 Mechanical Properties

The hardness of raw and dried samples, as an indicator of texture, was defined as the maximum force required to compress the corn grain tissue. The texture was measured using a Brookfiled CT3-4500 *texture* *analyzer (*Brookfield Engineering Laboratories, Middleboro, USA*).* The parameters that have been used were the followings: 8 kg force load cell, 2 mm/s test speed, 20 mm travel distance and 2 mm diameter of cylindrical probe. The maximum depth of penetration was 2 mm and trigger force was 10 g. A 115 mm diameter plate (rotary base table) was used as a base while compressing the corn samples. The samples were kept in a room temperature at 25°C until analysis. The penetrometer measurements are reported in Newton's (N).

2.5 Data Analysis

Each experiment included three replications. Excel software (Microsoft Office, 2013) was used for drawing graphs. Data were subjected to analysis of variance (ANOVA). Comparison of means was carried out by Duncan's multiple range test. Statistical analysis was performed using the Statistical Package for Social Science (SPSS 20.0 for windows, SPSS Inc., Chicago, IL, USA).

3 RESULTS AND DISCUSSIONS

3.1 Drying time

The influence of hybrid drying and freeze drying on drying time of sweet corn is shown in Fig. 1. It was found that all combined drying methods significantly reduced ($p<0.05$) the drying time of lyophilization. The results agree with what was reported by Zhang et al for freeze drying combined with air drying of kiwifruits [22]. *As pre-drying time increased at combined drying, moisture removal also increased and ultimately resulted in the reduction in total drying time. In terms of MIR-FD, HAD-FD and VD-FD, the drying time significantly decreased ($p<0.05$) with the increase in pre-drying time from 5 to 10 min and from 2 h to 3 h as expected.*

The freeze drying operation time is the highest of all drying solutions ($p<0.05$). While the freeze-drying process took 19 hours, the drying time after the 10 min-MIR-FD treatment was 12 hours, reducing the drying time by about 37%. A previous study showed that the FD-MIR dehydration method reduced the lyophilization operational time by about 48% with similar product quality [20].

There is no significant difference ($p>0.05$) between 3h-VD-FD and 2h-HAD-FD hybrid drying methods.

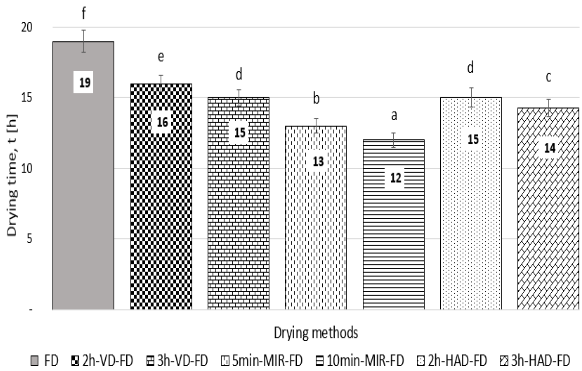

Fig. 1. Process time for different drying conditions

3.2 Physical and mechanical properties

Fig. 2 shows sweet corn grain samples of dried by one-stage and two-stage drying processes. There is no apparent difference between FD, VD-FD and 5min-MIR-FD maize seeds.

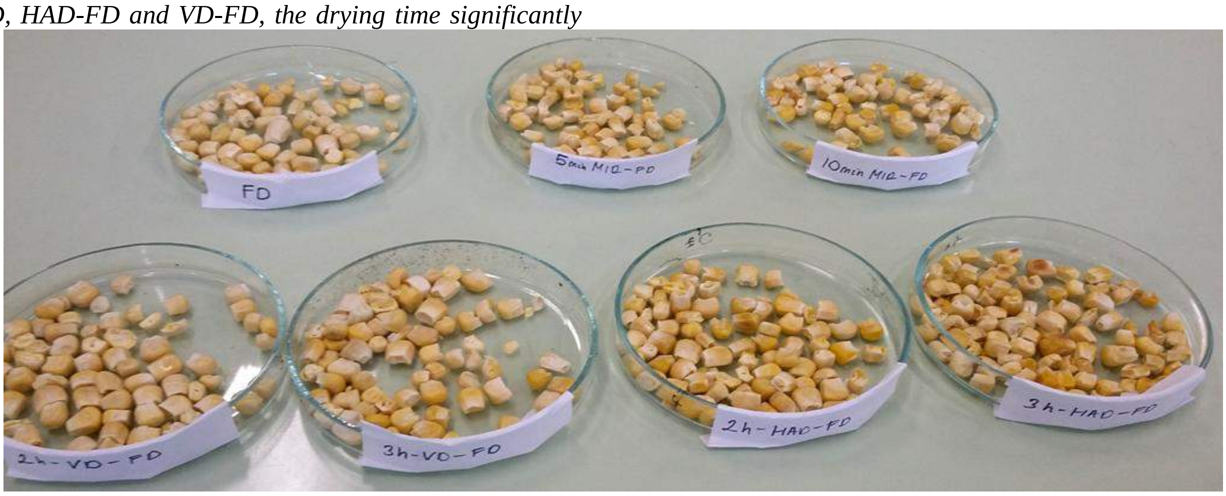

Fig. 2. Hybrid- (MIR-FD, VD-FD and HAD-FD) and freeze-dried (FD) sweet corn samples

While the freeze-dried (FD) samples faded slightly, the 10min-MIR-FD and HAD-FD materials were slightly darker compared to the raw material. In addition, brown spots on the surface of the 3h-HAD-FD samples are visible, which are the result of the Maillard reaction [2]. No shrinkage is observed in sweet corn products.

Table 2 summarizes the results of physical and mechanical properties of raw and dried sweet corn.

Water activity (a_w) was determined for each experiment before and after dehydration. According to Lewicki et al., the growth of most fungi, molds and bacteria is inhibited when a_w value is less than 0.7 [11]. It was found, that the dried products within the range of

0.19–0.36 water activity. The dried samples are in microbiologically stable condition. The water activity values of FD, HAD-FD, MIR-FD and VD-FD dried corn samples were found to be statistically different.

Table 2. Effect of drying methods on physical and mechanical properties

Drying methods	Water activity a_w [-]	L^* parameter [-]	Color difference ΔE [-]	Rehydration RR [-]	Firmness [N]
Fresh corn grain	0.795	87.71	-	-	1.012
5min-MIR-FD	0.211^{ab}	84.82^{c}	13.56^{d}	3.35^{ab}	0.172^{b}
10min-MIR-FD	0.275^{d}	81.33^{e}	16.21^{f}	2.19^{de}	0.262^{d}
2h-VD-FD	0.315^{e}	88.11^{a}	9.62^{a}	2.31^{d}	0.181^{b}
3h-VD-FD	0.306^{e}	86.15^{b}	11.94^{b}	2.61^{c}	0.194^{c}
2h-HAD-FD	0.361^{f}	84.25^{cd}	14.55^{e}	2.25^{d}	0.314^{e}
3h-HAD-FD	0.198^{a}	79.23^{f}	18.68^{g}	2.04^{f}	0.331^{ef}
FD	0.244^{c}	91.40^{d}	12.33^{bc}	3.48^{a}	0.153^{a}

The color parameters of the fresh and dried sweet corn grain are given in Table 2. Drying had an important effect on the color of samples. The Hunter value L^* is influenced by the drying temperature and pre-drying time. Our results indicated that values of L^* (91.40) for corn grain of FD were significantly higher *($p<0.05$)* than for those of hybrid dried and fresh materials (control). This is due to the fading of the maize grains during lyophilization, a finding consistent with a previous publication [3]. Among the combined drying methods, the samples treated with the VD-FD method had the highest L parameter values *($p<0.05$)*. The values of L^* were 84.82 and 81.33 respectively for MIR-FD and 84.25 and 79.23 for HAD-VD sweet corn. As a result, the color of corn grains in MIR-FD was lighter than HAD-FD. The low L^* color parameters of the 10min-MIR-FD and 3h-HAD-FD maize samples (81.33 and 79.23) indicate that a Maillard (so called non-enzymatic browning) reaction has occurred [1]. It is clear that samples dried with longer pre-drying time (for example increasing from 5 min to 10 min) had lower brightness (L) at hybrid drying.

Analyzing the ΔE values, the highest value was observed in 3h-HAD-FD samples (Table 2), as compared with the rest of the treatments ($p<0.05$). As the pre-drying time from 5 to 10 min and from 2h to 3h increased, the ΔE values of dried samples significantly increased ($p<0.05$). We found from the results that VD-FD maize seeds have lower total color difference (ΔE) than FD samples. There was a significant difference ($p<0.05$) between 2h-VD-FD and single-stage of FD dried maize. The relatively low color difference is probably due to the vacuum in the VD and FD dryers [8]. *The significantly largest ($p<0.05$) ΔE is observed for the HAD-FD and 10min-MIR-FD samples.*

The rehydration ratio (RR) values obtained in this work varied from 2.04 to 3.48 (Table 2). A maximum rehydration ratio (RR=3.48) was obtained for the freeze dried of corn grains. It should be noted that there is no significant difference ($p>0.05$) between the 5min-MIR-FD and FD samples. Previous publications attributed the low rehydration ratio to a prolonged drying time [15]. This is consistent with the data obtained in this study when the pre-drying time is taken into account. The 10min-MIR-FD and 2h- and 3h-HAD-FD samples have the lowest rehydration values. This is because the infrared and hot-air pre-drying causes the surface of the maize grain to harden, which prevents the product from absorbing water [18]. This is confirmed by the textural results.

If comparing the fresh samples with the dried corn grain, the hardness decreased from 1.012 N to 0.153-0.331 N (Table 2). Moreover, the increase in pre-drying time for the combined drying of the sweet corn, also produced a significantly effect (*$p<0.05$*) on hardness, i. e. increased. FD maize has the most favorable hardness value *(0.153 N)*. This is because lyophilised products have a porous, loose structure [14]. The hardness value of the FD samples approached the textural value of the 5min-MIR-FD and 2h-VD-FD maize seeds, although there was a significant difference (*$p<0.05$*) between them. Samples dried with hot-air have firmness values twice that of FD maize.

4 CONCLUSIONS

The effect of hybrid drying and freeze drying on operational time, physical and mechanical properties of sweet corn seed, i.e. water activity, rehydration, color and texture was studied.

Drying reduced the water activity (a_w) of the maize grain to <0.4. Generally, the vacuum and infrared application decrease the water activity, improve the product color, rehydration and reduce the hardness. The results indicate that lower drying temperature and pre-drying time in case of hybrid drying are more adequate to preserve these properties.

The results showed that the combination of MIR (pre-drying time: 5 min) followed by FD and VD (pre-drying time: 3 h) followed by FD saves 31.6% and 21% times compared to FD while keeping the product physical and mechanical properties at an acceptable level.

Among the four drying methods, FD led to the best quality properties, including rehydration and firmness.

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