Production and Characterization of Spray-Dried Tomato Powder Using Whey Protein and Acid-Modified Starch

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Tomatoes are one of the most widely used vegetables in the world, which are grown for fresh fruit consumption or processing into tomato paste, pulp, sauce, and ketchup. Nonetheless, tomatoes' high moisture content usually leads to increased water activity, which encourages deterioration of quality. For this reason, dried food powder is made via spray-drying, which also adds value to the raw material and helps to minimize postharvest losses. This study examined the spray-drying of tomatoes with the additives whey protein (WP) and acid-modified starch (MS) at the concentrations of 40% and 50%, using inlet temperatures of 160°C and 180°C. The study analyzed powder yield, bulk density, hygroscopicity, moisture content, color, and particle size. Moisture content ranged from 0.9% to 6.5%, with the tomato powder sample 4 (TP4) having the lowest value. The highest powder yield was 23.6% for TP4, followed by 21.8% for TP3, and the lowest was 11.2% for TP5. Color values (L*, a*, b*) ranged from 82.2 to 90.8, 2.8 to 6.1, and 13.2 to 15.2, respectively. Higher temperature and WP concentration improved yield and reduced moisture content, while higher temperature and fewer additives enhanced color. The results indicate that the use of WP is better than MS in terms of powder quality overall. Higher concentration (50%) and inlet temperature (180°C) gave a better overall performance, especially TP4 with WP, as it exhibited good characteristics, with a well-balanced combination of low moisture content, high water solubility, and optimal color values (L*, a*, b*). This study offers insightful information for maximizing spray-drying parameters in the manufacturing of premium tomato powders, which helps to reduce losses and enhance the raw product's value.

Keywords: Acid-modified starch, carrier agents, optimization, spray-drying, whey protein

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Tomato, or *Solanum lycopersicum*, is a key agricultural plant with fleshy fruits. Based on global production, tomatoes rank second after potatoes [1]. Tomato consumption is linked to lower risks of cardiovascular diseases and cancers, such as prostate, lung, and digestive malignancies [2, 3]. Tomatoes also contain bioactive compounds, like lutein, which may lower lung cancer risk, and β-carotene, valued for its pro-vitamin A properties [4]. Tomatoes and tomato products offer culinary benefits, including antibacterial and antioxidant properties.

In terms of tomato production, a large portion of tomatoes are thrown away despite the fact that they are still edible and nutritious since they are deemed "ugly" and unfit for sale due to their size, shape or color. In response to this problem, several organizations are trying to decrease food waste and increase the consumption of so-called "ugly" items by promoting the use of these tomatoes in soups, sauces, and smoothies [5]. For longer shelf-life, easier shipping, and more uses in various food applications, spray-dried tomato powder is favored [6-8]. However, sticky and caking end-products caused by the high concentrations of low relative molecular weight sugars, notably fructose, sucrose, and glucose, in tomatoes will always be an issue and affect the powder recovery. During spray-drying, these sugars' low glass transition temperature (Tg) makes the material stickier [9, 10]. High Tg additions, such as starch and whey protein (WP), are frequently used to reduce stickiness in fruit juices. Parameters of spray-drying, such as input temperature, air flow rate, feed flow rate, atomizer speed, carrier agent type, and concentration, all have an impact on particle size, bulk density, moisture content, yield, and hygroscopicity in spray-dried foods [11-13]. A powder's moisture content, particle size, bulk density, hygroscopicity, and morphology are all influenced by the temperature of the inlet air. When the drying temperature is increased, the moisture content will be lower and the drying rate will become higher [14, 15]. Tran & Nguyen [16] mentioned that the moisture content of spray-dried lemon grass powder decreased from 13.11% to 8.49% when the temperature was risen from 110°C to 150°C.

Adding various carrier agents during the spray-drying process can change the tomato powder's (TPs) physical qualities, stability, and ability to rehydrate [17-19]. Moreover, powders' characterizations are greatly affected by the working conditions, the use of carrier agents, and the amount of those agents. For instance, according to Obadina et al. [20], the parameters of spray-drying could change not only the color but also the amount of product that is produced. Importantly, it was discovered that higher temperatures lead to more yield. Additionally, temperatures during operations also have a big effect on the amount of moisture content [21].

To speed up the drying process and make the powder less sticky and water-attracting, WP and acid-modified starch (MS) can be utilized as carrier agents. WP has been reported a great antioxidant capacity [22-25]. According to Mann et al. [26], the hydrophobic and aromatic amino acids found in WP have the ability to donate protons to stabilize electron-deficient radicals, hence contributing to its antioxidant behavior. Maintaining the powders' free-flowing qualities is especially crucial for this characteristic, as it inhibits particle agglomeration during storage, which helps to increase recovery rates. WP serves to enhance the stability of the formulation by encapsulating lipids and protecting them throughout the spray-drying process, thereby decreasing the risk of oxidation. Other components of tomatoes, including taste, color, and functional additions, can be shielded by WP. Because of its emulsifying qualities, WP may combine with fats or oils to create stable emulsions. Acid MS is used in the food industry for enhancing the quality and functioning of a variety of food items [27]. In order to lessen the natural starch's propensity to retrograde and break down, which can cause problems with stickiness and higher viscosity in food items, acid MS is an essential procedure. Solubility, texture, and resistance to heating temperatures required for manufacturing operations are all improved by acid MS, especially when treated with hydrochloric acid (HCl) or sulphuric acid (H_2SO_4) [28].

Therefore, the purpose of this study is to confirm the effects of the carrier agents WP and acid MS on TP's properties and to determine the best spray-drying processing parameters by adjusting the spray-dryer's inlet temperature and the concentration of the carrier agents.

MATERIALS AND METHODS

Raw Materials and Chemicals

The materials and chemicals used in the production of TP with carrier agents include fresh tomatoes, WP, cornstarch, HCl (37%), and sodium hydroxide (NaOH) pellets. WP and cornstarch were supplied by Sigma-Aldrich Ltd. HCl (37%) and NaOH pellets were from Asia Chemie (Thailand) Co. Ltd.

Tomato Juice Preparation

5 kg of tomatoes were cleaned with lukewarm water to remove any dirt or contaminants. Once cleaned, the tomatoes were blanched by immersing them in boiling water for one min. Then, the tomatoes were blended in a blender until a smooth consistency is achieved. To refine the juice further, the juice was strained a cloth or a fine strainer to remove any remaining solids, resulting in a smooth and clear tomato juice.

Acid MS Preparation

A total of 300 g of starch was added to a 600 mL solution containing 37% HCl at room temperature and left standing for 192 hrs. without any stirring [29]. Following this, the mixture was neutralized using a 10% NaOH solution. The resulting starch slurry was rinsed five times with distilled water and then dried in a hot air oven at 40°C for a period of 24 hrs.

Tomato Juice with Carrier Agent Preparation

For 40% concentration of carrier agent, 120 g of WP and acid MS, respectively, was weighed and dissolved separately in hot water until fully dissolved. Each carrier agent was combined with the tomato juice (300 mL) in a blender and the mixture was mixed thoroughly to ensure even distribution and proper blending of the ingredients. The steps were repeated for 50% concentration of carrier agent by weighing 150 g of the carrier agents [30, 31].

Tomato Powder Preparation

In this study, the spray-dryer (Mobile Minor^{TM}, GEA, USA) was used to convert the tomato juice with the carrier agents into tomato powder. The spray-dryer was configured with an inlet temperature of 160°C and an outlet temperature of 85°C. Additionally, the atomizer pressure was set at 5 bar, and the peristaltic pump feed flow rate was fixed at 18 rotations per minute. After being prepared, the samples were loaded into the spray-dryer, and the powders produced were taken out of the cyclone for further processing. Specimens were kept for three to five days or weeks in preparation for further analysis. The experiment was repeated with the inlet temperature of 180°C and the same outlet temperature, atomizer pressure, and pump feed flow rate [32]. The inlet temperatures of 160ºC and 180ºC fall within the range commonly used in similar studies [31-33]. The outlet temperature of 85°C is consistent with other studies [31-33]. Tonon et al. [34] maintained outlet temperatures around 80ºC to 90ºC for spray-drying açai juice, highlighting the importance of keeping the outlet temperature below 90ºC to preserve product quality. An atomizer pressure setting of 5 bar falls within the typical range used in food product spray-drying. Table 1 shows the formulation for the 8 samples.

Table 1. Formulation of TP samples.

Sample	Carrier agent used	Volume of tomato juice, mL	Carrier agent concentration, %	Weight of carrier agent used, g	Inlet temperature, °C
TP1	WP	300	40	120	160
TP2			50	150	160
TP3			40	120	180
TP4			50	150	180
TP5	MS		40	120	160
TP6			50	150	160
TP7			40	120	180
TP8			50	150	180

*TP = Tomato powder

Powder Yield

Powder yield was determined using Equation 1, which is based on dry matter measurements and follows the procedure outlined by [35].

$$Powder\ yield, \% = \frac{a,\ g}{(b+c),\ g}\ x\ 100 \quad \text{Equation 1}$$

Where, a = weight of obtained powder (g), b = dry matter content (g) of juice, and c = mass (g) of the carrier agents used.

Bulk Density

To determine bulk density, a 20 mL dry cylinder was gradually filled with 5.0 ± 0.01 g of tomato powder. The apparent volume of the powder was measured after three taps on the cylinder. According to Caparino et al. [36], the procedure involves estimating the spray-dried powder's bulk density using Equation 2.

$$Bulk\ density, \frac{g}{cm^3} = \frac{Weight\ of\ powder,\ g}{Volume\ of\ powder, cm^3} \quad \text{Equation 2}$$

Hygroscopicity

A modified version of the approach of Tonon et al. [34] was utilized to calculate hygroscopicity. Each powder sample was weighed out at 25°C and placed in a glass jar filled with a saturated NaCl solution at 75% relative humidity (RH). The analysis was completed in triplicates. The samples were weighed after a week. Hygroscopicity is given in grams of absorbed moisture per 100 g of dry solids and was determined using Equation 3.

$$\%\ Hygroscopicity = \frac{(\%WI+\%FW)\times 100}{100+\%WI} \quad \text{Equation 3}$$

Where, $\%FW$ = % free water; $\%WI$ = $((c-b\ )\ /(b-a)) \times 100$; a = weight of plate (g); b = weight of plate + powder (g); and c = weight of plate + powder in equilibrium (g).

Moisture Content

The moisture content analysis was conducted according to the procedure for calculating mass loss under the operating conditions as described in the Association of Official Agricultural Chemists (AOAC) Official Method 934.0. After being first dried in a lab oven, a crucible and its cover were chilled in a desiccator. After measuring the weight of the empty crucible with the cover (a), the crucible was filled with a powder sample weighing around 2 g. The crucible containing 2.0 g of sample and the cover were weighed again (b). Without the cover, the crucible was put inside the oven. The sample was dried in the lab oven at 105°C for 24 h, or until a consistent weight was achieved. The crucible was then taken out of the oven and placed in a desiccator to cool, with the cover replaced, before being weighed. After chilling for fifteen minutes, the crucible was weighed (c). Equation 4 was used to calculate the TP samples' moisture content:

$$Moisture\ content, \% = \frac{(b-c),\ g}{(b-a),\ g} x100 \quad \text{Equation 4}$$

Where, a = weight of crucible + cover, b = weight of sample + crucible + cover before drying process, and c = weight of sample + crucible + cover after drying process.

Water Solubility Index (WSI)

The method described by Sabhadinde [37] was used to assess the water solubility index (WSI) of tomato powder. It involved mixing 25 mL of distilled water vigorously with 2.5 g of spray-dried TP in a 100 mL centrifuge tube, then incubating the mixture for 30 minutes at 37°C in a water bath. After that, the mixture was centrifuged (Gyrozen, UK) for 20 min at 10,000 rpm. The supernatant was gently gathered into a preweighed beaker and oven-dried at 103 ± 2 °C. WSI (%), in relation to the sample amount, was computed as a percentage of the dried supernatant using Equation 5.

$$WSI, \% = \frac{Weight\ of\ supernatant,\ g}{Weight\ of\ sample,\ g} \times 100 \qquad \text{Equation 5}$$

Water Absorption Index (WAI)

The method described by Sabhadinde [37] was used to calculate the WAI of the tomato powders. A 2.5 g solution of tomato powder in 20 mL of distilled water was centrifuged (Gyrozen, UK) at 3000 rpm for 10 mins after being agitated for an hour. To extract just the moist residue and to get rid of any free water, the supernatant was disposed of. After that, the moist residue was weighed.

$$\text{WAI}, \% = \frac{Weight\ of\ residual,\ g}{Weight\ of\ sample,\ g} x100 \qquad \text{Equation 6}$$

Color Analysis

In this experiment, a color spectrophotometer (Colorflex D65/10O, Hunterlab, USA) was used to examine the color properties of the tomato powders. The results are represented as $L*$ (lightness), $a*$ (redness), and $b*$ (yellowness) values of the samples in line with the CIELAB system. Prior to sample analysis, the apparatus was calibrated using a white plate (L=93.87, a=-0.73, b=+2.06) and a green plate (L=51.23, a=-25.32, b=15.14). Each sample was examined in three copies and the average was recorded. The 'L' value indicates the color lightness of the dried sample, which ranges from 0 (black) to 100 (white); the 'a' value indicates the degree of redness (+160) or greenness (-60); and the 'b' value indicates the degree of yellowness (+160) or blueness (-60). To evaluate the color attributes of food powders, a spectrophotometer should be used to measure these variables, which may vary based on the raw ingredients. The TP was put inside the clear container in the colorimeter. After placing the black lid, the 'read' button was pressed [38].

Particle Size

The particle size of TP aqueous solutions was measured using a particle size analyzer (Malvern Zetasizer, Nano Z, UK). 10 mL of distilled water was combined with 1 g of TP to create an aqueous suspension. The suspension was well mixed before being transferred to a disposable cuvette and loaded onto the measuring apparatus [39]. Particle size is expressed in nanometer (nm), and measurements were taken in triplicate for each sample. The mean z-average of each sample was used to compare sizes.

Zeta Potential

Zeta potential is a physical property that can be observed on the surface of any substances, macromolecules, or suspended particles. A zeta sizer (Malvern Panalytical Zetasizer, UK) was used to measure the zeta potential and particle size of the resulting TPs. The particles were introduced into the apparatus, examined at least four times, and then diluted with distilled water at a fixed ratio. For this study, 10 mL of distilled water was combined with 1 g of TP to create the aqueous suspensions [39].

RESULTS AND DISCUSSION

Powder Yield

The powder yield for the WP and MS samples are shown in Figure 1.

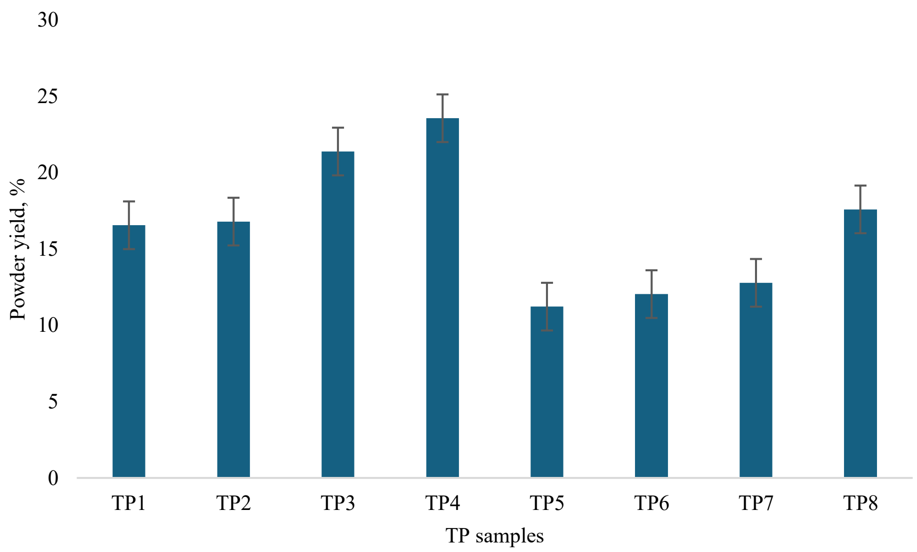

Figure 1. Graph of powder yield (%) vs TP samples.

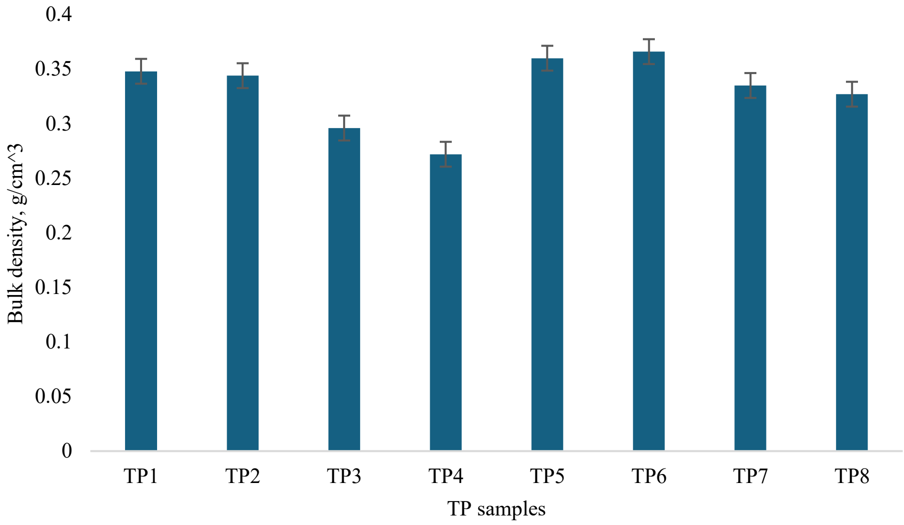

Figure 2. Graph of bulk density (g/cm³) vs TP samples.

It is evident from the results that yield rises in tandem with the concentration of carrier agents. Figure 1 demonstrates that the percentage of powder recovery decreases when different carrier agents are used, with WP exhibiting higher percentages than MS. Among all the powders, TP4 achieved a higher powder recovery percentage of 23.6%. In contrast, the tomato feed combination yielding the least amount of powder was TP5, with only an 11.2% powder yield. TP1 had the powder yield of 16.6%, TP2 16.8%, and TP3 21.4%. For samples containing acid MS, TP5 had the powder yield of 11.2%, TP6 12.0%, TP7 12.8%, and TP8 17.6%. These results indicate that higher concentration and temperature lead to higher percentage of powder yield.

Furthermore, WP samples typically generate more powder than samples that contain MS. According to Keshani et al. [40], WP reduces cohesion and wall deposition while generating a glassy coating surrounding droplets to boost encapsulation yield. Because WP can create a film and react with water at the droplet contact while spraying, it adds to the high value obtained; while MS has a higher viscosity that leads to agglomeration. According to Meganaharshini et al. [41], this interaction stabilizes the drops by homogenization, which enhances the drying process by decreasing stickiness and raising powder recovery. According to Sarabandi et al. [37], there may be a reason for the higher yield in the protein and maltodextrin (MD) blend. This could be because proteins migrate onto the droplet/particle surfaces and produce a protein film that decreases adherence to the drying chamber wall and adhesion between particles. On the other hand, when employing MS, the solution's higher viscosity may result in the creation of coarse droplets with enhanced agglomeration, which could increase wall deposition, making pumping more difficult and thus reduces yield. At lower temperatures, samples show lower yields because the powder does not reach the right temperature to form encapsulated powder, resulting in significant residue in the spray-dryer chamber. Yield is greatly affected by operating temperatures. Higher yields are the result of smaller droplets and higher drying temperatures. However, the WP results are not satisfactory, despite having the highest powder recovery value compared to the data reported by Bhusari et al. [42], who achieved a production yield of 68%-76.2% using spray-dried bayberry juice with WP and MD as carriers. According to Dantas et al. [21], higher yields can be achieved using higher drying temperatures and smaller droplets because operational temperatures significantly impact yield. This finding relates to the most probable reason for the exceptionally low yields in this study, likely due to the unchangeable flow rate of the feed pump.

Bulk Density

Figure 2 illustrates the experimental outcomes of the bulk density analysis of the WP and MS samples.

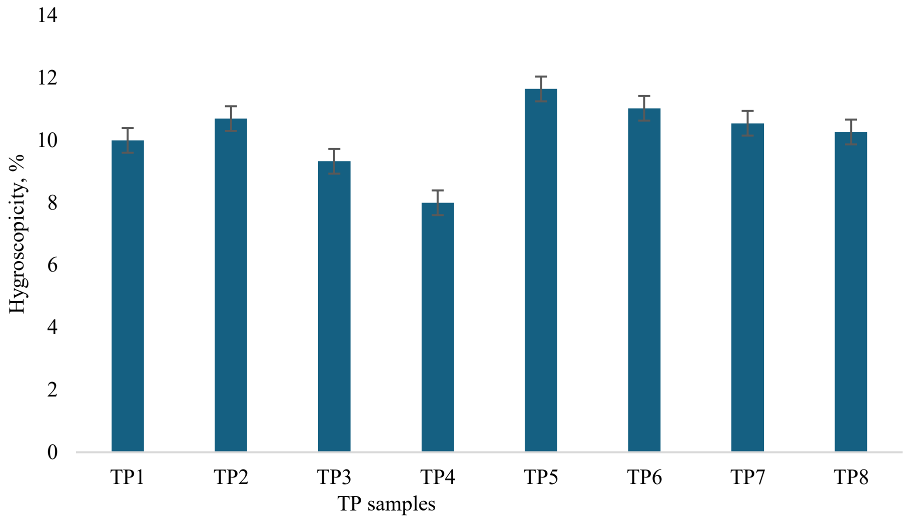

Figure 3. Graph of hygroscopicity (%) vs TP samples.

In this study, bulk density ranged from 0.272 to 0.366 g/cm³. TP6 exhibited the highest bulk density (0.366 g/cm³), while TP4 showed the lowest (0.272 g/cm³). TP1 had the bulk density of 0.348 g/cm³. TP2 and TP3 had the bulk density of 0.344 g/cm³ and 0.296 g/cm³, respectively. Regarding samples containing MS, TP5 had the bulk density of 0.360 g/cm³, TP6 0.366 g/cm³, and TP7 and TP8 0.335 g/cm³ and 0.327 g/cm³, respectively. Higher bulk density indicates a lower amount of air present in the powder, which can help prevent lipid oxidation during storage. The higher bulk density observed in TP6 may be due to the starch's ability to create a more compact and tightly packed structure around the particles. However, the results obtained from the samples using WP and MS did not show a significant difference and indicate that increased temperature and concentration of additives result in the decrease in bulk density. According to Chegini & Ghobadian [32], the results indicate that as inlet temperature increases, bulk density decreases, while insoluble solid content increases. Conversely, when inlet temperature decreases, bulk density increases. This statement is supported by the findings of Shrestha et al. [43], who found that as the concentration of additives increases, the bulk density of orange juice powder decreases. TP samples made with MS, especially TP5 and TP6, showed elevated levels of bulk density and moisture content, which is in line with the findings.

Hygroscopicity

Figure 3 illustrates the experimental outcomes of the hygroscopicity analysis of the WP and MS samples.

The TP samples showed hygroscopicity values between 8% and 11.7%. TP4 had the lowest hygroscopicity (8%), indicating better moisture resistance, while TP5 had the highest (11.7%). Since a hygroscopicity of 15–20% is regarded as very hygroscopic, the results indicate that the spray-dried microcapsules had low hygroscopicity [44]. Among all the powders tested, TP5, made with MS, exhibited the highest level of hygroscopicity, with a value of 11.7%. Because of its high hydrophilic group composition, the MS microcapsule is more hygroscopic than other groups, which increases its propensity to absorb water through hydrogen bonding. Conversely, the lowest hygroscopicity was observed in the tomato feed combination TP4, with a hygroscopicity of 8%. Other powder combinations showed varying levels of hygroscopicity: TP1, TP2, and TP3 were 10%, 10.7%, and 9.3%, respectively. Regarding samples with acid MS, TP5, TP6, TP7, and TP8 exhibit the hygroscopicity level of 11.7%, 11.1%, 10.6%, and 10.3%, respectively. The findings suggest that TP5 has a higher likelihood of rapid deterioration due to its high hygroscopic value, influenced by the lower inlet temperature. Due to its high inlet temperature of 180°C, TP4 exhibited the lowest and most desirable hygroscopic feature. The use of MS as a carrier significantly increased the powder's moisture absorption ability. Caparino et al. [36] noted that moisture content and particle size could affect hygroscopicity. High hygroscopicity in food powder can lead to caking, where the powder clumps together [45].

Moisture Content

Figure 4 illustrates the experimental outcomes of the moisture content analysis of the WP and MS samples.

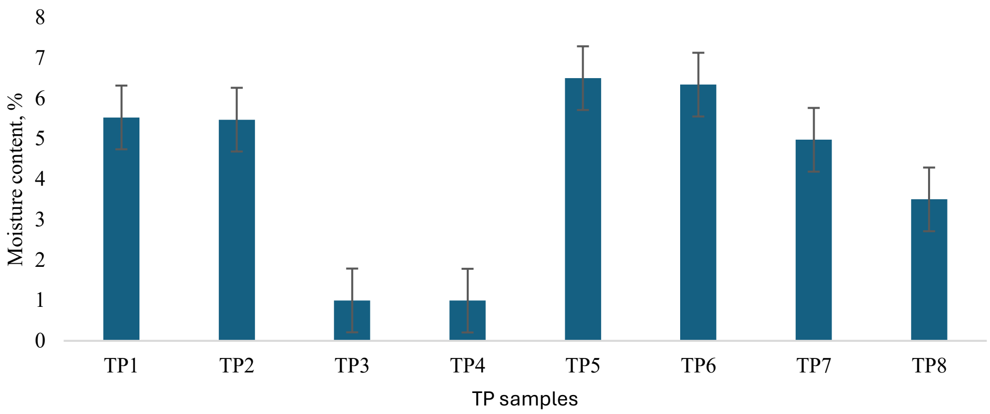

Figure 4. Graph of moisture content (%) vs TP samples.

Moisture content plays a crucial role in determining the storage duration and flowability of spray-dried powders. The ideal moisture content range for spray-dried products is between 3% and 5% to ensure stability and minimize microbial and chemical reactions. In this study, moisture content varied from 0.9% to 6.5%. The stability of a powder is greatly impacted by its moisture content because even a tiny amount of water can raise the temperature sufficiently to make the matrix more mobile while being stored [46]. Low moisture content extends the shelf-life of a product by reducing bacterial growth and preventing clumping. According to Figure 4, TP4 had the least amount of moisture (0.9%), while TP5 had the highest amount (6.5%). TP1, TP2, and TP3 had the moisture content of 5.5%, 5.5%, and 1%, respectively. Meanwhile, the samples containing acid MS, TP5, TP6, TP7 and TP8, had 6.5%, 6.3%, 4.9%, and 3.5% moisture content, respectively. These outcomes are explained by the fact that MS forms a viscous feed solution, which increases the moisture content by preventing moisture from diffusing during the spray-drying process. The resultant powder has a substantially decreased moisture content when the concentration of carrier agents and operating temperatures in the tomato juice are raised. Samples with higher operational temperatures exhibit less moisture content. Jittanit et al. [38] found that increasing the MD content in pineapple juice powder decreases its moisture content. Increasing the amount of carrier agents likely decreases the moisture content of TP. Osman and Endut [44] discovered that higher gum Arabica (GA) content in roselle-pineapple powder results in decreased moisture content, supporting the current study's results. Caparino et al. [36] found that increasing the GA proportion in tuna powder reduces its moisture content from 7.5% to 4.6%.

Water Solubility Index (WSI)

Figure 5 illustrates the experimental outcomes of the water solubility index analysis of the WP and MS samples.

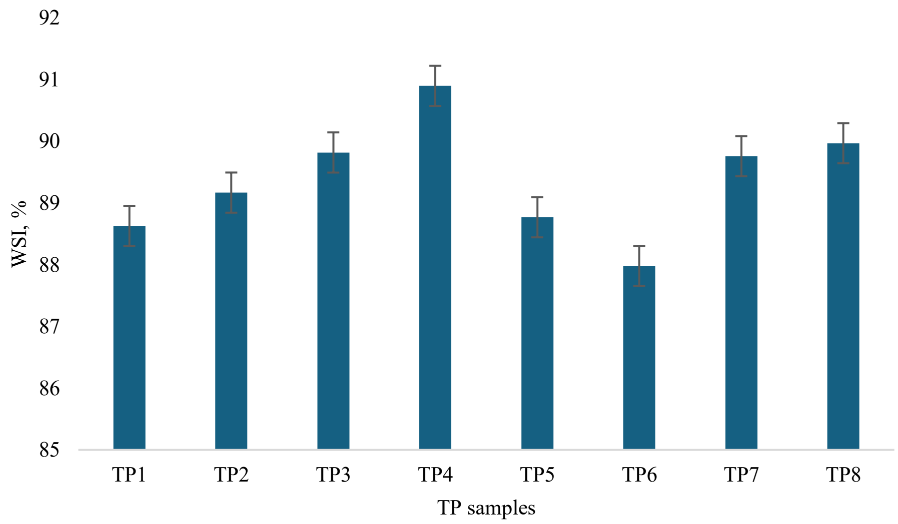

Figure 5. Graph of WSI (%) vs TP samples.

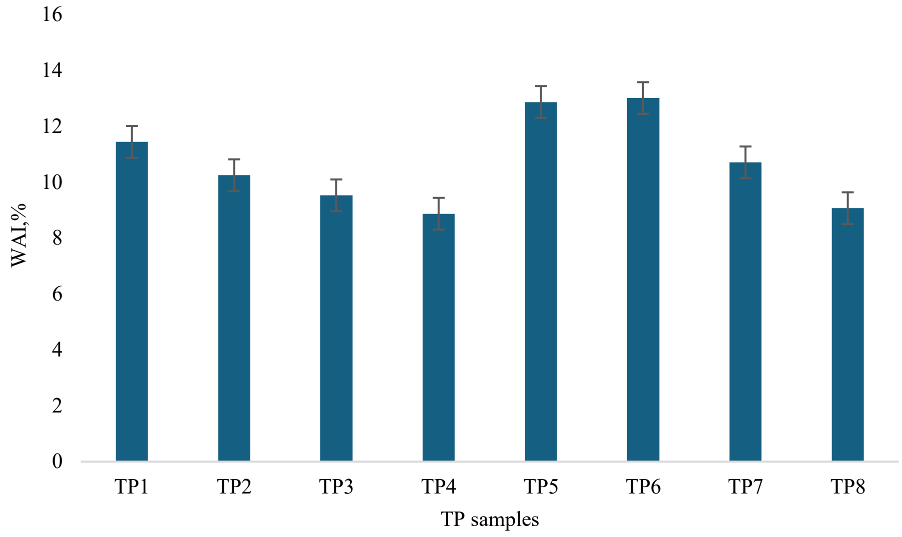

Figure 6. Graph of WAI (%) vs TP samples.

According to Figure 5, TP6 exhibited the lowest WSI at 87.9%, while TP4 had the highest WSI at 90.9%, indicating good solubility. The findings demonstrate that WSI increases with higher input temperatures [47]. Lower moisture content and increased solubility are shown to be strongly and adversely linked with both moisture content and water activity. Sarabandi et al. [37] observed that solubility increases with decreasing moisture content when spray-drying raisin extract concentrates. Particle size and moisture content of a spray-dried powder, as well as the underlying ingredients and additions, all have an impact on the solubility index of the powder [48].

Water Absorption Index (WAI)

Figure 6 illustrates the experimental outcomes of the WAI analysis of the WP and MS samples.

The WAI ranged from 8.9% to 13.0%. TP6 had the highest WAI at 13.0%, indicating the highest water absorption capacity, while TP4 had the lowest WAI. The increased WAI in TP6 is likely due to the higher content of modified starch, which enhances water absorption by protecting particles and altering their surface stickiness. The study found that WAI decreases with increasing additive concentration, consistent with spray-dried mango powder and sweet potato flour [36].

Color Analysis

Table 2 shows the experimental outcomes of the color analysis of the WP and MS samples, while Figure 7 illustrates the $a*$ values, Figure 8 illustrates the $b*$ values, and Figure 9 illustrates the $L*$ values of the samples.

Table 2. Color analysis experimental outcomes of TP samples.

Samples	$L*$	$a*$	$b*$
TP1	90.03	3.79	14.58
TP2	90.65	2.92	14.08
TP3	90.61	3.65	14.00
TP4	90.79	2.82	13.17
TP5	82.22	6.05	15.22
TP6	84.42	5.09	14.70
TP7	88.95	5.19	14.86
TP8	89.91	4.69	14.13

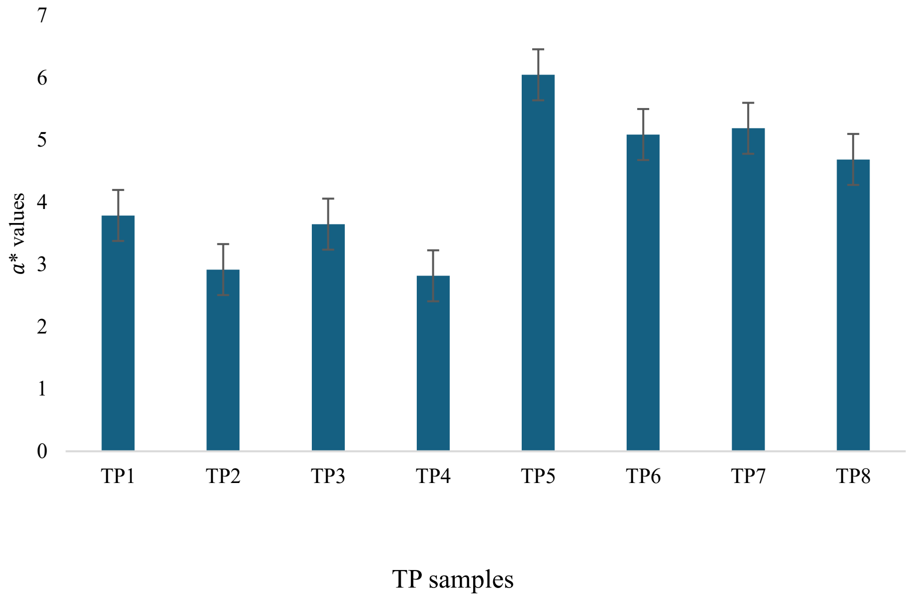

Figure 7. Color analysis: $a*$ values vs TP samples.

The $a*$ values of the TP samples, indicating redness, ranged from 2.8 to 6.1; despite being low, these values are positive, and a negative $a*$ would suggest a greenish color. TP5 exhibited the highest $a*$ value, which could be due to better preservation of lycopene, the red pigment in tomatoes. Conversely, TP4, which contained 50% WP but was processed at 180°C, had the lowest $a*$ value, likely due to pigment degradation from the higher temperature. Carrier agents like WP and MS affect the final color; MS, being yellowish, can enhance redness, while WP, being whitish, may dilute it. Additionally, double sieving the tomato juice removes debris that could affect color intensity.

The $b*$ values, which reflect the yellowness of the TP samples, ranged from 13.2 to 15.2, showing minimal differences between samples. TP5 had the highest $b*$ value, indicating the most yellowness. TP4 had the lowest $b*$ value of 13.17. Both the redness ($a*$) and yellowness ($b*$) readings decreased as the inlet temperature and carrier agent concentration increased. This decline is due to pigment loss from higher temperatures and the whitish or yellowish color of the carrier agents diluting the red hue of the TP.

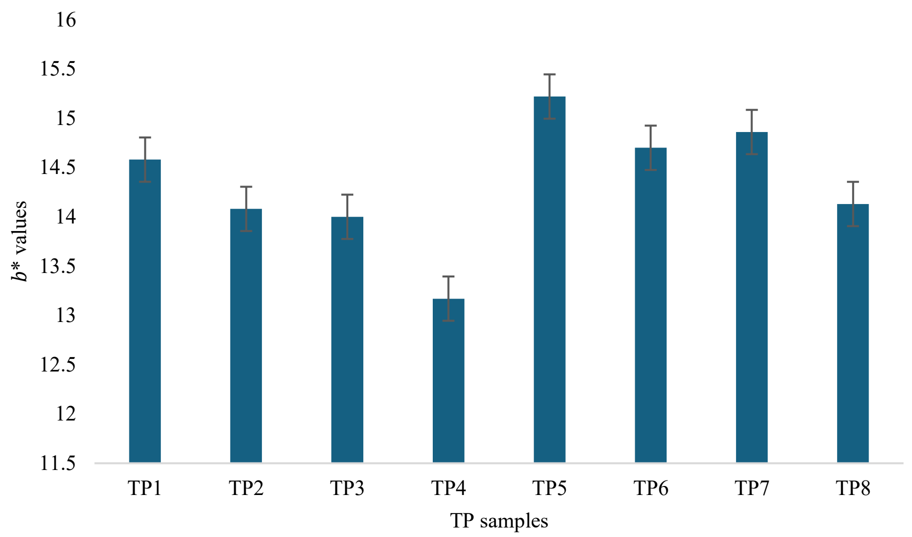

Figure 8. Color analysis: $b*$ values vs TP samples.

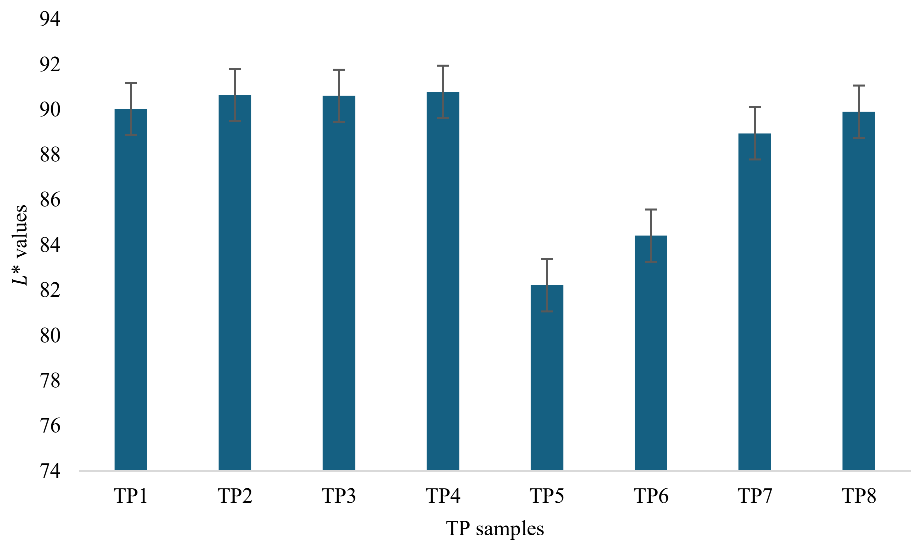

Figure 9. Color analysis: $L*$ values vs TP samples.

The $L*$ values, indicating lightness, ranged from 82.2 to 90.8. TP4 had the highest $L*$ value of 90.7. This high $L*$ value is attributed to the rapid moisture evaporation at 180°C, which reduces the final powder's moisture content and makes it appear lighter. Color consistency is important for quality, consumer perception, and product consistency. The TPs' color variation is a sign of product degradation or changes in chemical composition over time. By regularly checking the color, manufacturers can monitor the stability and shelf-life of their goods.

Particle Size

Figure 10 illustrates the experimental outcomes of the particle size analysis of the WP and MS samples.

The particle size in this study ranged from 1004.9 nm to 27926.8 nm. TP6 exhibited the largest particle size (27926.8 nm), while TP1 had the smallest (1004.9 nm). TP6 yielded the largest particle size, followed by TP8, both with the same concentration of MS at 50%. Regardless of the additive mix concentration, samples appeared to be larger when run at the 180°C inlet temperature. These results align with the findings of Jangam & Thorat [49], who observed that higher drying temperatures and carrier concentrations generally lead to larger particle sizes in spray-dried fruit powders. The bigger particles formed at higher input temperatures can be attributed to more swelling brought on by increased drying temperatures [50].

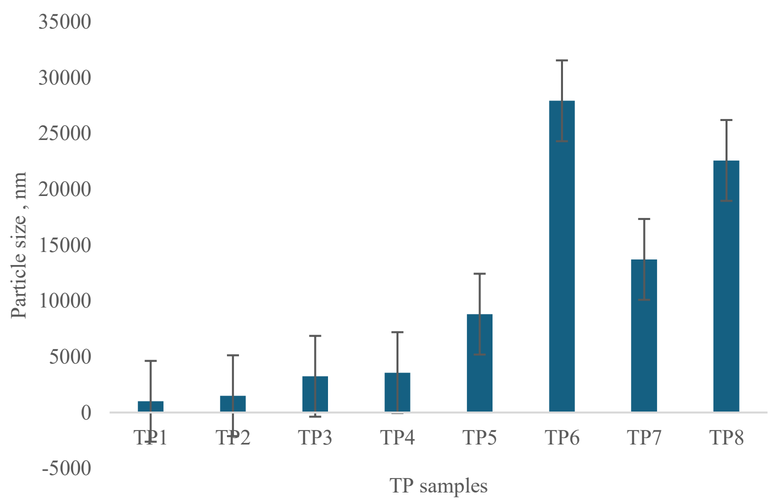

Figure 10. Particle size (nm) vs TP samples.

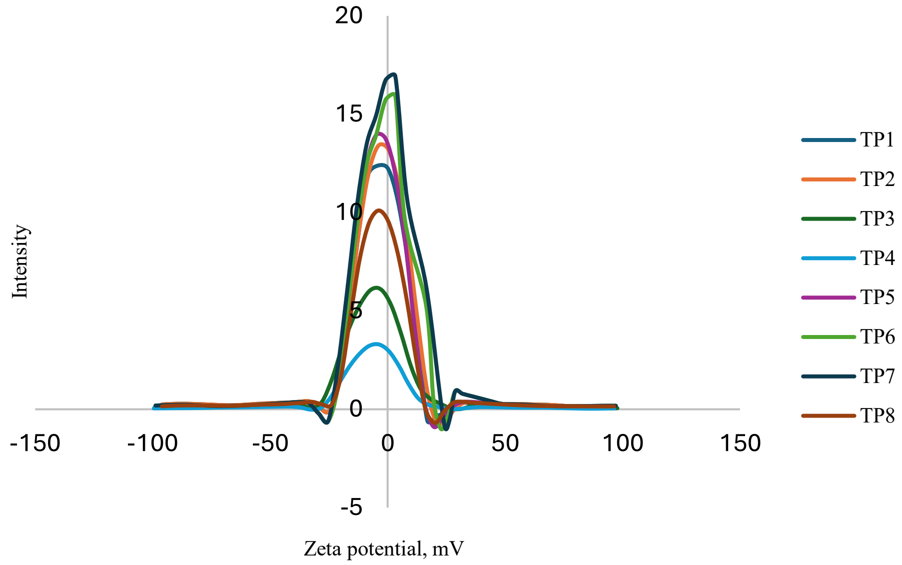

Figure 11. Graph of Intensity vs zeta potential (mV).

Zeta Potential

Figure 11 illustrates the experimental outcomes of the zeta potential analysis of the WP and MS samples.

Zeta potential measures the stability of colloidal systems, with values for the tomato powders ranging from -5.51 to -2.17 mV. TP4 had the highest zeta potential (-5.51 mV), indicating better stability, while TP7 had the lowest zeta potential (-2.17 mV), indicating poorer stability. A high zeta potential, whether positive or negative, correlates with greater stability. Particles with a low zeta potential coagulate or flocculate more easily, while particles with a high zeta potential exhibit better dispersion [51]. This indicates that TP7, with a low MS concentration, had decreased zeta potential, making it less suitable for mixing purposes. In contrast, TP8 produced a larger zeta potential compared to TP6, which used a lower temperature of 160°C for the inlet but the same concentration and outlet temperature.

Final Verdict

A master table compiles and examines all gathered data to provide a comprehensive assessment, making it easier to compare and order samples according to different standards. Points are awarded to each sample based on how well it ranks across several analyses; higher ranks provide greater points. By highlighting the best qualities, this method offers insightful information that helps with well-informed decision-making. The overall results ranking master table is shown in Table 3.

Table 3. Master table of overall results ranking.

	Samples							
	TP1	**TP2**	**TP3**	**TP4**	**TP5**	**TP6**	**TP7**	**TP8**
Powder yield, %	4	5	7	8	1	2	3	6
Bulk density, g/cm³	5	6	7	8	2	1	3	4
Hygroscopicity, %	6	3	7	8	1	2	4	5
Moisture content, %	3	4	7	8	1	2	5	6
WSI, %	5	6	7	8	2	1	3	4
WAI, %	5	6	7	8	2	1	3	4
Color (a* value)	4	2	3	1	8	6	7	5
Particle size	8	7	6	5	4	1	3	2
Zeta potential	5	4	7	8	3	2	1	6
Total	45	43	58	62	24	18	32	42

From Table 3, the overall ranking of the TP samples shows TP4 achieving the highest total score of 62 points, followed closely by TP3 with 58 points. These samples, produced at a higher operational inlet temperature of 180°C, demonstrated superior performances across various quality parameters [52,53]. TP1, TP2, and TP8 fall in the middle range with scores of 45, 43, and 42, respectively; TP1 and TP2 were produced at a lower inlet temperature of 160°C. TP7, TP5, and TP6 score lower with 32, 24, and 18 points, respectively. According to the formulation specifics, TP4 gets a high rating by using a combination of 50% WP as the carrier agent. TP5 and TP6, on the other hand, employed MS as the carrier agent; both of these samples score lower than the rest, suggesting a less ideal formulation for producing TP of superior quality. Additionally, the concentration of the carrier agents has a major impact on the powder's performance. Higher carrier agent concentrations enhance the powders' performance, especially when WP is utilized as a carrier agent. Higher temperatures are correlated with greater overall performance, which is particularly noticeable in samples like TP3 and TP4. This indicates that operating temperatures have an impact [54, 55]. Better qualities, including increased powder production, decreased bulk density, preferred hygroscopicity, and improved water solubility and absorption indices, were often displayed by these samples. Yet, samples such as TP5 and TP6, which were manufactured at a lower temperature (160°C), exhibited poorer performance in all of these metrics, emphasizing how crucial temperature control is to obtain the necessary quality traits.

CONCLUSION

This study on spray-dried TP using WP and acid MS highlights key findings for a suitable spray-drying process. Among the samples, TP4 showed the best results, with a combination of low moisture content, high water solubility, and favorable color values ($L*$, $a*$, $b*$). TP4 also had a fine particle size, making it ideal for food formulations due to its smooth texture and uniformity. The use of 50% WP and an inlet temperature of 180°C resulted in superior TP characteristics, including increased stability and better color and nutritional preservation. TP4 specifically achieved an intermediate particle size of 3575.8 nm, the lowest moisture content of 0.995%, the highest yield of 23.6%, a low bulk density of 0.272 g/cm^3, the lowest hygroscopicity of 8%, a high WSI of 90.9%, and a low WAI of 8.9%. Based on these results, it is recommended to utilize WP as a primary carrier agent and maintaining higher inlet temperatures, particularly around 180°C.

CONFLICTS OF INTEREST

The authors declare no competing interests.

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REFERENCES

1. Peixoto, J. V. M., Neto, C. de M. S., Campos, L. F. C., Dourado, W. de S., Nogueira, A. P. O. & Nascimento, A. dos R. (2017) Industrial tomato lines: Morphological properties and productivity. *Genetics and Molecular Research*, **16(2)**, 1–15.

2. Bhat, N. A., Wani, I. A. & Hamdani, A. M. (2020) Tomato powder and crude lycopene as a source of natural antioxidants in whole wheat flour cookies. *Heliyon*, **6(1)**, e03042.

3. Souza, A. L. R., Hidalgo-Chávez, D. W., Pontes, S. M., Gomes, F. S., Cabral, L. M. C. & Tonon, R. V. (2018) Microencapsulation by spray drying of a lycopene-rich tomato concentrate: Characterisation and stability. *LWT*, **91**, 286–292.

4. Martí, R., Roselló, S. & Cebolla-Cornejo, J. (2016) Tomatoes as a source of carotenoids and polyphenols targeted to cancer prevention. *Cancer*, **8(6)**, 58.

5. Hartmann, T., Jahnke, B. & Hamm, U. (2021) Making ugly food beautiful: Consumer barriers to purchase and marketing options for suboptimal food at the retail level – A systematic review. *Food Quality and Preference*, **90**, 104179.

6. Altay, Ö., Köprüalan, Ö., İlter, I., Koç, M., Ertekin, F. K. & Jafari, S. M. (2022) Spray drying encapsulation of essential oils: process efficiency, formulation strategies, and applications. *Critical Reviews in Food Science and Nutrition*, **64(4)**, 1139–1157.

7. Bucurescu, A., Blaga, A. C., Estevinho, B. N. & Rocha, F. (2018) Microencapsulation of curcumin by a spray-drying technique using gum Arabic as an encapsulating agent and release studies. *Food Bioprocess Technology*, **11(10)**, 1795–1806.

8. Elik, A., Yanık, D. K. & Göğüş, F. (2021) A comparative study of encapsulation of carotenoid-enriched flaxseed oil and flaxseed oil by spray freeze-drying and spray-drying techniques. *LWT*, **143**, 111153.

9. Lee, J. K. M., Taip, F. S. & Abdullah, Z. (2018) Effectiveness of additives in spray-drying performance: a review. *Food Research*, **2(6)**, 486–499.

10. Muzaffar, K., Nayik, G. A. & Kumar, P. (2015) Stickiness problem associated with spray drying of sugar- and acid-rich foods: A mini review. *Journal of Nutrition & Food Sciences S12:003*, 1–3.

11. Tay, J. B. J., Chua, X., Ang, C., Subramanian, G. S., Tan, S. Y., Lin, E. M. J., Wu, W. Y., Goh, K. K. T., Lim, K. (2021) Effects of spray-drying inlet temperature on the production of high-quality native rice starch. *Processes*, **9**, 1557.

12. Yousefi, S., Emam-Djomeh, Z. & Mousavi, M. S. (2011) Effect of carrier type and spray drying on the physicochemical properties of powdered and reconstituted pomegranate juice (*Punica Granatum L.*). *Journal of Food Science and Technology*, **48**, 677–684.

13. Shishir, M. R. I. & Chen, W. (2017) Trends of spray drying: A critical review on drying of fruit and vegetable juices. *Trends in Food Science and Technology*, **65**, 49–67.

14. Sidhu, G. K., Singh, M., & Kaur, P. (2019) Effect of operational parameters on physicochemical quality and recovery of spray-dried tomato powder. *Journal of Food Processing and Preservation*, **43(10)**.

15. Wong, C., Pui, L. & Ng, J. (2015) Production of spray-dried Sarawak pineapple (*Ananas comosus*) powder from enzyme-liquefied puree. *International Food Research Journal*, **22(4)**,1631–1636.

16. Tran, T. & Nguyen, V. H. (2018) Effects of spray-drying temperatures and carriers on physical and antioxidant properties of lemongrass leaf extract powder. *Beverages*, **4(4)**, 84.

17. Shelke, G., Kad, V., Pandiselvam, R., Yenge, G., Kakade, S., Desai, S., Kukde, R. & Singh, P. (2023) Physical and functional stability of spray-dried jamun (*Syzygium cumini* L.) juice powder produced with different carrier agents. *Journal of Texture Studies*, **54(4)**, 560–570.

18. Kandasamy, S. & Naveen, R. (2022) A review on the encapsulation of bioactive components using spray-drying and freeze-drying techniques. *Journal of Food Process Engineering*, **45(8)**, e14059.

19. Hussain, F., Chen, K., Jaskulski, M., Piątkowski, M. & Tsotsas, E. (2022) Experimental study of the parametric impact on size growth of maltodextrin particles in a counter-current spray dryer. *Powder Technology*, **409**, 117792.

20. Obadina, A., Ibrahim, J. & Adekoya, I. (2018) Influence of drying temperature and storage period on the quality of cherry and plum tomato powder. *Food Science and Nutrition*, **6(4)**, 1146–1153.

21. Dantas, D., Pasquali, M. A., Cavalcanti-Mata, M., Duarte, M. E. & Lisboa, H. M. (2018) Influence of spray-drying conditions on the properties of avocado powder drink. *Food Chemistry*, **266**, 284–291.

22. Mahalakshmi, L., Choudhary, P., Moses, J. & Anandharamakrishnan, C. (2023) Emulsion electrospraying and spray drying of whey protein nano- and microparticles with curcumin. *Food Hydrocolloids for Health*, **3**, 100122.

23. Jaqueline, D. J. S., Costa, T. V., Santos, M. L., Da Silva E Silva, L. T., Santos, P. H., De Carvalho Tavares, I. M. & Chaves, M. A. (2023) Encapsulation of açaí (Euterpe oleracea) pulp with whey protein isolate by spray-drying: An optimisation study using response surface methodology (RSM). *Food Humanity*, **1**, 1539–1546.

24. Guilherme D. Silva, M., Ribeiro, E. S., De Farias, B. S., De Quadros Da Luz, G., Oliveira, G., Cadaval, T. R., De Almeida Pinto, L. A. & Díaz, P. V. L. (2023) Microencapsulation of Lacticaseibacillus casei CSL3 using cheese whey, fructo-oligosaccharide and xanthan gum by spray drying. *Food Bioscience*, **56**, 103348.

25. Farrokhi, F., Ehsani, M. R., Badii, F. & Hashemi, M. (2018) Structural and thermal properties of nanofibrillated whey protein isolate in the glassy state. *LWT*, **95**, 274–281.

26. Mann, B., Kumari, A., Kumar, R., Sharma, R., Prajapati, K., Mahboob, S. S. & Athira, S. (2015) Antioxidant activity of whey protein hydrolysates in a milk beverage system. *Journal of Food Science and Technology*, **52**, 3235–3241.

27. Saboonchi, S., Mehran, A., Bahramizadeh, P. & Massoud, R. (2021) Applications of modified starch in food. *3rd International Congress on Engineering, Technology and Innovation. Darmstadt, Germany*.

28. Ashogbon, A. O. & Akintayo, E. T. (2013) Recent trends in the physical and chemical modification of starches from different botanical sources: A review. *Stärke/Starch*, **66(1-2)**, 41–57.

29. Okunlola, A. & Akingbala, O. (2013) Characterisation and evaluation of acid-modified starch of Dioscorea oppositifolia (Chinese yam) as a binder in chloroquine phosphate tablets. *Brazilian Journal of Pharmaceutical Sciences*, **49(4)**, 699–708.

30. Butt, Z. A., Bashir, S., Imran, M. & Masood, M. A. (2020) Development of methodology for the production of tomato powder and evaluation of antioxidant activity of tomato powder. *International Journal of Food Science and Nutrition*, **5(4)**, 127–130.

31. Chang, L. S., Tan, Y. L. & Pui, L. P. (2020) Production of spray-dried enzyme-liquefied papaya (*Carica papaya* L.) powder. *Brazilian Journal of Food Technology*, **23**, 1–16.

32. Chegini, G. R. & Ghobadian, B. (200) Spray dryer parameters for fruit juice drying. *World Journal of Agricultural Sciences*, **3(2)**, 230–236.

33. Cabrera-Roque, D., Aragüez-Fortes, Y., Amador Valladares, M., Rodríguez, J. L. & Pino, J. A. (2023) Optimization of spray-drying process for tomato paste. *Journal of Raw Materials to Processed Foods*, **4(2)**, 9–88.

34. Tonon, V. R., Brabet, C. & Hubinger, M. (2008) Influence of process conditions on the physicochemical properties of acai powder produced by spray drying. *Journal of Food Engineering*, **88(3)**, 411–418.

35. Garofulić, I. E., Zorić, Z., Pedisić, S. & Dragović-Uzelac, V. (2016) Optimisation of sour cherry juice spray drying as affected by carrier material and temperature. *Food Technology and Biotechnology*, **54(4)**, 441–449.

36. Caparino, O. A., Tang, J., Nindo, C. I., Sablani, S. S., Powers, J. R. & Fellman, J. K. (2012) Effect of drying methods on the physical properties and microstructures of mango (Philippine 'Carabao' var.) powder. *Journal of Food Engineering*, **111(1)**, 135–148.

37. Sabhadinde, V. N. (2014) The physicochemical and storage properties of spray-dried orange juice powder. *Indian Journal of Fundamental and Applied Life Sciences*, **4(4)**, 153–159.

38. Jittanit, W., Niti-Att, S. & Techanuntachikul, O. (2010) Study of spray drying of pineapple juice using maltodextrin as an adjunct. *Chiang Mai Journal of Science*, **37**, 498–506.

39. Tonon, V. R., Brabet, C. & Hubinger, M. (2011) Spray drying of acai juice: Effect of inlet temperature and type of carrier agent. *Journal of Food Processing and Preservation*, **5**, 691–700.

40. Keshani, S., Daud, W. R. W., Nourouzi, M. M., Namvar, F. & Ghasemi, M. (2015) Spray drying: An overview on wall deposition, process and modelling. *Journal of Food Engineering*, **146**, 152–162.

41. Meganaharshini, Sudhakar, V., Dhivyabharathi, N. & Deepak, S. (2023) Review on recent trends in the application of protein concentrates and isolates – A food industry perspective. *Food and Humanity*, **1**, 308–325.

42. Bhusari, S., Muzaffar, K. & Kumar, P. (2014) Effect of carrier agents on physical and microstructural properties of spray-dried tamarind pulp powder. *Powder Technology*, **266**, 354–364.

43. Shrestha, A. K., Ua-arak, T., Adhikari, B. R., Howes, T. & Bhandari, B. R. (2007) Glass transition behaviour of spray-dried orange juice powder is measured by differential scanning calorimetry (DSC) and thermal mechanical compression test (TMCT). *International Journal of Food Properties*, **10**, 661–673.

44. Ng, M. L. & Sulaiman, R. (2018) Development of beetroot (Beta vulgaris) powder using foam mat drying. *LWT*, **88**, 80–86.

45. Sarkar, A., Singh, A. & Singh, M. (2015) Spray drying technology for fruit powders: A critical review on fruit powder production, quality, and behaviour during storage. *Journal of Food Processing and Preservation*, **39(5)**, 356–369.

46. Osman, A. F. A. & Endut, N. (2009) Spray drying of roselle-pineapple juice effects of inlet temperature and maltodextrin on the physical properties. *2nd International Conference on Environmental and Computer Science, Dubai, United Arab Emirates*, 267–270.

47. Phoungchandang, S. & Sertwasana, A. (2010) Spray-drying of ginger juice and physicochemical properties of ginger powders. *ScienceAsia*, **36**, 40–45.

48. Lee, J. K. M., Taip, F. S. & Abdullah, Z. (2018) Effectiveness of additives in spray-drying performance: a review. *Food Research*, **2(6)**, 486-499.

49. Jangam, S. V. & Thorat, B. N. (2010) Optimisation of spray drying of ginger extract. *Drying Technology*, **28(12)**, 1426–1434.

50. Gouaou, I., Shamaei, S., Koutchoukali, M. S., Bouhelassa, M., Tsotsas, E. & Kharaghani, A. (2019) Impact of operating conditions on a single droplet and spray drying of hydroxypropylated pea starch: Process performance and final powder

properties. *Asia-Pacific Journal of Chemical Engineering*, **14(1)**, e2268.

51. Pochapski, D. J., Carvalho, Dos Santos C., Leite, G. W., Pulcinelli, S. H. & Santilli, C. V. (2021) Zeta potential and colloidal stability predictions for inorganic nanoparticle dispersions: Effects of experimental conditions and electrokinetic models on the interpretation of results. *Langmuir*, **37(45)**, 13379–13389.

52. Souza, A. L. R., Hidalgo-Chávez, D. W., Pontes, S. M., Gomes, F. S., Lourdes, M. C., Cabral, L. M. C. & Tonon, R. V. (2018) Microencapsulation by spray drying of a lycopene-rich tomato concentrate: Characterization and stability. *LWT*, **91**, 286–292.

53. Dezyani, A., Ziaiifar, A. M., Jafari, S. M., Ghorbani, M. & Mahoonak, A. S. (2017) Optimization of tomato paste powder efficiency production by spray dryer and evaluation of its quality characteristics. *Iranian Food Science and Technology Research Journal*, **13(5)**, 647–662.

54. Oliveira, B. E., Junior, P. C. G., Cilli, L. P., Contini, L. R. F., Venturini, A. C., Yoshida, C. M. P., Braga, M. B. (2018) Spray-drying of grape skin-whey protein concentrate mixture. *Journal of Food Science and Technology*, **55(9)**, 3693–3702.

55. Deng, Y., Liu, G., Zhang, H., Zhou, P., Tang, X., Li, P, Zhao, Z., Zhang, Y., Wang, Z., Wei, Z. & Zhang, M. (2024) Effects of wall materials on the physicochemical properties of spray-dried bitter gourd (Momordica charantia L.) powders. *NPJ Science of Food*, **8(1)**, 37.