LWT - Food Science and Technology 160 (2022) 113262

Contents lists available at ScienceDirect

LWT

journal homepage: www.elsevier.com/locate/lwt

Influence of coating-blanching in starch solutions, on the drying kinetics, transport properties, quality parameters, and microstructure of celery root chips

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ARTICLE INFO

Keywords:
Celery root chips
Coating-blanching pre-treatment
Corn starch
Microstructure
Drying kinetics

ABSTRACT

The possibility of using different types of starches as the drying aid materials before hot air drying (HAD) (110 °C, 1.5 m/s) of celery root chips to improve drying kinetics and the quality of products were investigated. The influence of coating-blanching pre-treatment of the samples in the native and modified corn, tapioca, and wheat starch solutions (0.1%, 0.3%, 0.5% (w/w)) on the drying kinetics, transport properties, microstructure, color, and texture of the samples was studied. The effective diffusion coefficients varied from 0.735×10^{-9} m^2/s to 2.396×10^{-9} m^2/s. The drag force, heat, and mass transfer coefficients were determined as 8.327 × 10−6 N, 41.21 W/m^2K, and 0.0341 m/s, respectively. In terms of mathematical modeling, the Midilli & Kucuk model was the best for describing the drying behavior of the samples. The fracturability of all samples increased after coating-blanching and the highest L^* value and the maximum compact microstructure were observed in the native and modified corn starch samples. Coating-blanching in the native and modified corn starch solutions was a promising alternative technique to reduce drying time and improve drying kinetics, texture, and color of celery root chips.

1. Introduction

Celery (*Apium graveolens* L.) is an aromatic vegetable, a member of the family Apiaceae. Celery is a globally cultivated vegetable with three botanical varieties: *var. Rapaceum*, known as 'celeriac' with a large root tuber (popular in Europe); *var dulce*, forming a crisp stalk (popular in the USA and Western Europe); and *var. secalinum* (Asia) (Bruznican, De Clercq, Eeckhaut, Van Huylenbroeck, & Geelen, 2020). Celery root which has low calories can be consumed either raw or cooked. Celeriac is rich in nutrient compounds such as vitamins C and K, and it is a good source of iron, manganese, potassium, phosphorus, and magnesium (Godlewska et al., 2020). In addition, it is rich in flavonoids, protein, volatile oils, cellulose, dietary fiber, and antioxidants and exhibits antimicrobial, antiviral, anticarcinogenic, and antioxidant properties (MINAROVIČOVÁ et al., 2018; Godlewska et al., 2020).

Celery root is a winter vegetable with high water content, causing its rapid decay. Hot air drying (HAD) is the most common unit operation and universally cost-effective drying technology used in the food industry. The food manufacturing sector use HAD to decrease the moisture content of food to preserve food from microbial or enzymatic degradation, decrease the packaging and storage costs, and increase the shelf life of products (Kian-Pour & Karatas, 2019). It is a complex process due to simultaneous mass, heat, and momentum transfer. During HAD, the heat energy transfers from the hot air into the surface of raw food (by convection), and then heat penetrates the food (by conduction), increasing the temperature of the sample. Accordingly, water inside the food is transferred by different mechanisms such as liquid diffusion, vapor diffusion, or capillary action to the outer surface, and the evaporated moisture is carried by the hot air (Fig. 1A).

However, a long drying time can change the quality of food products; therefore, to achieve high-quality dried products, drying must occur rapidly (Mujumdar, 2006). The external (temperature, velocity, density, viscosity of drying air) and internal (diffusion coefficient, thermal conductivity, specific heat, density of food) parameters affect the drying process (Kian-Pour & Karatas, 2019). It was reported that pre-treatments such as ultrasound, high pressure, blanching, and coating of food before drying can improve the drying characteristics of food products (Islam, Saha, Monalisa, & Hoque, 2019; Osae et al., 2020).

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https://doi.org/10.1016/j.lwt.2022.113262
Received 18 September 2021; Received in revised form 27 January 2022; Accepted 15 February 2022

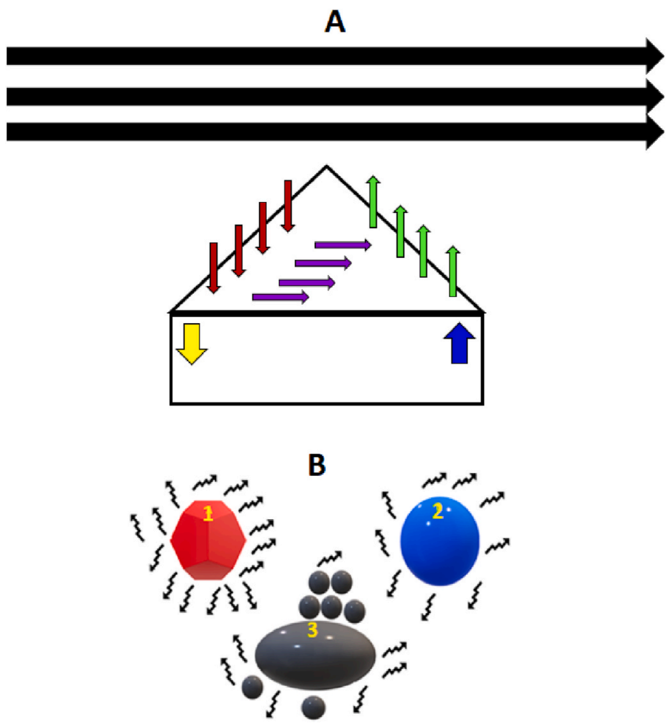

Fig. 1. (A): Schematic view of external and internal parameters affect the drying characteristics of celery root chips, Red arrow) Heat transfer coefficient, Yellow arrow) Thermal conductivity, specific heat, and density, Purple arrow) Friction drag force, Blue arrow) Effective diffusion coefficient, Green arrow) Mass transfer coefficient, Black arrow) Hot air (B): Schematic view of the releases of amylose from B1) corn starch granules, B2) tapioca starch granules, B3) wheat starch granules. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The celery can be dried in the food industry to produce flakes, powder, or slices with different geometric shapes (such as circle, triangle, square) depending on the consumer's, manufacturer's, and application's requirements. The food manufacturing sector can use it in the formulation of dried soup, pasta, bread dough, salt, spice mixes, and sauce. Also, the celery dried in the form of particles with different geometric shapes can be added to the powder soup mixture instead of dried bread particles (instant dry soup mix). Furthermore, they can be used directly by consumers to decorate salads and other kinds of food, or they can be used as healthy snacks between meals such as chips (in the slice form) or as salty and spicy snacks (in the small particle form). Therefore, the effort of the food industry is to improve the existing drying characteristics and decrease the drying time to eliminate the drawbacks of long drying time to obtain economical and high-quality food products.

Starch is highly available in nature and can be used as a coating material before drying. It was stated that coating with starch solutions before drying could improve the drying characteristics, color, and physical properties of papaya samples (Islam et al., 2019). Velić et al. (2005) showed that immersing celery root in the starch solutions before the fluid bed dryer enhanced the drying time, color, texture, and rehydration properties of samples. Starch granules consist of amylose (AM) and amylopectin (AMP) molecules, capable of absorbing water and forming gels when heated (Balet, Guelpa, Fox, & Manley, 2019; Maniglia, Castanha, Le-Bail, Le-Bail, & Augusto, 2021). The starches from different botanic sources show different granular and crystalline structures, affecting their physicochemical and functional properties. Besides, differences in the AM/AMP ratio and the microstructure of starch influence its behavior such as swelling, viscosity, and gelatinization properties (Li, Dhital, & Wei, 2017). However, starches in their native forms exhibit some limited functionalities such as poor solubility, paste instability, etc. Dry heat treatment (DHT) is a safe and simple physical method that can decrease the undesirable properties of native starch (Gou et al., 2019; Maniglia et al., 2021). Therefore, coating the samples with the modified starch solutions before drying may improve the drying characteristics of the samples.

Generally, blanching is a primary stage, widely applied to the vegetables and fruits before drying, and can make the enzymes inactive and enhance the drying and quality properties of the samples. Blanching can be done by different methods such as hot water, steam, microwave, ohmic, etc. Commonly, water blanching is preferred due to its simplicity (Dziki, 2020). Suriya, Baranwal, Bashir, Reddy, and Haripriya (2016) showed that the water blanching of elephant foot yam slices before drying increased the amylose content and water solubility of elephant foot yam flour while decreasing its foam capacity and foam stability compared with the unblanched flour. Jorge et al. (2018) reported that water blanching of tomato before drying increased the phenolic materials, lycopene, and β-carotene while decreasing the sugars and ascorbic acid of tomato. Krzykowski et al. (2018) showed that blanching red pepper before drying significantly reduced the drying time (to approximately 30%) in comparison with the unblanched samples. Wang, Fu, Chen, Hu, and Xie (2018) reported that blanching apple slices before drying caused higher mass loss with a shorter drying time. Dried celery with its aromatic properties is often used as a replacement for fresh celery or as an additive to different foods such as various soups, stews, salads, pasta, bread dough, pickles, and sauce. It can be added to salt to produce celery salt or combined with many herbs to produce spice mixes. Furthermore, it can be blended into barbeque rubs or marinades or used as a dry rub for meat (steak, sausage) and seafood (shrimp, fish). Besides, dried crispy celery chips are often used as a healthy snack between meals. In addition to the use of dried celery as a culinary ingredient, it has been used to treat some illnesses, because it is a good source of macro and micronutrients (MINAROVIČOVÁ et al., 2018; Godlewska et al., 2020). The color, texture, and structure of dried crispy celery chips are mainly affected by the drying process; therefore, the investigation of parameters influencing the drying characteristics of celery is important for improving and optimizing the quality parameters of the final dried chips. The goal of improving the appetizing factors of the celery chips is to encourage people especially children and the young to consume more celery in form of chips and take their health benefits.

To the best of our knowledge, the effect of a one-step combination of blanching and coating on the drying and quality properties of celery root chips has not been studied. Therefore, this study aimed at determining the impact of coating-blanching of celery root in different types of starch solutions before HAD on the drying kinetics, transport properties, color, microstructure, and texture of celery root chips.

2. Material and methods

2.1. Materials

Native corn, tapioca, and wheat starches (Cargill, Co, USA) were used as the drying aids for blanching celery roots. Fresh celery roots were provided by a local market in Istanbul, Turkey, and kept in a refrigerate at 4 °C. Before the experiment, the celery roots were stabilized at room temperature, and then peeled and cut into slices (2-mm thickness). Afterward, they were cut to the triangular (13-mm base and height) shape.

2.2. Investigations on starch concentration (phase 1)

2.2.1. Coating-blanching in native starch

The fresh celery roots were blanched in the aqueous solution of native tapioca (NTS), corn (NCS), and wheat (NWS) starches. The blanching solutions were prepared by dissolving starches in the distilled water to obtain 0.1, 0.3, and 0.5% (w/w) concentrations (NTS1, NTS3, NTS5, NCS1, NCS3, NCS5, NWS1, NWS3, and NWS5). A hotplate stirrer

(160 rpm) (Wisd, Daihan Scientific. Co., Ltd. Model MSH-20A, Korea) was used for blanching the celery root at 95 °C for 10 min. A water-blanched sample was considered the control sample (CON). The experiments were replicated two times.

2.2.2. *Drying of samples blanched in native starch*

A laboratory hot air dryer (Kian-Pour & Karatas, 2019) was used in this study. The drying experiments were performed at 110 °C air temperature and constant air velocity of 1.5 m/s. The online weight loss of the samples was monitored every 60 s using an analytical balance (Fz-500i/AND, JAPAN, ± 0.001 g). The drying process was terminated when the weight of the celery root chips stayed constant. The drying experiment was performed in duplicate and average values were reported.

All blanched (NTS1, NTS3, NTS5, NCS1, NCS3, NCS5, NWS1, NWS3, NWS5, CON) and non-blanched (RAW) samples were dried by HAD. The initial moisture content of fresh celery root was measured utilizing the standard (AOAC, 1990) (no.934.06) method of drying. The experiments were replicated two times and the average values were reported. A schematic view of the development of celery root chips was shown in Fig. 2.

2.3. *Production of celery root chips blanched in modified starches (phase 2)*

2.3.1. *Modification of starch by dry heat treatment (DHT)*

Based on the results of phase 1 (Section 2.2.2), 0.5% modified starch solution of corn and tapioca (MCS5/MTS5) and 0.1% modified starch solution of wheat (MWS1) were prepared. The dry heat treatment (DHT), as an environmentally friendly simple method, was preferred for starch modification by drying 50 g of native starches in an oven dryer (BINDER GmbH, model 9010-0078ED53, Germany) at 150 °C for 2 h (Zou, Xu, Tang, Wen, & Yang, 2020).

2.3.2. *Coating-blanching in modified starch*

As mentioned before, phase 1 was applied to find the proper starch concentration for phase 2 according to the highest diffusion coefficient values and shortest drying time. Therefore, the fresh celery root were blanched in the aqueous solution of modified tapioca (MTS5) (0.5% w/w), modified corn (MCS5) (0.5% w/w), and modified wheat (MWS1) (0.1% w/w) starches. The experiments were replicated two times.

2.3.3. *Drying of samples blanched in modified starch*

The samples blanched in modified starch (MTS5, MCS5, and MWS1) were dried according to the method described in section 2.2.2. The drying experiment was performed in duplicate and average values were reported.

2.4. *Drying kinetics and empirical models*

2.4.1. *Moisture ratio*

The drying rate of celery root chips was computed by Eq. (1):

$$DR = \frac{M_{t2} - M_{t1}}{t_2 - t_1} \tag{1}$$

where DR is the drying rate (kg water/kg dey solid. min); M_{t2} and M_{t1} are the moisture contents (kg water/kg dry solid) of celery root at the drying time of t_2 and t_1 (min), respectively.

The moisture ratio (*MR*) of the sample was calculated according to Eq. (2) (Kian-Pour & Karatas, 2019):

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

where, $\overline{M}$, M_e, and M_0 represent average, equilibrium, and initial moisture contents (kg water/kg dry solid), respectively.

2.4.2. *Pasting properties of starch granules (peak viscosity (PV) and gelatinization temperature)*

The pasting properties of both native and modified starches were determined according to the standard conditions for starch characterization (%14 w/w) (Maniglia et al., 2020). A Rapid Visco-Analyzer (Anton Paar MCR-302, Graz, Austria) (probe: ST-24) was used for measuring the pasting properties of starches according to the method developed by Karakelle, Kian-Pour, Toker, and Palabiyik (2020) with some modifications. The aqueous solutions of native and modified starches were prepared to obtain 14% (w/w) concentrations. Briefly, the initial temperature was adjusted at 50 °C and the slurries were mixed in

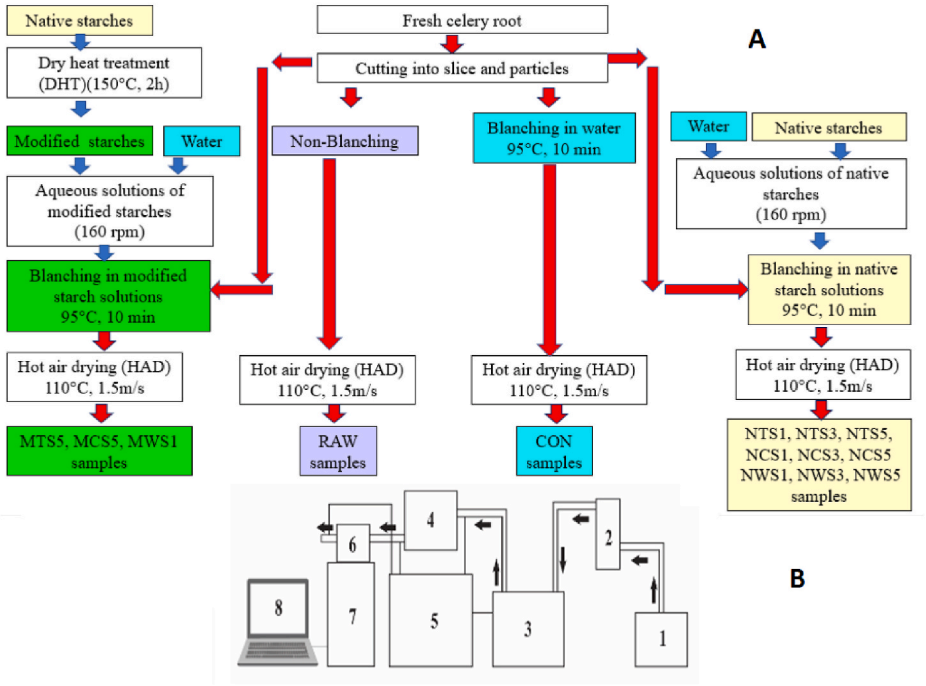

Fig. 2. (A): Schematic view of development celery root chips, (B): Schematic of the laboratory convective dryer. B1) Fan, B2) Rotameter, B3) Humidifier, B4) Heating units, B5) PID temperature controller, B6) Sample loading chamber, B7) Balance, B8) PC. RAW = non-blanched dried celery; CON = water blanched dried celery; NTS1, NTS3, NTS5 = samples pre-treated at 0.1, 0.3%, and 0.5 % w/w solutions of native tapioca starch, respectively; NCS1, NCS3, NCS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native corn starch, respectively; NWS1, NWS3, NWS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native wheat starch, respectively; MTS5 = samples pre-treated at 0.5 %w/w solutions of modified tapioca starch; MCS5 = samples pre-treated at 0.5 %w/w solutions of modified corn starch; MWS1 = samples pre-treated at 0.1 %w/w solutions of modified wheat starch.

a starch cell at 960 rpm for 10 s. Then, the shearing speed decreased to 160 rpm (initial stage/or mixing stage), and the starch slurries heated from 50 °C to 95 °C in 4 min (heating stage), maintained at 95 °C for 4 min, and then cooled to 50 °C at a rate of 15 °C/min. The experiments were replicated two times and the average values were reported.

2.4.3. *Mathematical modeling of drying curves*

The drying curves were fitted to the empirical models (Table 1) by nonlinear regression analysis with the Levenberg-Marquardt algorithm (SPSS statistics 23, IBM. 2015) (Macedo, Vimercati, Araújo, Saraiva, & Teixeira, 2020). The goodness of fit was computed according to the determination coefficient (R^2), root mean square error (*RMSE*), and reduced chi-square (x^2), shown in Eq. (3), Eq. (4), Eq. (5), respectively.

$$R^2 = 1 - \left[\frac{\left(\sum_{i=1}^{N} MR_{pre,i} - MR_{exp,i}\right)^2}{\left(\sum_{i=1}^{N} \overline{MR}_{pre,i} - MR_{exp,i}\right)^2}\right] \tag{3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - n} \tag{5}$$

where, $MR_{exp,i}$, $MR_{pre,i}$, N, and n represent the experimental moisture ratio, predicted moisture ratio, the number of observations, and the number of model constants, respectively.

2.4.4. *Effective moisture diffusivity (Deff)*

The analytical solution of Fick's second law of diffusion for plate geometry was used to determine the Deff by applying linear regression analyses to experimental data (Eq. (6)) (Macedo et al., 2020).

$$MR = \frac{8}{\pi^2}\sum_{0}^{\infty}\frac{1}{(2n+1)^2}\exp\left\{-\frac{(2n+1)^2}{4}\frac{\pi^2 D_{eff}\, t}{{x_1}^2}\right\} \tag{6}$$

where, D_{eff} , n, t, and x_1 are the diffusion coefficient (m/s^2), a positive integer, time (s), and the half-thickness of the sample (m), respectively.

2.5. *Transport properties*

2.5.1. *Momentum transfer*

The friction drag force F_D (N), created by the flowing of dry air on the celery root chips, was calculated by Eq. (7) (Çengel & Cimbala, 2006).

$$F_D = F_{D,friction} = \frac{1}{2} C_f A \rho V^2 \tag{7}$$

where C_f , A , ρ , V are the friction drag coefficient, the total surface area of chips (m), air density (kg/m^3), and air velocity (m/s), respectively. When Reynolds number Re_L (Eq. (8)) is less than 5×10^5, C_f in the laminar boundary layer can be calculated using Eq. (9)

$$Re_L = \frac{L\, V\, \rho}{\mu} \tag{8}$$

$$C_f = \frac{1.33}{Re_L^{1/2}},\ Re_L < 5 \times 10^5 \tag{9}$$

where L and μ represent the characteristic length of the chips in the flow direction (m), and air viscosity (kg/m.s), respectively.

Table 1
Mathematical drying models.

Model number	Model name	Equation
1	Newton	$MR = Exp\,(-kt)$
2	Henderson & Pabis	$MR = a\exp(-kt)$
3	Wang & Singh	$MR = 1 + at + bt^2$
4	Modified Page	$MR = Exp\,(-(kt)^n)$
5	Logarithmic	$MR = a\exp(-kt) + c$
6	Midilli & Kucuk	$MR = a\exp(-kt^n) + bt$

2.5.2. *Heat transfer*

The heat transfer for the laminar boundary layer was shown by the average heat transfer coefficient h_{heat} (W/m^2 K) (Eq. (10)).

$$Nu = \frac{h_{heat}L}{k_{air}} = 0.664 Re^{0.5} Pr^{1/3}\ ,\ Re_L < 5 \times 10^5 \tag{10}$$

where Nu, L, k_{air}, and Pr are Nusselt number, characteristic lengths (m), air thermal conductivity (W/m K), and Prandtl number, respectively (Kian-Pour & Karatas, 2019).

2.5.3. *Mass transfer*

The mass transfer was shown by the convective average mass transfer coefficient h_{mass} (m/s) (Eq. (11)) (Geankoplis, 1993).

$$Sh = \frac{h_{mass}L}{D_{AB}} = 0.664 Re^{0.5} Sc^{1/3}\ ,\ Re_L < 5 \times 10^5 \tag{11}$$

where Sh, D_{AB}, and S_C are the Sherwood number, the mass diffusivity of air-water vapor mixture (2.2×10^{-5} m^2/s), and Shmidt number, respectively (Agrawal & Methekar, 2017). Besides, a Chilton-Colburn analogy can be used to determine h_{mass} (Eq. (12)) (Çengel, 2007).

$$\frac{h_{heat}}{h_{mass}} = \rho C_p \left(\frac{\alpha}{D_{AB}}\right)^{2/3} = \rho C_p Le^{2/3},\ 0.6 < Pr < 60,\ 0.6 < Sc < 3000 \tag{12}$$

where C_p is specific heat (J/kg K), α is thermal diffusivity (m^2/s), and Le denotes Lewis number.

2.6. *Thermodynamic properties*

The thermodynamic properties of celery root chips were determined according to their moisture content by Eq. (13), Eq. (14), and Eq. (15) (Pasban, Sadrnia, Mohebbi, & Shahidi, 2017):

$$k = 0.148 + 0.493 M_{wb} \tag{13}$$

$$C_p = (1.26 + 2.97 M_{wb}) \times 1000 \tag{14}$$

$$\rho = 770 + 16.18\, M_{db} - 295.1 \times \exp(-M_{db}) \tag{15}$$

where k, C_p, M_{wb}, M_{db} and ρ represent the thermal conductivity (W/m K), specific heat (J/kg K), wet basis moisture content (%), dry basis moisture content (kg water/kg dry solid), and the density (kg/m^3) of the samples.

2.7. *Quality measurments*

2.7.1. *Texture analysis*

ATA-HD plus Texture Analyser (Stable Micro Systems, UK) was used to determine the hardness (g) and fracturability (mm) of dried samples. According to the small dimension of samples, not suitable for texture analysis, the celery root slices with 2-mm thickness were blanched and dried under the same experimental conditions. The small Three-Point Bend Rig was utilized to perform the fracture test of the samples, while the test condition was as follows: the pre-test speed 1 mm/s, test speed 3 mm/s, post-test speed 10 mm/s, 50% strain, and trigger force 0.049 N. The experiment replicated four times.

2.7.2. *Color evaluation*

CIE *L*a*b** color parameters of the dried celery root chips were determined by a Hunter colorimeter (Minolta CR-400, Europe) with three replications. The measured L* (lightness), *a** (redness/greenness), and *b** (yellowness/blueness) values were used in the determination of Hue angle (H°) (Eq. (16)) and the total color difference (ΔE) between all dried samples with water-blanched dried (CON) samples (Eq. (17)) (Senadeera, Adiletta, Önal, Di Matteo, & Russo, 2020).

$$H^{\circ} = arctan\left(\frac{b^*}{a^*}\right) \tag{16}$$

$$\Delta E = \sqrt[2]{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{17}$$

2.7.3. *Microstructure evaluation*

The microstructure of celery root chips and the native and modified starch granules were examined using a Scanning Electron Microscope (SEM) (Zeiss EVO® LS 10, Germany) (Lohani & Muthukumarappan, 2016). A schematic view of experimental analysis was shown in Fig. 3.

2.8. *Statistical analysis*

The experimental results were submitted to analysis of variance (ANOVA) with Tukey's tests using the software package (SPSS statistics 23, IBM. 2015) and the significant level was considered $p < 0.05$.

3. Results and discussion

3.1. *Drying kinetics*

3.1.1. *Drying time and moisture ratio of samples pre-treated in native starch*

The initial moisture content of fresh celery root was found to be 92.55%. The drying kinetics of the samples are shown in Fig. 4. For all samples as the drying time increased, the moisture content decreased exponentially (Fig. 4A). The coating-blanching pre-treatment significantly decreased the drying time of the samples at different levels (Table 2). The results revealed that among the native starches, the drying time of NCS5, NTS5, and NWS1 samples were 70%, 56.66%, and 63.33% lower than the control samples, respectively, while the minimum drying time belonged to the NCS5 samples. It means that the pretreatment of celery roots before drying in the native tapioca, corn, and wheat starch solutions could improve the drying characteristics of the samples at a different level. The results showed that the shortest drying time and highest Deff (which will be discussed in section 3.4) of the samples pretreated with native tapioca starch solutions belonged to the samples blanched at 0.5% w/w concentration. The experimental results of native corn starch confirmed similarity with tapioca starch. However, for the samples pretreated in the native wheat starch solutions, the shortest drying time and the highest Deff were observed at 0.1% w/w starch concentration. In addition, the increase in the concentration of starch from 0.1% to 0.3% and 0.5% led to a decrease in the Deff and an increase in the drying time. As an extracellular matrix supporting plant cells, the plant cell wall (PCW) directly affected the texture of vegetables and fruits. Furthermore, PCW consists of soluble and insoluble carbohydrates (Padayachee, Day, Howell, & Gidley, 2017). Blanching of celery roots in hot water caused a loss in integrity of the cell wall, facilitating the separation of moisture from celery cells; therefore, the water blanched samples dried faster than the non-blanched samples. Moreover, high blanching temperature caused a structural change in the samples and produced a more compact structure, resulting in a product with higher crispness. These structural changes of the samples during drying formed an extra force to push out moisture from the cell, causing a significant decrease in the drying time and an increase in the Deff of starch-blanched samples in comparison with the water-blanched samples. Our results were in good agreement with those of the other authors on the effect of blanching on the reduction of drying time of food products (Krzykowski et al., 2018; Wang et al., 2018).

Islam et al. (2019) studied the effect of coating pre-treatment on the drying characteristics of papaya. The aqueous solutions of potato starch (1%, 2%, 3% w/w) and calcium gluconate salt (0.5% w/w) were prepared by heating the solution at 70 °C and then cooling the solution to room temperature. After that, the papaya slices were immersed in the solutions for 1 min before hot air drying (50 °C, 60 °C, 70 °C). The authors reported that as the concentration of coating material increased, the drying rate decreased. However, in our experiments, pre-treatment was done by both blanching and coating. Higher drying rate and lower drying time in our research compared to that of Islam et al. (2019) was attributed to the use of starch with a lower concentration, simultaneous blanching and coating in starch solutions in one step at higher temperature (95 °C) and longer pre-treatment time (10 min). Velić et al. (2005) showed that blanching and coating of celery root in the solution containing 2.5% starch and 2% $CaCl_2$ for 5 min in comparison with dipping (just coating) in 2.5% starch solution (40 °C, 5 min) before fluidized bed drying at 80 °C, increased drying rate while decreasing

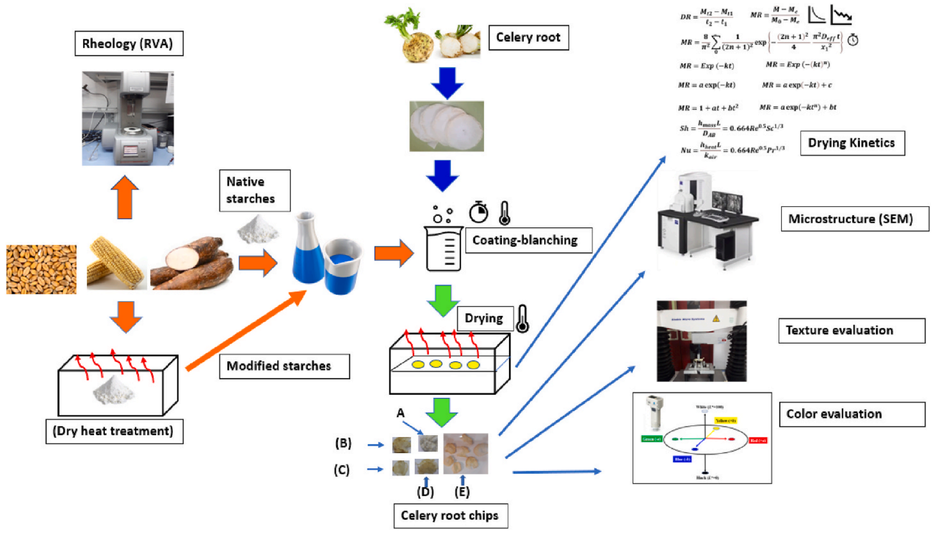

Fig. 3. Schematic view of experimental analysis of celery root chips. (A): RAW = non-blanched dried samples, (B): CON = water blanched dried samples; (C): MTS5 = dried samples pre-treated at 0.5 %w/w solutions of modified tapioca starch), (D): MWS1 = dried samples pre-treated at 0.1 %w/w solutions of modified wheat starch, (E): MCS5 = dried samples pre-treated at 0.5 %w/w solutions of modified corn starch.

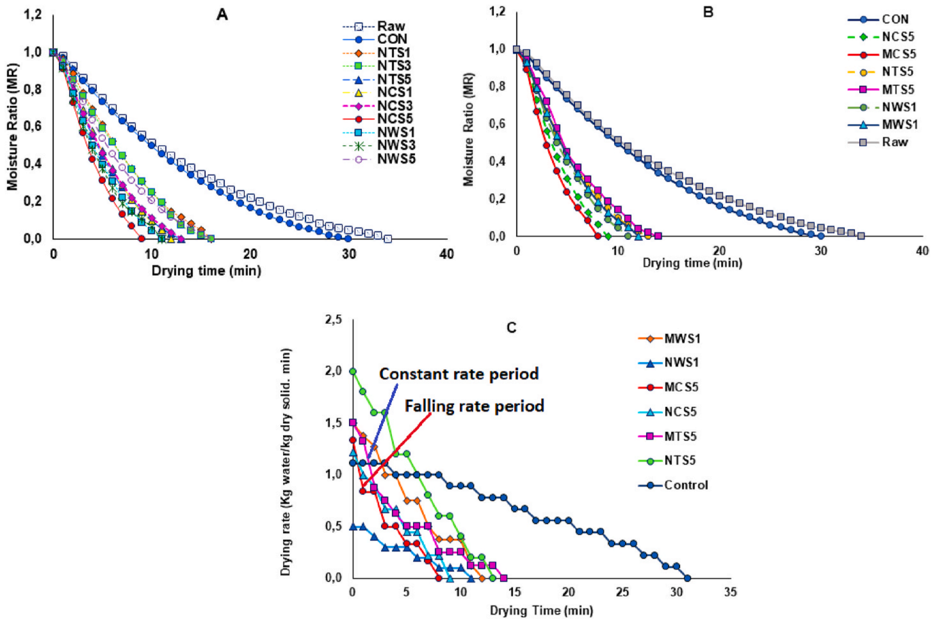

Fig. 4. Drying kinetics curves. A) Moisture ratio of samples pre-treated in native starches (Phase 1), B) Comparison between moisture ratio of samples pre-treated in selected native and modified starches (Phase 2), C) Comparison between drying rates of samples pre-treated in selected native and modified starches (Phase 2). RAW = non-blanched dried celery; CON = water blanched dried celery; NTS1, NTS3, NTS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native tapioca starch, respectively; NCS1, NCS3, NCS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native corn starch, respectively; NWS1, NWS3, NWS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native wheat starch, respectively; MTS5 = samples pre-treated at 0.5 %w/w solutions of modified tapioca starch; MCS5 = samples pre-treated at 0.5 %w/w solutions of modified corn starch; MWS1 = samples pre-treated at 0.1 %w/w solutions of modified wheat starch.

Table 2
Drying kinetics of celery root chips.

	Starch concentration (%) (w/w)	Code	Difusion coefficient Deff * 10^{-9} m^2/s ± SD	Change in Deff comapred with control (%)	Drying time (min)
Raw celery (No blanching)	0	RAW	0.735 ± 0.002^{a}	- 0.15	34
Control (Water blanching)	0	CON	0.866 ± 0.018^{a}	0	30
Native Tapioca Starch	0.1	NTS1	1.326 ± 0.021^{b}	+53.12	16
	0.3	NTS3	1.543 ± 0.056^{c}	+78.18	16
	0.5	NTS5	1.906 ± 0.028^{ef}	+120.09	13
Native Corn Starch	0.1	NCS1	1.802 ± 0.069^{de}	+108.03	12
	0.3	NCS3	1.807 ± 0.037^{de}	+108.66	13
	0.5	NCS5	2.220 ± 0.010^{g}	+156.35	9
Native Wheat Starch	0.1	NWS1	2.009 ± 0.007^{f}	+131.99	11
	0.3	NWS3	1.927 ± 0.083^{ef}	+122.52	11
	0.5	NWS5	1.479 ± 0.001^{bc}	+70.79	16
Modified Wheat Starch	0.1	MWS1	1.733 ± 0.070^{d}	+100.12	12
Modified Tapioca starch	0.5	MTS5	1.817 ± 0.009^{de}	+109.81	14
Modified Corn Starch	0.5	MCS5	2.396 ± 0.013^{h}	+176.67	8

Different letters in the same column indicate differences significant at $p < 0.05$. Mean ± standard deviation is computed from two replicates.
(−): decreases.
(+): increases.
RAW = non-blanched dried celery; CON = water blanched dried celery; NTS1, NTS3, NTS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native tapioca starch, respectively; NCS1, NCS3, NCS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native corn starch, respectively; NWS1, NWS3, NWS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native wheat starch, respectively; MTS5 = samples pre-treated at 0.5 %w/w solutions of modified tapioca starch; MCS5 = samples pre-treated at 0.5 %w/w solutions of modified corn starch; MWS1 = samples pre-treated at 0.1 %w/w solutions of modified wheat starch.

drying time. It is in agreement with our results; however, higher drying rate and lower drying time in our experiment in comparison with that of Velić et al. (2005) were related to longer blanching time, lower concentration of starch, higher drying temperature, and different geometric shape (triangle) of the sample in our study.

3.1.2. *Drying time and moisture ratio of samples pre-treated in modified starch*

The drying curves of both modified and selected native starches are shown in Fig. 4B. The minimum drying time belonged to the MCS5 samples. The effect of modification with DHT on the corn starch was more pronounced in terms of decreases in drying time and increases in diffusion coefficient compared with the tapioca and wheat starches. The drying time of the samples blanched in the modified wheat and tapioca starches slightly increased compared with the native wheat and tapioca starches, attributable to the viscosity properties of starches. After DHT, the peak viscosity of wheat and tapioca starches decreased compared to the native starches (section 3.6.), leading to a decrease in the positive influence of blanching-coating pretreatment on the drying characteristics of these samples. However, modification by DHT increased the PV of corn starch in comparison with native starch. One possible reason for the improvement in the drying characteristics (drying time, Deff) of the sample blanched in the modified corn starch was an increase in its viscosity after the modification by DHT. Our results agreed with other authors in terms of the effect of DHT on the PV of starches (Gou et al., 2019; Qiu, Cao, Xiong, & Sun, 2015; Maniglia et al., 2021).

3.2. *Drying rate curves of samples pre-treated in modified and selected native starches*

The respective drying rate curves of the blanched celery root chips are shown in Fig. 4C. In a typical drying rate curve, different drying stages can be seen. In a constant rate period, the unbound water is removed from the surface of the sample, and during this period the surface of the celery root remains wet (Mujumdar, 2006). In this stage, the rate of water evaporation from the surface is equal to that of the moisture supplied to the surface of celery root samples. However, as drying progresses, the rate of water migration from inside of the sample is not equal to that of evaporation. Therefore, when water in the samples reached the critical moisture content, the drying rate decreased, and the dry spots could be seen upon the surface of the samples. In the next step, the falling rate period, the drying rate is governed by the mechanisms of internal water migration due to the moisture concentration gradients between the inside and the surface of the sample (Mujumdar, 2006). As shown in Fig. 4C, the drying rate of the control samples started in the constant rate period, while for the pre-treated samples, it generally started from the falling rate period. It represented that the internal moisture movement (from inside the celery root samples to outside) is the main factor in controlling the drying rate (Fig. 4C) (Srikiatden & Roberts, 2005). However, it was observed that the drying rate of the samples blanched in the native wheat starch (NWS1) started from the constant rate period like a control sample (Fig. 4C). It confirmed that blanching in the native wheat starch solution had no significant effect on the decrease in the free water of the sample during blanching. As can be seen in Fig. 1B, wheat starch granules (Fig. 1B3) showed a complex structure compared to corn (Fig. 1B1) and tapioca starch (Fig. 1B2) and it consisted of both large flat-oval large and small spherical shapes granules (Balet et al., 2019; Kang et al., 2021). The absorption of free water from samples by this complex structure can be more difficult in comparison with tapioca and corn starch granules with simple structures. Consequently, blanching the samples in the native wheat starch solutions could not decrease the free water of the samples; therefore, the drying started from the constant rate periods. In contrast, blanching in native corn and tapioca starches caused a decrease in the free water of the samples; thus, the drying started at the falling rate period. The DHT process can change the thermal and physical properties of starch. The faster drying of MCS5 was related to improving the swelling properties of starch after DHT, causing the absorption of a larger amount of moisture from the surface of the celery during pre-treatment, in turn leading to a decrease in the drying time. Our results agreed with those of the other authors on the increases in the swelling power of rice starch (Oh, Bae, & Lee, 2018) and sweet potato starch (Gou et al., 2019) after DHT.

3.3. *Mathematical modeling*

The predicted drying model parameters are shown in Table 3. In all cases, the R^2 values ranged from 0.8521 to 0.9997, the *RMSE* values changed from 0.0054 to 0.1374 and the χ^2 values varied from 0.00003 to 0.02157. The criteria for the selection of the best empirical model were the highest R^2 and the lowest χ^2 and *RMSE* (Kian-Pour & Karatas, 2019). Among all empirical models, the Midilli-Kucuk model was best fitted for all samples, in agreement with other studies such as those carried out on apple (Kian-Pour & Karatas, 2019), papaya (Islam et al., 2019), and banana (Macedo et al., 2020).

3.4. *Effective moisture diffusivity (Deff)*

The Deff of the celery root chips ranged from 0.735 to 2.396 × 10^{-9} m^2/s (Table 2), within the range determined for food products (10^{-12}–10^{-8} m^2/s) (Dadali, Demirhan, & Özbek, 2007). An increase in the concentration of native starches from 0.1% to 0.5% significantly ($p < 0.05$) increased the Deff of the tapioca starch samples. In the case of wheat starch, as concentration increased, Deff values decreased.

Table 3
The predicted drying model parameters.

Models	Parameters	RAW	CON	NCS5	MCS5	NTS5	MTS5	NWS1	MWS1
Newton	k	0.068	0.068	0.181	0.202	0.149	0.127	0.152	0.151
	R^2	0.9569	0.9295	0.8569	0.8521	0.8971	0.9201	0.8806	0.8875
	RMSE	0.0637	0.0868	0.1342	0.1374	0.1092	0.0989	0.1112	0.1147
	x^2	0.00418	0.00779	0.02025	0.02157	0.01292	0.01054	0.01331	0.01436
Henderson & Pabis	a	1.180	1.216	1.416	1.454	1.338	1.281	1.360	1.349
	k	0.080	0.082	0.256	0.293	0.198	0.163	0.206	0.203
	R^2	0.9863	0.9710	0.9611	0.9667	0.9721	0.9784	0.9648	0.9694
	RMSE	0.0360	0.0557	0.0699	0.0652	0.0568	0.0514	0.0604	0.0599
	x^2	0.00138	0.00332	0.00629	0.00567	0.00382	0.00308	0.00425	0.00430
Wang & Singh	a	−0.050	−0.047	−0.107	−0.121	−0.099	−0.088	−0.097	−0.098
	b	0.001	0.000	0.000	0.001	0.002	0.002	0.001	0.001
	R^2	0.9938	0.9903	0.9647	0.9579	0.9741	0.9825	0.9710	0.9708
	RMSE	0.0243	0.0321	0.0667	0.0733	0.0548	0.0463	0.0548	0.0585
	x^2	0.00063	0.00111	0.00571	0.00717	0.00355	0.00250	0.00350	0.00410
Modified Page	k	0.066	0.066	0.182	0.204	0.146	0.124	0.151	0.150
	n	1.417	1.613	2.023	2.022	1.799	1.648	1.899	1.851
	R^2	0.9972	0.9975	0.9956	0.9931	0.9973	0.9971	0.9965	0.9972
	RMSE	0.0163	0.0163	0.0236	0.0296	0.0175	0.0189	0.0189	0.0183
	x^2	0.00028	0.00029	0.00071	0.00117	0.00036	0.00042	0.00042	0.00040
Logarithmic	a	1.305	1.526	1.853	1.749	1.560	1.462	1.686	1.628
	c	−0.199	−0.415	−0.617	−0.474	−0.355	−0.291	−0.474	−0.418
	k	0.054	0.043	0.112	0.146	0.110	0.097	0.102	0.107
	R^2	0.9994	0.9981	0.9956	0.9941	0.9967	0.9983	0.9959	0.9957
	RMSE	0.0077	0.0141	0.0236	0.0274	0.0196	0.0146	0.0207	0.0224
	x^2	0.00006	0.00022	0.00083	0.00120	0.00050	0.00027	0.00055	0.00067
Midilli & Kucuk	a	1.069	1.033	1.085	1.106	1.076	1.080	1.073	1.071
	b	−0.002	−0.003	−0.007	−0.006	−0.004	−0.004	−0.005	−0.004
	k	0.043	0.022	0.061	0.080	0.058	0.062	0.051	0.053
	n	1.140	1.371	1.625	1.603	1.478	1.326	1.554	1.551
	R^2	**0.9997**	**0.9997**	**0.9991**	**0.9971**	**0.9993**	**0.9994**	**0.9993**	**0.9993**
	RMSE	**0.0054**	**0.0058**	**0.0105**	**0.0194**	**0.0088**	**0.0085**	**0.0085**	**0.0091**
	x^2	**0.00003**	**0.00004**	**0.00020**	**0.00075**	**0.00011**	**0.00010**	**0.00010**	**0.00013**

RAW = non-blanched dried celery; CON = water blanched dried celery; NTS1, NTS3, NTS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native tapioca starch, respectively; NCS1, NCS3, NCS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native corn starch, respectively; NWS1, NWS3, NWS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native wheat starch, respectively; MTS5 = samples pre-treated at 0.5 %w/w solutions of modified tapioca starch; MCS5 = samples pre-treated at 0.5 %w/w solutions of modified corn starch; MWS1 = samples pre-treated at 0.1 %w/w solutions of modified wheat starch.

However, the highest Deff values among different types of native starches belonged to the samples blanched in 0.5% native corn starch. The concentration of 0.5% w/w of native corn and tapioca starch (NCS5, NTS5) and 0.1% w/w of native wheat starch (NWS1) were selected for the next step, according to high values of their Deff. The low drying time of NCS5, NTS5, and NWS1 samples was related to the high values of Deff in these samples. In addition, among the samples blanched in the modified starches, MCS5 showed the maximum Deff compared with other modified starches. The Deff of the samples blanched in the modified tapioca (MTS5) and wheat starches (MWS1) was significantly higher than that of the water blanched samples (CON). However, Deff of MTS5 and MWS1 samples slightly decreased compared to the sample blanched in native wheat and tapioca starch, attributed to decreases in their viscosity after DHT. In contrast, the sample blanched in modified corn starch solutions (MCS5) showed a higher Deff in comparison with native corn starch, probably due to the increase in the viscosity of corn starch after the modification by DHT. As mentioned before, DHT with an increase in the swelling power of starch caused an increase in the removal of water from celery root during pre-treatment, leading to an increase in Deff. In addition, the structural change of celery root during pre-treatment could be another factor for the increase in the Deff of MCS samples. Among all starches, the corn starch showed the best effect on drying time and diffusion coefficient of products.

The results revealed that the use of the starch solution for blanching the celery roots could significantly improve the Deff and drying time of the samples. Our results were in agreement with those of other authors (Velić et al., 2005; Krzykowski et al., 2018; Wang et al., 2018; Islam et al., 2019). However, the excellent drying characters in our experiment (Deff, drying rate, drying time) compared with previous studies were related to the selection of a lower concentration of starch, blanching in the higher temperature for a longer time, and finally, use of higher air temperature for drying celery root. All of these parameters are simple enough to apply by the industry for improving the drying properties of celery root and significantly decreasing its drying time. However, the only challenge that might occur in the existing industrial drying factories without blanchers is to add a simple water-blanching tank to their process line. Although, a blancher is one of the main equipment, generally used at the vegetable process line in food factories. Our results can be used simply by food factories to address the disadvantage of long drying time in their process.

3.5. *Momentum, heat, and mass transfer*

The transport properties were determined by Eqs. 7–12. According to the results, the external condition affecting the drying process was determined as Reynolds number (990), friction drag coefficient (0.04227), friction drag force (8.327×10^{-6} N), Nusselt number (18.713), heat transfer coefficient (41.21 W/m^{2}K), and mass transfer coefficient (0.03410 m/s). Besides, the internal properties of the sample such as thermal conductivity, specific heat, and density were determined (Table 4). The thermal conductivity, the specific heat, and the density of celery chips varied from 0.572 to 0.615 W/m. K, 3815.58 to 4071.60 (J/kg. K), and 869.16 to 1057.19 (Kg/m3), respectively, with the maximum and minimum values in NWS1 and MCS5 samples, respectively. It might be related to the effect of the starches on the moisture content of the samples. Furthermore, the results revealed that blanching celery root in the 0.1% NWS1 solution caused an increase in the moisture content of samples, likely related to the absorption of more water in these samples. In contrast, the MCS5 decreased the moisture content of celery root; therefore, the thermodynamic properties of MCS5 represented a lower value compared to NWS1. In addition, the MCS5 samples showed the lowest drying time and the highest Deff between all straches, probably related to a change in the microstructure of MCS5 during pre-treatment. Therefore, simultaneous internal and external conditions affected the drying kinetics of the samples. Our results confirmed that coating-blanching and drying of celery roots at the mentioned condition with the suggested starch concentration could significantly increase moisture diffusion coefficient, decrease drying time, and enhance the mass and heat transfer during drying in comparison with other studies. Our results were consistent with those of another study about the drying of apples (Kian-Pour & Karatas, 2019). The slightly higher values of our specific heat might be related to the differences between the chemical composition and the structure of celery root with apple. The data on external and internal properties can be useful for simulating the drying of celery roots and beneficial in understanding the drying mechanisms.

3.6. *Peak viscosity and gelatinization temperature of starch granules*

The pasting properties of starches are shown in Fig. 5. The results revealed that DHT significantly decreased the peak viscosity (PV) of MWS1 and MTS5 in contrast with native starches, while the PV of MCS5

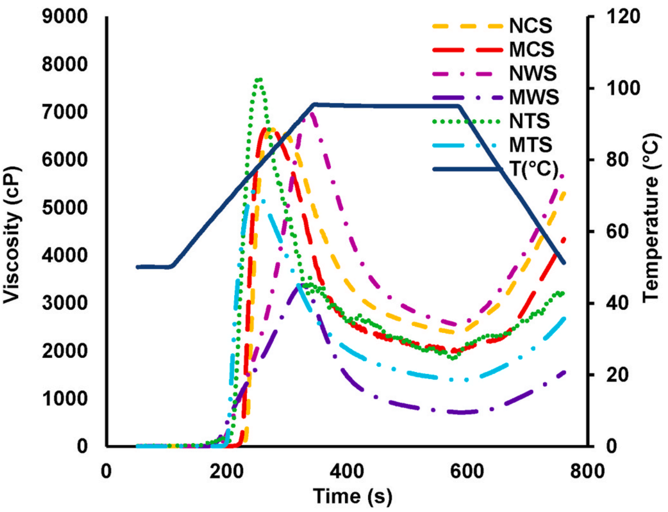

Fig. 5. Pasting curves of native and modified starch granules. NSC = native corn starch; MCS = modified corn starch; NWS = native wheat starch; MWS = modified wheat starch; NTS = native tapioca starch; MTS = modified tapioca starch.

Table 4
Transport and thermophysical parameters.

Thermophysical Properties of sample	RAW	CON	NCS5	MCS5	NTS5	MTS5	NWS1	MWS1
Thermal conductivity *k* (W/m. K)	0.603	0.607	0.603	0.572	0.611	0.601	0.615	0.599
Specific heat *Cp* (J/kg. K)	4003.714	4023.988	3998.571	3815.581	4048.902	3986.557	4071.600	3979.895
Density ρ (Kg/m^3)	966.18	987.08	961.46	869.16	1019.17	951.21	1057.19	945.95

RAW = non-blanched dried celery; CON = water blanched dried celery; NTS1, NTS3, NTS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native tapioca starch, respectively; NCS1, NCS3, NCS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native corn starch, respectively; NWS1, NWS3, NWS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native wheat starch, respectively; MTS5 = samples pre-treated at 0.5 %w/w solutions of modified tapioca starch; MCS5 = samples pre-treated at 0.5 %w/w solutions of modified corn starch; MWS1 = samples pre-treated at 0.1 %w/w solutions of modified wheat starch.

increased (Fig. 5). Among native starches, corn starch had the lowest PV, while after DHT-modification, the corn starch showed the highest PV. Maniglia et al. (2021) reported that DHT affected differently on the PV and gelatinization temperatures of various starches. Qiu et al. (2015) showed that PV of rice starch after DHT at 130 °C for 2 and 4 h increased compared with native rice starch, in agreement with our results about corn starch. It might be related to the same polyhedral shape in both corn starch and rice starch granules. Besides, Gou et al. (2019) reported that the PV of sweet potato starch after 18 h DHT significantly decreased. Generally, the sweet potato starch granules have oval round, spherical, shapes similar to our tapioca starch (Chen, Schols, & Voragen, 2003).

The pasting temperature of all starches decreased after DHT, and the highest gelatinization temperatures belonged to the corn starches. Similar results were reported by Sun, Si, Xiong, and Chu (2013), showing that the pasting temperature of corn, potato, and pea starches decreased after DHT. As seen before in Table 2, the corn starches showed the highest Deff and lowest drying times, attributable to the higher gelatinization temperature and longer time to reach the gelatinization temperature of corn starch in comparison with tapioca and wheat starch (Fig. 5). A long time before gelatinization could cause starch granules to absorb more water; therefore, corn starch solution might have more time to act as an absorbance solution to remove water from celery root compared with other starch. Accordingly, the celery roots pre-treated with corn starch showed the best drying characteristic among other starches.

3.7. Quality paraters of celery root chips

3.7.1. Texture

The hardness is defined as the maximum peak force required to break down the samples i.e. the higher value of hardness means more force needed to break down the chips (Li, Zhang, Jin, & Hsieh, 2005). However, the fracturability was determined according to the contact distance of the break (mm) and the smaller local crackdown distance represented the greater fracturability (Liu, Liu, Huang, & Zhang, 2021). In addition, the crispness of chips can be predicted from fracturability. Therefore, the lower force and distance measured at breakdown represented the lower hardness, higher fracturability, and higher crispness of chips (Li et al., 2005; Lohani & Muthukumarappan, 2016).

The RAW samples (non-blanched dried celery) showed the maximum hardness among all samples because they did not blanch in hot water; therefore, the cell wall integrity was not destroyed in RAW samples. Consequently, a higher force was required to break down this sample. Furthermore, among the blanched samples, the hardness values of the control sample were significantly higher than those of all starch blanched samples; nonetheless, it was lower than that of the RAW samples (Table 5). As will be seen in section 3.7.3., blanching in hot water changed the internal structure of celery root and partially destroyed the heterogeneous honeycomb microstructures of the cell wall, resulting in softening in the texture of the sample. In the case of the starch-blanched samples, significant ($p < 0.05$) decreases in hardness were observed in comparison with the water-blanched samples. Generally, with the increases in the concentration of native corn and native tapioca starch, the hardness of chips decreased, while that of the native wheat starch increased. Further investigation about molecular weight, crystalline structure, the ratio of amylose to amylopectin, amylose content, and chain length need to explain the differences between wheat, corn, and tapioca starches on the hardness of samples (Roman, Reguilon, Gomez, & Martinez, 2020).

In addition, DHT significantly ($p < 0.05$) increased the hardness of MTS5 and MWS1 compared with NTS5 and NWS1. The decrease in the hardness of MCS5 compared with NCS5 was not statistically significant ($p > 0.05$). However, the minimum value of hardness among native and modified starches belonged to NCS5, and MCS5, respectively. Blanching the samples in the starch solutions significantly ($p < 0.05$) increased the fracturability values of all chips compared with the water blanched samples and the maximum and the minimum fracturability values were observed at the MCS5 and RAW, respectively (Table 5). The results reveal that blanching of celery root in the 0.5% solution of corn starch showed the minimum hardness and maximum fracturability values compared to other samples (Kian-Pour & Karatas, 2019; Li et al., 2005; Lohani & Muthukumarappan, 2016). Bierhals, Chiumarelli, and Hubinger (2011) reported that dipping fresh-cut pineapple slices in the cassava starch solution did not significantly change the hardness of the sample during storage at 5 °C. However, Chiumarelli, Pereira, Ferrari, Sarant'opoulos, and Hubinger (2010) studied the effect of the combination of cassava starch coating and citric acid (CS) and coating with the mixture of cassava starch, citric acid, and glycerol (CSG) on the textural properties of the fresh-cut mango during storage at 5 °C. A reduction in the maximum penetration force, firmness loss, and softening of mango tissue during storage was observed, which was higher in the CSG samples. In contrast, Islam et al. (2019) stated that coating papaya with potato starch solution (1%, 2%, 3% w/w) and calcium gluconate salt (0.5% w/w) before hot air drying increased the hardness of all the dried papaya samples compared with the control samples. However, the

Table 5
Textural and color properties of dried celery root chips.

Dried Samples	Hardness (g)	Fracturability (mm)	L*	a*	b*	H°	*ΔE*
RAW	6521.26 ± 67.97^{a}	13.53 ± 0.32^{a}	80.81 ± 0.47^{g}	-5.40 ± 0.14^{a}	17.52 ± 0.08^{bc}	72.86 ± 0.32^{a}	18.88 ± 0.46^{h}
CON	2641.47 ± 32.46^{b}	15.77 ± 0.22^{b}	62.71 ± 0.46^{c}	-4.23 ± 0.09^{bc}	22.80 ± 0.43^{de}	79.47 ± 0.32^{de}	0
NCS1	1647.79 ± 53.73^{d}	29.08 ± 0.66^{ef}	60.22 ± 0.16^{b}	-3.59 ± 0.34^{cde}	23.39 ± 0.65^{ef}	81.29 ± 0.71^{ef}	2.70 ± 0.18^{ab}
NCS3	1159.76 ± 81.74^{gh}	32.66 ± 0.27^{h}	85.14 ± 0.71^{i}	-5.23 ± 0.32^{a}	16.07 ± 0.43^{b}	71.96 ± 0.66^{a}	23.44 ± 0.74^{j}
NCS5	475.27 ± 20.65^{k}	35.03 ± 0.66^{i}	83.15 ± 0.06^{h}	-5.57 ± 0.27^{a}	23.86 ± 0.26^{efg}	76.84 ± 0.59^{bc}	20.51 ± 0.07^{i}
NTS1	1225.94 ± 87.06^{fgh}	28.39 ± 0.45^{e}	65.94 ± 0.75^{d}	-4.27 ± 0.16^{bc}	25.00 ± 0.78^{g}	80.30 ± 0.07^{de}	3.99 ± 0.45^{cd}
NTS3	1422.95 ± 105.68^{e}	26.92 ± 0.75^{d}	60.50 ± 0.68^{b}	-3.30 ± 0.35^{e}	24.81 ± 0.12^{fg}	82.43 ± 0.76^{f}	3.16 ± 0.48^{bc}
NTS5	919.63 ± 81.81^{i}	31.31 ± 0.07^{gh}	66.71 ± 0.04^{d}	-3.48 ± 0.23^{de}	22.77 ± 0.35^{de}	81.30 ± 0.64^{ef}	4.08 ± 0.01^{cd}
NWS1	719.74 ± 19.85^{j}	31.15 ± 0.46^{g}	70.40 ± 0.15^{e}	-4.14 ± 0.17^{bc}	13.14 ± 0.40^{a}	72.49 ± 0.96^{a}	12.36 ± 0.30^{f}
NWS3	1056.39 ± 2.73^{hi}	29.07 ± 0.06^{ef}	61.66 ± 1.08^{bc}	-3.73 ± 0.13^{bcde}	23.70 ± 0.49^{efg}	81.06 ± 0.39^{ef}	1.76 ± 0.25^{a}
NWS5	1373.25 ± 93.71^{ef}	25.86 ± 0.57^{d}	57.88 ± 0.56^{a}	-4.28 ± 0.35^{bc}	21.58 ± 1.10^{d}	78.78 ± 0.71^{cd}	5.06 ± 0.58^{de}
MCS5	370.81 ± 21.65^{k}	37.06 ± 0.75^{j}	76.95 ± 0.32^{f}	-5.43 ± 0.23^{a}	18.68 ± 0.71^{c}	73.79 ± 0.56	14.88 ± 0.43^{g}
MTS5	2280.01 ± 91.01^{c}	24.40 ± 1.12^{c}	66.88 ± 0.44^{d}	-4.37 ± 0.27^{b}	18.21 ± 0.34^{c}	76.49 ± 0.99^{b}	6.22 ± 0.18^{e}
MWS1	1270.73 ± 98.62^{efg}	30.27 ± 0.11^{fg}	77.20 ± 0.65^{f}	-5.54 ± 0.28^{a}	17.38 ± 0.30^{bc}	72.31 ± 0.79^{a}	15.53 ± 0.70^{g}

Different letters in the same column indicate differences significant at $p < 0.05$. Mean ± standard deviation is computed from four replicates.
RAW = non-blanched dried celery; CON = water blanched dried celery; NTS1, NTS3, NTS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native tapioca starch, respectively; NCS1, NCS3, NCS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native corn starch, respectively; NWS1, NWS3, NWS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native wheat starch, respectively; MTS5 = samples pre-treated at 0.5 %w/w solutions of modified tapioca starch; MCS5 = samples pre-treated at 0.5 %w/w solutions of modified corn starch; MWS1 = samples pre-treated at 0.1 %w/w solutions of modified wheat starch.

difference between our and their results was related to the pretreatment condition i.e. they coated the samples in the starch solution at room temperature for 1 min before drying, while we coated the samples in the starch solutions at 95 °C for 10 min. Blanching in high temperatures caused a loss in the integrity of the cell wall and a decrease in the hardness of samples. Furthermore, using calcium gluconate salt by Islam et al. (2019) was another reason to increase the hardness of their sample.

3.7.2. *Color*

Generally, various pre-treatment processing is widely used before drying to preserve the color such as thermal blanching (Deng et al., 2019), ultrasound, and pulsed electric field (Llavata, Garcıa-Perez, Simal, & Carcel, 2020). The color parameters of the dried celery root chips are detailed in Table 5. According to L* values, significant differences ($p < 0.05$) were observed between control and all other samples excepting the NWS3 sample. The results revealed that the brightness of NCS1, NTS3, and NWS3 was less than that of the control samples, while the maximum lightness belonged to the NCS3 samples. Besides, NCS5 showed a higher level of lightness compared with MCS5, meaning that blanching the celery root samples in 0.3% and 0.5% native corn starch solutions could significantly improve the lightness of the samples. The highest *a** value was found in the NTS3 samples. However, an increase

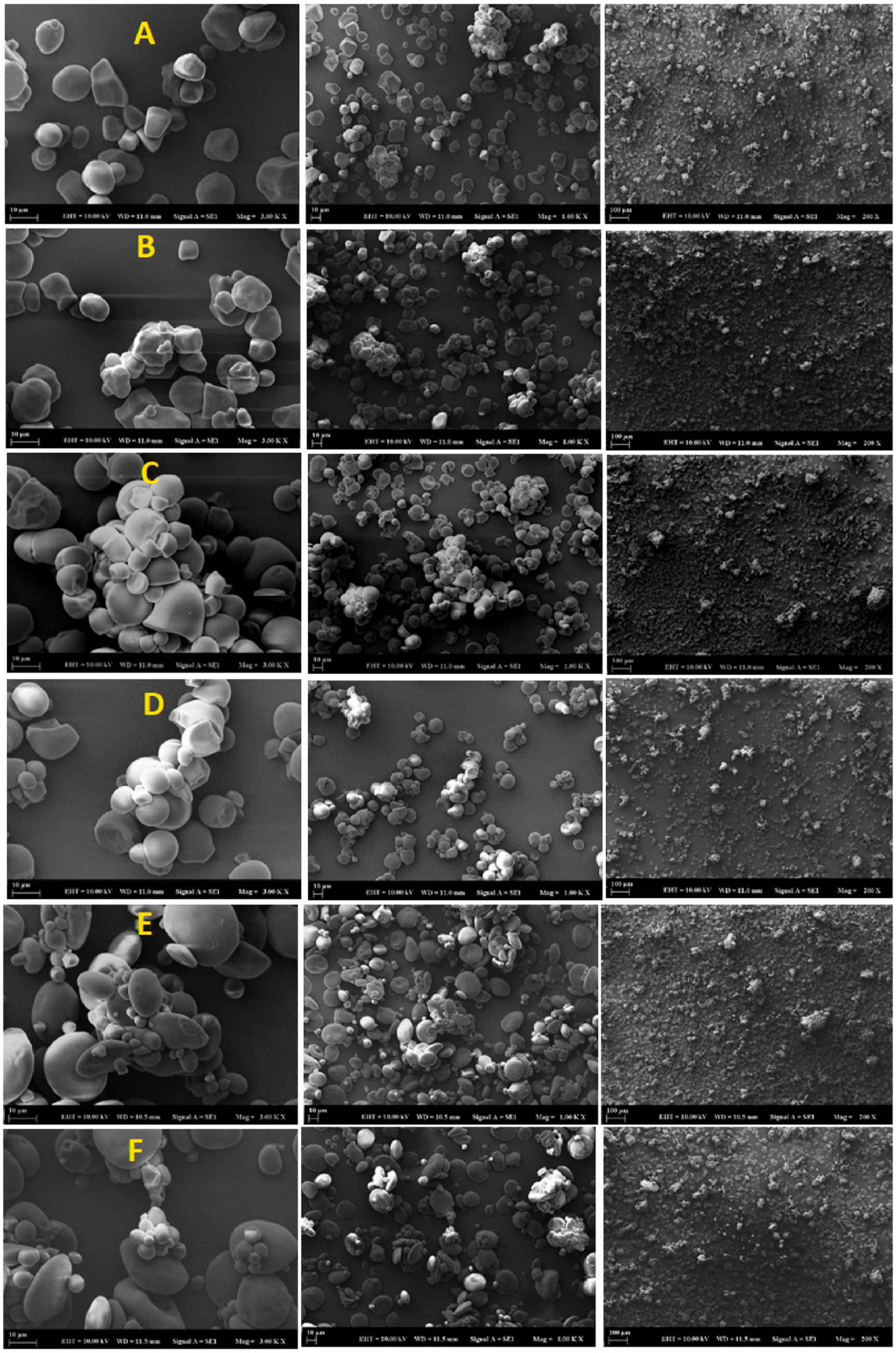

Fig. 6. SEM images of native and modified starch granules: A) native corn, B) modified corn, C) native tapioca, D) modified tapioca, E) native wheat, and F) modified wheat.

in *a** value (redness) maybe represent the higher amount of browning in the NTS3 samples (Sakooei-Vayghan, 2020). In contrast, there were no significant differences ($p > 0.05$) among *a* * values of NCS3, NCS5, MCS5, and MWS1 samples with the dried raw celery root (RAW), meaning that the green color was dominant in these samples and good similarities between these samples and RAW samples were observed.

There were no significant differences ($p > 0.05$) in *b** values between NTS5, NCS1, NCS5, NWS3, and NWS5 samples and the control samples. While the NTS1 and NCS3 samples with the maximum and minimum yellowness, respectively, showed significant differences ($p < 0.05$) in *b** values in comparison with CON. In comparison with the dried water-blanched sample (CON), the maximum total color difference was observed in the samples blanched in 0.3%w/w naive corn starch (NCS3). In contrast, the samples blanched in 0.3%w/w naive wheat starch (NWS3) showed the least ΔE value. However, inconsistent with the results, the NCS3 samples with ΔE of 23.44, and MCS5 (modified corn starch) samples with ΔE of 14.88 had the best color in comparison with other samples (Table 5). Starch type and concentration affected the color properties of celery root chips at different levels. Our results revealed that coating-blanching improved the color properties of the samples compared to the water-blanched ones. Riva, Campolongo, Leva, Maestrelli, and Torreggiani (2005) demonstrated that the pre-treatment of apricots in sorbitol solution protected the samples from color changes and improved color characteristics of samples. Garcia, Caetano, Silva, and Mauro (2014) also reported that the pre-treatment of papaya in the pectin solution before drying improved the color properties of samples. Sakooei-Vayghan, Peighambardoust, Hesari, and Peressini (2020) reported the improvement of color properties of apricot as a result of pre-treatment in osmotic and pectin solutions. Our results confirmed that coating-blanching pre-treatment at starch solutions could significantly improve drying characteristics, color and texture of celery root chips.

3.7.3. *Microstructure evaluation*

SEM images are shown in Fig. 6. The native corn starch granules (NCSG) had irregular polyhedral shapes with 7–25 μm diameter and relatively smooth surfaces with some pits and without any evidence of pores or fissures (Fig. 6A) (Zhao et al., 2018; Balet et al., 2019). However, after DHT treatment, both morphology and the surface of starch changed. The granules showed a slight expansion with a rough surface (Fig. 6B). In addition, DHT caused granules to adhere to each other and the structure appeared to be more compact compared to NCSG. These phenomena could be attributed to the rupture or collapse due to high temperature, accelerating the leaching of amylose from granules. The leached amylose produced a network surrounded by the starch granules, causing adhesiveness on the surface and forming a more compact microstructure. Similar results were reported about the effect of DHT on the microstructure of sweet potato starch by Zhang et al. (2020).

Native tapioca starch granules (NTSG) showed a spherical shape with 10–25 μm diameter and relatively smooth surfaces (Fig. 6C) (Javadian, Nafchi, & Bolandi, 2021), adhering to each other and producing a large lump microstructure. However, the modified starches showed less compaction compared with the native starch and DHT treatment decreased the size of the lumped granules (Fig. 6D). The size of native wheat starch granules (NWSG) was not homogeneous, consisting of flat-oval large lenticular polyhedral shape with the 20–30 μm diameter and small granules with spherical shapes of 2–8 μm diameter (Fig. 6E) (Balet et al., 2019; Kang et al., 2021). Besides, the small and large granules adhered to each other and formed a large lump microstructure in the umbilical point. The umbilical point of starch is referred to as the point in which starch granules start to grow (Liu, Hao, Chen, & Gao, 2019). However, after the DHT (Fig. 6F), many small lumps were formed with less compaction compared with NWSG, probably related to the damage of the umbilical point during the modification by dry heat treatment (Liu et al., 2019; Kang et al., 2021). Similar results about the effect of DHT on the decrease in the size of rice starch granules were reported by Qiu et al. (2015). The change in the microstructure and geometrical shape of corn starch after DHT was more obvious than those of tapioca and wheat starches. The increase in the number of the sharp edge of corn starch granules made the facility for leaching amylose from these points. The sharp edges of granules were more sensitive against the high temperature of DHT than the smooth and round edges (tapioca and wheat starch); thus, the damage of sharp edges during DHT helped to leach more amylose from corn starch granules (Fig. 1B). The impact of the sharp edge of triangle samples on the kinetics drying of apples was shown by Kian-Pour and Karatas (2019). Accordingly, leached amylose produced a network around the granules leading to an increase in the compact microstructure of MCS5 (Fig. 6B). However, to deeply understand the effects of DHT on the different starches, more investigation needs to be done on the crystalline structure, amylose and amylopectin content, solubility, thermal parameters, and swelling power of starches.

The SEM image of dried celery root chips is shown in Fig. 7. The image of the RAW samples presented the heterogeneous honeycomb microstructures with large and irregular pores. However, the control demonstrated a denser structure in comparison with RAW. Besides, the microstructure of all dried celery roots pre-treated with starches was characterized by cell shrinkage and a compact structure. The cell parenchyma microstructure was partially destroyed in the CON, NTS3, and NWS3, while fully destroyed in other samples. The NTS5, NCS5, and MCS5 samples had more severe damage and denser microstructure than other samples. Generally, shrinkage, deformation, and collapse of the cell during drying are related to the loss of cell turgor pressure (Fig. 7) (Vega-Gálvez et al., 2012).

Monteiro, Link, Tribuzi, Carciofi, and Laurindo (2018) reported that the HAD of pumpkin slices caused shrinkage in the products and formed a compact microstructure. Drying at a high temperature could increase the evaporation rate of water from the sample, leading to higher shrinkage and a more compact layer near the celery root surface (Yao, Fan, & Duan, 2020). This suggested that blanching the samples in the native tapioca, native corn, and modified corn starch solutions (NTS5, NCS5, MCS5) favored a compact microstructure, aiding the drying process via increasing the Deff and decreasing the drying time. Furthermore, Kian-Pour and Karatas (2019) proved that the apple samples with triangle shape had more shrinkage compared with circle and square-shaped samples during HAD. Therefore, the high shrinkage of celery root caused a decrease in the dimension of the samples. The shrinkage started from the sample surface and moved towards the center of chips (Golestani, Raisi, & Aroujalian, 2013). Accordingly, shrinkage generated the internal pressures inside the sample and facilitated moisture transport from the interior to the surface, increasing the drying rate (Mujumdar, 2006). Another reason might be related to the network produced by leached amylose from starch granules. Besides, the geometric shape of the modified corn starch might facilitate leaching amylose from granules. The high amount of amylose produced a more compact microstructure (Feltre, Almeida, Sato, & Dacanal, 2020).

4. Conclusion

In this study, coating-blanching pre-treatments with native and modified corn, tapioca, and wheat starch solutions were selected before hot air drying for improving the drying characteristics and quality properties of dried celery roots. The effects of coating-blanching pre-treatments in all native and modified starch solutions were significant on the drying times, diffusion coefficients, microstructure, and quality parameters of samples compared with control samples. The coating-blanching pre-treatments due to the affinity of starch for swelling and absorbing water from the sample, made the moisture removal easier during the hot air drying and significantly decreased the drying time. Among the native starches, corn starch showed the maximum diffusion coefficient and the minimum drying time. The modification of tapioca and wheat starches by dry heat treatment did not significantly improve the drying characteristics of samples compared with native wheat and

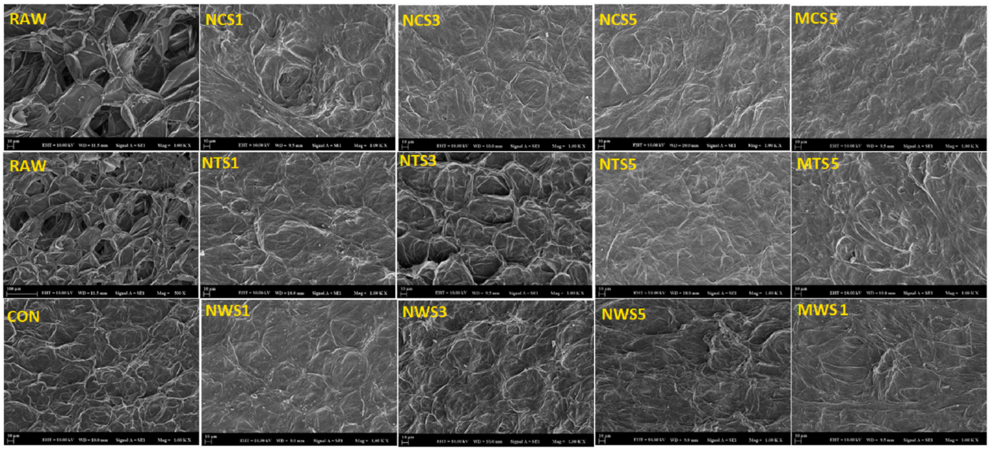

Fig. 7. SEM images of dried celery root chips pre-treated with different starches. RAW = non-blanched dried celery; CON = water blanched dried celery; NTS1, NTS3, NTS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native tapioca starch, respectively; NCS1, NCS3, NCS5 = samples pre-treated at 0.1, 0.3%, and 0.5 % w/w solutions of native corn starch, respectively; NWS1, NWS3, NWS5 = samples pre-treated at 0.1, 0.3%, and 0.5 %w/w solutions of native wheat starch, respectively; MTS5 = samples pre-treated at 0.5 %w/w solutions of modified tapioca starch; MCS5 = samples pre-treated at 0.5 %w/w solutions of modified corn starch; MWS1 = samples pre-treated at 0.1 %w/w solutions of modified wheat starch.

tapioca starch. This was related to the decrease in the starch viscosity after modification. In contrast, the modified corn starch showed the highest Deff and lowest drying time between all starch owing to its higher viscosity. It was determined that coating-blanching pre-treatments enhanced the texture and color quality of samples in comparison with control samples. Furthermore, it was detected that the pre-treatment process significantly changed the microstructure of samples from large and irregular porous to compact microstructure without any pore. The coating-blanching pre-treatment was suggested as an alternative technique to reduce the drying time, improve the drying kinetics, quality parameters, and microstructure of celery root chips. In our study, we improved the drying characteristics and quality of dried celery without the need to change the dryer, helping the existing hot air-drying industry. According to the simplicity of methods, ingredients, and conditions, our results have the potential to apply to an industrial extent to overcome the disadvantage of long drying time.

CRediT authorship contribution statement

Nasim Kian-Pour: Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Esra Akdeniz:** Data curation, Formal analysis. **Omer Said Toker:** Writing – original draft, Writing – review & editing.

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