Effect of Maltodextrin Addition during Spray Drying of Tomato Pulp in Dehumidified Air: II. Powder Properties

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Effect of Maltodextrin Addition during Spray Drying of Tomato Pulp in Dehumidified Air: II. Powder Properties

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This work investigates the effect of maltodextrin addition on the main powder properties during spray drying of tomato pulp in dehumidified air. A pilot-scale spray dryer was employed for the spray-drying process. The modification made to the original design consisted in connecting the spray dryer inlet air intake to an absorption dryer. 21 DE, 12 DE, and 6 DE maltodextrins were used as drying agents. Tomato pulp was spray dried at inlet air temperatures of 130, 140, and 150 °C and (tomato pulp solids)/(maltodextrin solids) ratios of 4.00, 1.00, and 0.25. The tomato powders were analyzed for rheological properties, moisture content, bulk density, solubility, hygroscopicity, and degree of caking. It was found that maltodextrin addition improved powder hygroscopicity, caking, and solubility, whereas it deteriorated slightly its moisture content and density. In addition, analysis of experimental data yielded correlations between powder properties and the above-mentioned variable operating conditions. Regression analysis was used to fit a full second-order polynomial, reduced second-order polynomials, and linear models to the data of each of the properties evaluated. F values for all reduced and linear models with an $R^2 \geq 0.70$ were calculated to determine if the models could be used in place of full second-order polynomials.

Keywords: Bulk density; Hygroscopicity; Moisture content; Solubility; Spray dryer; Tomato powder

INTRODUCTION

Spray drying is the transformation of feed from a fluid state into a dried product by spraying the feed into a hot drying medium. The resulting dried product conforms to powder, granules, or agglomerates, the form of which depends upon the physical and chemical properties of the feed and the dryer design and operation. The design of a spray-drying process includes establishment of the operating conditions that increase product recovery and produce an end product of a precise quality specification.

Product recovery is mainly determined by powder collection efficiency. Material loss in a spray-drying system is due mostly to the attachment of sprayed droplets and dry powder to the wall of the dryer. The adherence of powder to the drying chamber walls is a commonly recognized effect in spray drying of solutions containing sugars, such as fruit juices and tomato products.[1] During spray drying of such products, initially the droplets are dispersed individually in a large volume of the dryer, avoiding agglomeration although the high moisture content particles are sticky. Toward the lower parts of the dryer or in the recirculation zones, the particles are already solid and should not stick together or agglomerate. However, due to the presence of high sugar content, the surface of the droplets may remain plastic because of the high product temperature, which is generally approaching the outlet air temperature. The extent of stickiness or the consequence on structural change of the powder depends on the difference between the temperature of the product and the glass transition temperature ($T_g$). It can be assumed that the temperature of the particle surface during drying should not reach 10–20°C above $T_g$. [2] Various ways of coping with such sticky products have been researched for many years.[3] Additives, such as maltodextrins, have been used to reduce the stickiness and wall deposition in spray drying of various sugar-rich foods such as orange;[4] tamarind;[5] blackcurrant, raspberry, and apricot juice;[6] honey;[6] mango pulp;[7] raisin juice;[8] lime juice;[9] watermelon pulp;[10] and sweet potato puree.[11]

The process of spray drying has been investigated extensively. However, there have been no systematic studies on prediction of the physical properties of a spray-dried product.[12] According to Huntington,[13] powder properties are a function of formulation, slurry, atomization, drying air, and tower geometry and most of them are not single variables but influence the others. In the literature, there are studies dedicated to the effect of feed properties and drying conditions on physical properties of powders like moisture content,[14–18] bulk density,[17–22] hygroscopicity,[15,17,23] solubility,[17–19,23] flow behavior,[24] and degree of caking,[7] but the available results are sometimes ambiguous.
Generally, in a spray-drying system, the moisture content is controlled by the temperature of the exhaust air leaving the drying chamber. The humidity of the air may also be a factor. High ambient air humidity may require an increase in outlet air temperature in order to maintain the desired powder moisture content. The residual moisture in the powder influences many other powder properties such as bulk density, hygroscopicity, solubility, and flow behavior. Bulk density is also affected by particle size and density, occluded and interstitial air content, which are related to the feed properties, drying air temperature, drying time, and powder-handling procedures; e.g., crushing and grinding. Al-Kahtani and Hassan studied the effects of spray dryer operating variables on the main properties of Roselle powder and concluded that the moisture content, the solubility, and the bulk density decreased with an increase in drying temperature. Nath and Satpathy developed a systematic approach for investigation of spray-drying processes for chemical and biological systems and found that spray-drying experiments carried out at the lower inlet drying temperature of 140°C yield superior powder properties (moisture content, bulk density, solubility, hygroscopicity) for the examined salt-polymer systems. Papadakis et al. spray dried raisin extract concentrate and found that the solubility and hygroscopicity of the powder increased with decreases of its moisture content. Walton and Mumford studied the effects of process variables upon some properties of spray-dried powders. Their results demonstrated that while the bulk density of some materials decreased with an increase in drying air temperature, it increased for others even though they were spray dried under identical conditions. As far as the addition of maltodextrin is concerned, the hygroscopicity and the degree of caking of mango powder were found to decrease with an increase in the amount of used maltodextrin, the bulk density of orange juice/maltodextrin powders decreased with increasing maltodextrin concentration, and higher maltodextrin concentrations decreased the viscosity of reconstituted sweet potato powder. Quek et al. produced watermelon powder using different maltodextrin concentrations, concluded that the moisture content of the powder decreased when the maltodextrin added increased, whereas Adhikari et al. studied the effect of addition of maltodextrin on drying kinetics and stickiness of sugar and acid-rich foods during convective drying, mentioned that the addition of maltodextrin lowers the drying rate, since it is difficult for water molecules to diffuse past the larger maltodextrin molecules. In addition, Quek et al. found a positive relationship between dissolution and moisture content of watermelon/maltodextrin powders. Cano-Chauca et al. studied the effect of various carriers on the functional properties of spray-dried mango powder and concluded that powder solubility increases in function of maltodextrin concentration.

In Part I of the study, a new technique for spray drying tomato concentrate using dehumidified air as drying medium and maltodextrin as drying agent was developed. Maltodextrins were found to alter the surface stickiness of tomato droplets and make it possible to enter the safe drying regime sooner. The achieved values of product recovery (80-90%) were much higher than those reported by other researchers, who added maltodextrins to sugar-rich foods to reduce wall deposition problems, although they used similar operating conditions and maltodextrin contents. This difference was attributed to the lower outlet air temperatures and higher drying rates when dehumidified air is used as the drying medium instead of undehumidified air. Thus, the combination of maltodextrin addition and use of dehumidified air as drying medium may be the solution of the wall depositions problem during spray drying of tomato pulp.

However, when designing a spray-drying process, required powder properties are a significant consideration. The effect of process variables and feed properties upon powder properties is difficult to assess in general terms. This is due to the lack of information within the literature and to the specific drying nature of most materials. Thus, the objective of this work was to investigate the effect of maltodextrin type and concentration during spray drying of tomato pulp in dehumidified air under various drying temperatures on the main powder properties.

MATERIALS AND METHODS
Production of Tomato Powders
Tomato powders were prepared as described in Part I of this study. A modified laboratory spray dryer, again described in Part I, was employed for the spray-drying process. Twenty-seven different experiments were conducted in triplicate. The controlled parameters were the dextrose equivalent of the maltodextrin (DE), the (tomato pulp solids)/(maltodextrin solids) ratio (t:m), and the inlet air temperature (T). 21 DE, 12 DE, and 6 DE maltodextrins were used as drying agents. Tomato pulp was spray dried at inlet air temperatures of 130, 140, and 150°C (±1°C) and (tomato pulp solids)/(maltodextrin solids) ratios of 4.00, 1.00, and 0.25. In all experiments the atomizer pressure, the feed rate, the feed solids concentration, the feed temperature, the drying air flow rate, and the compressed air flow rate were kept at 5.0 ± 0.1 bar, 1.75 ± 0.05 g/min, 14.00 ± 0.05%, 32.0 ± 0.5°C, 22.75 ± 0.18 m³/h, and 800 ± 20 L/h, respectively.

Analysis of Powders
- Rheological testing: Powder samples were reconstituted to the same solids content as the spray dryer feed (14.00 ± 0.05%). The reconstituted...
solutions were well mixed before conducting the rheological tests and therefore the observed settling rate was very low. Rheological properties measurements of tomato pulp feed and reconstituted solution were conducted using a Brookfield viscometer (LVDV-II +, Brookfield Engineering Laboratories, Inc., Stoughton, Massachusetts). The shear rate, $\gamma$, was varied between 2.2 and 220.0 s$^{-1}$. The flow curves were analyzed using the Bingham model:

$$\tau = \tau_B + n_B \cdot \gamma$$

(1)

where $\tau$ is the shear stress in Pa, $\tau_B$ is the yield stress in Pa, and $n_B$ is the Bingham viscosity in Pa s.

To study the effect of temperature on the rheological properties, the shear rate sweeps were performed on the samples at 25, 35, 50, and 60°C. The viscometer temperature was controlled using an Edmund Buhler thermostatic circulating water bath (Model 7400, Edmund Buhler GmbH & Co., Tuebingen, Germany) and the samples were maintained at rest for 5 min in the viscometer to equilibrate at the set temperature before the shear rate sweeps were performed.

- Moisture: The moisture content was determined by drying at 70°C up to constant weight and expressed in terms of the percentage wet basis (w.b.) (100 x kg water/kg wet material).
- Bulk density: 2 g of powder were transferred to a 50-mL graduated cylinder. The bulk density was calculated by dividing the mass of the powder by the volume occupied in the cylinder.\[17,18\]
- Solubility: The solubility of the spray-dried powder was carried out by adding 2 g of the material to 50 mL of distilled water at 26°C. The mixture was agitated in a 100-mL low form glass beaker with a Heidolph magnetic stirrer (No 50382, MR 82, Heidolph Instruments GmbH & Co. KG, Schwabach, Germany) at 892 rpm, using a stirring bar with a size of 2 mm x 7 mm. The time required for the material to dissolve completely was recorded.\[17,18,29\]
- Hygroscopicity: About 1 g of powder was spread evenly on Petri dishes (9 cm diameter) to allow for a high surface area between humid air and powder. Samples of each powder in the dishes were placed in a desiccator under the following conditions: 23°C and 76% relative humidity using HNO$_3$ solution. A 10-min interval was selected to get the kinetics of moisture sorption. The gain in weight of the samples was considerably lower after 90 min. Although hygroscopicity is based on the equilibrium moisture content, to compare hygroscopicities, the weight increase per gram of powder solids after being subjected to the atmosphere with relative humidity of 76% for 90 min was determined.\[17,19\]

- Degree of caking: After the determination of hygroscopicity, the wet sample was placed in a drying oven at 70°C. After cooling, the dried sample was weighed and transferred into a sieve of 500 μm size. The sieve was then shaken for 5 min in a shaking apparatus. The weight of the powder remaining in the sieve was measured. The degree of caking was calculated as:\[7\]

$$CD = \frac{100 \cdot a}{b}$$

(2)

where $CD$ is the degree of caking (%), $a$ is the amount of the powder used in sieving, and $b$ is the amount of the powder remained on the sieve after sieving.

All analyses were done in triplicate and the averages of these triplicate measurements were recorded. Additional determinations were carried out if the single values from the triplicates deviated by more than ±1.5% from the triplicate mean.

### Statistical Analysis

The data were analyzed using the statistical software MINITAB (Release 13.32). Regression analysis was used to fit full second-order polynomials, reduced second-order polynomials containing the three linear terms, and linear models to the data of each of the variables evaluated (response variables). $F$ values for all reduced and linear models with a coefficient of determination ($R^2$) greater than 0.70 were calculated to determine whether the models could be used in place of full second-order polynomials to predict the response of a variable to dextrose equivalent of maltodextrin, (tomato pulp solids)/(maltodextrin solids) ratio, and inlet air temperature (independent variables). The best fitting models were determined on the basis of a high $R^2$, a low square root of mean square error (S), and a Mallows’ $C$ statistic close to the number of predictors contained in the model. The statistical analysis is described analytically in Part I of the study.

### RESULTS AND DISCUSSION

#### Rheological Properties

Figure 1 shows the flow curves of the tomato pulp with a (tomato pulp solids)/(6 DE maltodextrin solids) ratio of 4 at 25, 35, 50, and 60°C. As it can be seen, the pulp shows a non-Newtonian behavior, which can be attributed to the presence of high-molecular-weight materials such as pectins. According to Sharma et al.,\[30\] pectin, cellulose, and...
polysaccharides, a mixture of arabans, galactans, and xylans, are the major factors that affect the viscosity of tomato pulp. The pulp requires a certain amount of yield stress before flow can begin. This suggests that the pulp has a coherent network structure, which requires a certain amount of force to rupture it before flow can occur. The Bingham model, shown by solid lines in Fig. 1, fits the data well. Other rheological models, such as the power law model, were tested but did not adequately fit the flow curves. Abu-Jdayil et al.\cite{28} also reported that the flow behavior of tomato pulp is best described by the Bingham model, whereas Sharma et al.\cite{30} concluded that both the Herschel-Bulkley and Casson models contain yield stress terms and, hence, can be used to calculate yield stress of tomato paste from experimental data.

Figure 1 also provides the flow curve of the tomato pulp at 25°C in the backward direction. As it can be concluded, the pulp is shear thinning and displays slight thixotropy. Vercet et al.\cite{31} also found that tomato paste exhibits a thixotropic behavior. Abu-Jdayil et al.,\cite{28} who studied the flow curves and time-dependent flow properties of tomato paste at various concentrations and temperatures, mentioned that tomato pulp shows a thixotropic behavior at low shear rates \(<28.38 \text{ s}^{-1}\), whereas at higher values of shear rate the paste behaves like an anti-thixotropic material. However, this behavior was observed for pastes with high solids contents \((>13.36\%\)). Similar results were reported by De Kee et al.\cite{32}

The flow curves of all tomato pulp samples reflected Bingham behavior. Table 1 summarizes the model parameters for the measurements in the forward direction at 25°C. The calculated values of yield stress are comparable to those reported by other researchers for tomato paste. Abu-Jdayil et al.\cite{28} reported a \(\tau_B\) value of 13.8 Pa for tomato pulp with a total solids concentration of 13.36%. Sharma et al.\cite{30} obtained yield stress values between 13.5 and 28.1 Pa for thin pulps with a solids concentration varying from 4.66 to 7.66% and mentioned that the yield stress increases when the total solids increase. Thus, according to them, the \(\tau_B\) at a solids concentration of 14%, which the samples used in this work have, would be much higher than the calculated value of 18.37 Pa. This variation may be due to the higher insoluble solids concentration of the samples.

### TABLE 1

<table>
<thead>
<tr>
<th>DE of the maltodextrin, DE</th>
<th>(Tomato pulp solids)/(maltodextrin solids) ratio, (tm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4:1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Yield stress, (\tau_B) (Pa)</th>
<th>6</th>
<th>12</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17.97</td>
<td>17.61</td>
<td>17.27</td>
</tr>
<tr>
<td>Without maltodextrin</td>
<td>18.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bingham viscosity, (n_B) (Pa s)</td>
<td>0.141</td>
<td>0.139</td>
<td>0.137</td>
</tr>
<tr>
<td></td>
<td>0.133</td>
<td>0.131</td>
<td>0.129</td>
</tr>
<tr>
<td>Without maltodextrin</td>
<td>0.147</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
used in the work of Sharma et al.\textsuperscript{[30]} According to Mizrahi and Berk,\textsuperscript{[33]} an increase in concentration of insoluble solids increases the yield stress value by interacting with the soluble pectins in the solution structure.

As it can be seen in Table 1, the yield stress and the Bingham viscosity decrease with increase in maltodextrin concentration. This effect may be attributed to the interactions between the maltodextrin and the other polysaccharides, which do not allow these polysaccharides to fully extend in solution. According to Grabowski et al.,\textsuperscript{[24]} who studied the rheological properties of spray-dried sweet potato-maltodextrin powders, a maltodextrin-polysaccharide interaction facilitates a decreased solution viscosity, since longer molecules have a larger hydrodynamic volume, which increases solution viscosity. As regards the dextrose equivalent of maltodextrin, the lower the DE, the higher the yield stress and the Bingham viscosity of the pulp. This is due to the fact that the maltodextrin with the lower DE is composed of longer chain molecules, which create a greater mass transfer resistance. Werner et al.,\textsuperscript{[34]} who used a probe tack test to map the molecules, which create a greater mass transfer resistance.

This effect, which was observed for all tomato pulp samples, is due to changes in pectins and other long-chain carbohydrate polymers that are degraded by the heat, resulting in smaller molecules, which affect the colloidal properties of the pulp. The temperature dependence of the yield stress and the Bingham viscosity can be expressed by the equations:

\begin{equation}
\tau_B = A \cdot e^{B T} \quad (3)
\end{equation}

\begin{equation}
n_B = C \cdot e^{D T} \quad (4)
\end{equation}

where \( T \) is the temperature in K and \( A, B, C, \) and \( D \) are coefficients. Multiple regression analysis was used to develop equations predicting the effect of maltodextrin addition on the coefficients \( A, B, C, \) and \( D. \)

\begin{equation}
A = 101 + 4.76 \cdot DE - 50.5 \cdot (t:m) + 0.0278 \cdot DE^2 \\
+ 5.12 \cdot (t:m)^2 + 0.676 \cdot DE \cdot (t:m); \quad (R^2 = 0.96)
\end{equation}

\begin{equation}
B = -65.6 \cdot 10^{-4} - 9.2 \cdot 10^{-5} \cdot DE + 75.1 \cdot 10^{-5} \cdot (t:m) \\
- 8.0 \cdot 10^{-6} \cdot DE \cdot (t:m); \quad (R^2 = 0.96)
\end{equation}

\begin{equation}
C = 0.165 + 22.6 \cdot 10^{-4} \cdot DE - 42.1 \cdot 10^{-3} \cdot (t:m) \\
+ 37.5 \cdot 10^{-3} \cdot DE \cdot (t:m) + 7.1 \cdot 10^{-3} \cdot (t:m^2); \quad (R^2 = 0.96)
\end{equation}

\begin{equation}
D = -90.7 \cdot 10^{-5} - 5.4 \cdot 10^{-5} \cdot DE \\
+ 11.3 \cdot 10^{-4} \cdot (t:m) - 7.0 \cdot 10^{-6} \cdot DE \cdot (t:m) \\
- 18.7 \cdot 10^{-5} \cdot (t:m)^2; \quad (R^2 = 0.98)
\end{equation}

Shear rate ramps were performed at 25, 35, 50, and 60°C to investigate shear and temperature effects on the shear stress of all the spray-dried powders reconstituted to the same solids concentration as the original tomato pulp. Figure 2 shows the flow curves of the tomato powder produced with an air inlet temperature of 130°C and a (tomato pulp solids)/(6 DE maltodextrin solids) ratio of 4 at 25, 35, 50, and 60°C, whereas Figs. 3 and 4 present the effect of the process variables DE of the maltodextrin (DE), (tomato pulp solids)/(maltodextrin solids) ratio (\( t:m \)), and inlet air temperature (\( T \)) on the yield stress and the Bingham viscosity of the tomato powders at 25°C.

All the powders show a non-Newtonian behavior and the Bingham model was used to fit the relationship between shear stress and shear rate. On the contrary, Grabowski et al.,\textsuperscript{[24]} who studied the rheological properties of spray-dried sweet potato-maltodextrin powders, mentioned that the powders did not have a yield stress, fit the power law model, and have high, nearing Newtonian, flow behavior.
indexes, while the puree shows pseudoplastic behavior with a yield stress. However, Abu-Jdayil et al.\textsuperscript{[28]} who studied the flow curves of tomato powders at various concentrations, concluded that a Newtonian behavior is observed only at low solids concentration ($\sim 5.6\%$). In addition, the flow curves of all the spray-dried powders display slight thixotropy. Abu-Jdayil et al.\textsuperscript{[28]} reported an antithixotropic behavior of tomato-reconstituted solutions. However, this behavior was observed for solutions with high ($>25\%$) or low ($<7\%$) solids concentration.

The solids concentration in the pulps and reconstituted solutions was the same ($14.00 \pm 0.05\%$); however, at all temperatures, the powders have lower yield stress and Bingham viscosity than the corresponding pulps. This difference can be attributed to the fact that during spray drying, heat alters the structure of pectins and other long-chain carbohydrate polymers by means of hydrolysis. Similarly, Grabowski et al.\textsuperscript{[24]} reported that during spray drying of sweet potato puree, starch molecules are degraded, losing the ability to swell. Colloidal properties then may be altered, resulting in lower apparent viscosity of the reconstituted concentrates. In addition, according to Harper and El Sahrigi,\textsuperscript{[35]} large differences in particle size between dried powder and feed paste, which has suspended particles in colloidal serum, can account for differences in yield stress and viscosity. Sharma et al.\textsuperscript{[30]} also mentioned that yield stress of tomato juice decreases with decreases in particle size. In this study, while the particle size of the reconstituted tomato powders ranges between 19 and 55 $\mu$m, the tomato pulp consists of suspended particles above 140 $\mu$m in size.

The viscosity of all tomato powder samples decreases with increasing temperature. This observation is similar to that obtained by other researchers for various foodstuffs powders.\textsuperscript{[31,33,35]} However, the apparent viscosity of potato-amylase-maltodextrin powders increases as the temperature increases from 25 to 55°C.\textsuperscript{[24]} This variation may be due to the fact that during heating, the interaction between maltodextrin and polysaccharides present in potatoes is slightly disrupted, thus releasing these long-chain molecules into solution and slightly increasing viscosity. As in the case of tomato pulp, the temperature dependence of the yield stress and the Bingham viscosity can be expressed by the equations:

$$\tau_B = A' \cdot e^{B'T}$$

$$n_B = C' \cdot e^{D'T}$$

where $T$ is the temperature in K and $A'$, $B'$, $C'$, and $D'$ are coefficients. Multiple regression analysis was used to develop equations predicting the effect of maltodextrin addition on the coefficients $A'$, $B'$, $C'$, and $D'$.

$$A' = 7.17 + 26.9 \cdot 10^{-3} \cdot DE - 67.5 \cdot 10^{-2} \cdot (t:m) + 12.7 \cdot 10^{-2} \cdot (t:m)^2; \quad (R^2 = 0.99)$$

$$B' = -47.5 \cdot 10^{-4} - 1.8 \cdot 10^{-5} \cdot DE + 46.7 \cdot 10^{-5} \cdot (t:m) - 8.9 \cdot 10^{-5} \cdot (t:m)^2; \quad (R^2 = 0.97)$$

$$C' = 38.3 \cdot 10^{-3} + 14.3 \cdot 10^{-3} \cdot DE - 36.0 \cdot 10^{-4} \cdot (t:m) + 67.8 \cdot 10^{-5} \cdot (t:m)^2; \quad (R^2 = 0.99)$$

$$D' = -29.1 \cdot 10^{-4} - 1.0 \cdot 10^{-5} \cdot DE + 28.1 \cdot 10^{-5} \cdot (t:m) - 5.6 \cdot 10^{-5} \cdot (t:m)^2 + 0.1 \cdot 10^{-5} \cdot DE \cdot (t:m); \quad (R^2 = 0.96)$$

As regards the effect of the process variables, the higher the maltodextrin concentration, the lower the $\tau_B$ and the $n_B$ of the powder. This effect is due to the high values of maltodextrin solubility.\textsuperscript{[36]} With more of the spray-dried powder solubilized into solution, there are less tomato solids to create resistance to flow. In addition, the lower the DE, the higher the yield stress and the Bingham viscosity of the powder. As in the case of tomato pulp, this observation may be attributed to the fact that the higher the DE, the lower the maltodextrin glass transition profile is and, thus, the less viscous the mixture is.\textsuperscript{[34,37]} Finally, the yield stress and the Bingham viscosity decrease with increase in inlet temperature.
air temperature, as elevated temperatures weaken molecular interactions.

**Powder Moisture Content**

The moisture content of the tomato powders varied from 2.91 to 12.41% w.b. Figure 5 shows the achieved values against inlet air temperature and (tomato pulp solids)/(maltodextrin solids) ratio for different maltodextrin dextrose equivalents. Each data point in the figure represents the averaged values of three determinations. The repeatability for moisture content, expressed as the average standard deviation of the three determinations, was 0.07%.

As shown in Fig. 5, an increase in inlet air temperature leads to a decrease in moisture content. This observation is similar to that obtained by other researchers.[10,20] The greater the temperature difference between the drying medium and the particles, the greater will be the rate of heat transfer into the particles, which provides the driving force for moisture removal. When the drying medium is air, temperature plays a second important role. As water is driven from the particles in the form of water vapor, it must be carried away, or the moisture will create a saturated atmosphere at the particle surface. This will slow down the rate of subsequent water removal. The hotter the air, the more moisture it will hold before becoming saturated. Thus, high temperature air in the vicinity of the drying particles will take up the moisture being driven from the food to a greater extent than with cooler air.

Moisture content shows an increase with an increase in maltodextrin concentration. This can be attributed to the fact that it is difficult for water molecules to diffuse past the larger maltodextrin molecules. A similar observation was obtained by Adhikari et al.[26] who studied the effect of maltodextrin addition on drying kinetics and stickiness of sugar- and acid-rich foods during convective drying and concluded that the addition of maltodextrin lowers the drying rate. On the contrary, Quek et al.[10] reported that the moisture content of spray-dried watermelon powders decreased when the added maltodextrin increased. However, in that case, the addition of the drying additive increased the total solids content of the feed and reduced the amount of water for evaporation.

As it can be drawn from Fig. 5, the higher the maltodextrin dextrose equivalent, the higher the powder moisture content. According to Werner et al.[34] low-DE maltodextrins have slower drying rates. This was attributed to the fact that the lower the DE of a maltodextrin, the higher the glass transition profile is and the more viscous the mixture is for any given temperature and moisture content. This leads to a lower evaporation rate due to the higher resistance to mass transfer. In addition, Rodriguez-Hernandez et al.[38] who used maltodextrins as carrier agents during spray drying of cactus pear juice, reported that the lowest values of powder moisture content were obtained with the maltodextrin with the highest DE. According to them, the functional properties of maltodextrins depend on the polymerization degree, expressed as DE, and the lower the DE, the better binder agent the maltodextrin...
is. However, in this study, the higher the DE, the lower the drying rate. This observation may be explained by the fact that high-DE maltodextrins develop stickiness slower and reach a state of non-adhesion slower than low-DE maltodextrins.[26] The more sticky a material is, the lower its drying rate.[14]

**Powder Bulk Density**

Bulk density results, ranging from 0.091 to 0.271 g/mL, are given in Fig. 6. Data represent the average values of the three determinations. The repeatability for bulk density, expressed as the average standard deviation of the three determinations, was 0.005 g/mL.

Increased inlet air temperature causes a reduction in bulk density, as evaporation rates are faster and products dry to a more porous or fragmented structure. According to Walton,[22] increasing the drying air temperature generally produces a decrease in bulk and particle density, and there is a greater tendency for the particles to be hollow. The former can be caused by particle inflation-ballooning or puffing and is particularly common in skin-forming materials.

As shown in Fig. 6, an increase in maltodextrin concentration leads to a decrease in bulk density. This effect may be attributed to the fact that maltodextrin addition minimizes thermoplastic particles from sticking and the sticky or less free-flowing nature of a powder is associated with a high bulk density.[25] In a previous work,[18] it was reported that the stickier the tomato powder was, the lower its bulk density was. However, in that case, where the spray drying was conducted without drying additives, the drop remained sticky even when it was completely dry at the dryer exit, as described in Part I of this work, and, thus, the powder was in the form of agglomerates. The stickier the particles of an agglomerate-like powder are, the more interspaces are formed between them and the lower the powder bulk density is. In addition, the effect of maltodextrin on bulk density may be explained by the fact that an increase in maltodextrin concentration may cause an increase in the volume of air trapped in the particles, as maltodextrin is a skin-forming material. According to Kwapisz and Zbicinski,[12] particles of skin-forming spray-dried materials often contain air bubbles, which can occur as a result of desorption of air that was initially present in the liquid feed or was absorbed during atomization. Generally, an increase in the volume of trapped air causes a decrease in the apparent density of the particles and this apparent density primarily determines the powder bulk density.

In addition, higher maltodextrin dextrose equivalent causes an increase in powder bulk density due to its effect on powder stickiness. The higher the maltodextrin DE, the lower its glass transition temperature and, as a consequence, the lower the elevation of the $T_g$ of the tomato pulp-maltodextrin mixture is and the more stickier the mixture is.[26,34]

**Powder Solubility**

Figure 7 shows powder solubility in relation to inlet air temperature, (tomato pulp solids)/(maltodextrin solids) ratio, and maltodextrin dextrose equivalent. Solubility of the tomato powders varied from 119 to 213 s. The repeatability expressed as the average standard deviation of the three determinations was 5 s.

Solubility showed an increase with an increase in inlet air temperature and a decrease in maltodextrin dextrose equivalent. This is due to the effect of inlet air temperature and DE on residual moisture content. The lower the powder moisture content, the more soluble the powder.[18] In addition, increasing the drying air temperature generally produces an increase in particle size,[22] and so a decrease in time required for the powder to dissolve. According to Potter,[39] large particles may sink, whereas small ones are dustier and generally float on water, making for uneven wetting and reconstitution. In a previous work,[17] where tomato pulp was spray-dried in a standard spray dryer with dehumidified air as drying medium, it was found that the solubility of tomato powder shows a decrease with an increase in inlet air temperature due to the fact that the higher air temperature may have resulted in denaturing more protein and, hence, affected solubility. This variation may be due to the much lower air and, thus, droplet temperatures when using dehumidified air, which reduce
the extent of protein denaturation and, thus, its effect on powder solubility.

The relationship between dissolution and moisture content is in agreement with the conclusions of Quek et al.\[10\] However, increased maltodextrin concentration does not cause a reduction in powder solubility, although it increases its moisture content (Fig. 5). This variation may be attributed to the fact that maltodextrin has superior water solubility.\[24\] According to Cano-Chauca et al.,\[27\] maltodextrin is one carrier that is mainly used in the process of spray drying due to its physical properties, such as high solubility in water. Grabowski et al.\[11\] also reported that the water solubility index of sweet potato powder increases as the amount of maltodextrin increases.

**Powder Hygroscopicity and Degree of Caking**

Moisture adsorption of the spray-dried powders at 23°C and 76% relative humidity after 90 min is shown in Fig. 8. Data represent the average values of the three replications. The repeatability for hygroscopicity expressed as the average standard deviation of the three replications was 0.002 g/g of powder solids.

Generally, tomato powder is evidently hygroscopic. Spray-dried particles can easily absorb moisture from the surrounding air, and unless necessary precautions are taken, the surface of the powder becomes sticky and powder caking occurs. The hygroscopicity values presented in Fig. 8 are much lower than those obtained when tomato pulp was spray dried without drying additives and with undehumidified air as drying medium.\[17\] According to Roos,\[40\] physical changes in low-moisture, high-sugar dehydrated powdered foods, including hygroscopicity, are attributable to the glass transition temperature. Figure 9 presents the glass transition temperature of the spray-dried tomato powders, calculated as described in Part I of this work. As it can be seen comparing Figs. 8 and 9, the higher...
the powder $T_g$, the lower its hygroscopicity. Thus, the effect of the process variables inlet air temperature, (tomato pulp solids)/(maltodextrin solids) ratio, and maltodextrin dextrose equivalent on powder hygroscopicity depends on their effect on $T_g$. Powder hygroscopicity decreases with an increase in inlet air temperature and maltodextrin concentration and with a decrease in maltodextrin dextrose equivalent. Jaya and Das\cite{7} also reported that mango powder, and tomato soup powder being made of high-molecular-weight substances like starch, maltodextrin, corn, and wheat flour. In addition, these values are within the reported desired values for foodstuffs powders, which vary between 9 and 34%.\cite{7} According to Downton et al.\cite{62} caking of high-sugar dehydrated powdered foods can be attributed to moisture absorption. Water absorbs on particle surfaces, forming a saturated solution and thereby making the particles sticky and capable of forming liquid bridges. Thus, the effect of the process variables on powder caking degree depends on their effect on powder hygroscopicity. Degree of caking decreases with an increase in inlet air temperature and maltodextrin concentration and with a decrease in maltodextrin dextrose equivalent.

Model Fitting

Table 2 presents the best model predictions for the tomato powder properties in relation to the process variables, air inlet temperature, (tomato pulp solids)/(maltodextrin solids) ratio, and dextrose equivalent of maltodextrin. Although the development of drying kinetics and structural models may provide a more general method to the solution of a predictive equation, the development of empirical models provides an accurate and practical approach to describe the relationships that exist between operating variables during spray drying and various process responses. The use of polynomials to describe effects in a spray-drying system is a usual approach for products with a sticky nature, which affects their drying behavior. Such models will most likely have to be tested in different types of spray dryers of larger scale, but a few simple test runs would allow for any adjustments that need to be made.

\begin{table}[h]
\centering
\caption{Best model predictions for the powder properties in relation to the process variables, inlet air temperature ($T_i$), (tomato pulp solids)/(maltodextrin solids) ratio ($t:m$), and dextrose equivalent of maltodextrin ($DE$)}
\begin{tabular}{|c|c|}
\hline
Property & Model \\
\hline
Moisture content (% wb) & $29.7 - 0.143 \cdot T_i - 4.31 \cdot (t:m) + 0.114 \cdot DE + 0.708 \cdot (t:m)^2$ \\
Bulk density (g/mL) & $0.478 - 0.00278 \cdot T_i + 0.0678 \cdot (t:m) + 0.002 \cdot DE - 0.0102 \cdot (t:m)^2$ \\
Solubility (s) & $325 - 1.41 \cdot T_i + 38.8 \cdot (t:m) - 6.90 \cdot (t:m)^2 + 0.326 \cdot (t:m) \cdot DE$ \\
Hygroscopicity (g/g solids) & $0.0738 - 0.000215 \cdot T_i - 0.00164 \cdot (t:m)^2 + 0.000061 \cdot (t:m) \cdot DE$ \\
Degree of caking (%) & $28.6 - 0.139 \cdot T_i + 7.49 \cdot (t:m) - 1.37 \cdot (t:m)^2 + 0.0474 \cdot (t:m) \cdot DE$ \\
\hline
\end{tabular}
\end{table}
CONCLUSIONS

A new technique for spray drying tomato concentrate using dehumidified air as drying medium and maltodextrin as drying agent was developed and the effect of maltodextrin type and concentration on the main powder properties was studied. It was observed that:

- Tomato powders show a non-Newtonian behavior and have lower yield stress and Bingham viscosity than the corresponding pulps. In addition, the yield stress and the Bingham viscosity decrease with an increase in inlet air temperature, maltodextrin concentration, and dextrose equivalent.
- Moisture content decreases with an increase in inlet air temperature and a decrease in maltodextrin concentration and dextrose equivalent.
- Bulk density increases with an increase in dextrose equivalent and with a decrease in inlet air temperature and maltodextrin concentration.
- Solubility increases with an increase in inlet air temperature and maltodextrin concentration and a decrease in dextrose equivalent.
- Hygroscopicity and degree of caking decrease with an increase in inlet air temperature and maltodextrin concentration and with a decrease in maltodextrin dextrose equivalent.

Generally, the lower the moisture content, the hygroscopicity, and the caking degree and the higher the bulk density and the solubility, the better a powdered product will be considered. Thus, maltodextrin addition improved powder hygroscopicity, caking, and solubility, whereas it deteriorated slightly its moisture content and density. However, in experiments conducted using dehumidified air, powder moisture content was much higher and bulk density was much lower. In addition, as concluded in Part I of this work, maltodextrins alter the surface stickiness of tomato droplets, make it possible for them to enter the safe drying regime sooner and, hence, reduce wall deposition, which is the main problem during spray drying of tomato pulp. Thus, the combination of maltodextrin addition and use of dehumidified air as drying medium seems to be an effective way of producing a free-flowing tomato powder.

\[ DE \] Dextrose equivalent of maltodextrin

\[ d \] Bulk density (g/mL)

\[ F \] Ratio of variation explained by a model with the \( K - q \) terms to variation left unexplained

\[ H \] Hygroscopicity (g/g solids)

\[ n_B \] Bingham viscosity (Pa s)

\[ R^2 \] Coefficient of determination

\[ S \] Square root of mean square error

\[ S_0 \] Solubility (s)

\[ T_g \] Glass transition temperature (°C)

\[ T_i \] Inlet air temperature (°C)

\[ \tau/m \] Ratio (tomato pulp solids)/(maltodextrin solids)

\[ X \] Moisture content (% w.b.)

\begin{tabular}{ll}
\textbf{Greek Letters} & \\
\[ \gamma \] Shear rate (s\(^{-1}\)) & \\
\[ \tau \] Shear stress (Pa) & \\
\[ \tau_B \] Yield stress (Pa) & \\
\end{tabular}

\begin{tabular}{ll}
\textbf{Subscript} & \\
\[ p \] Powder & \\
\end{tabular}

**REFERENCES**


