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Effects of spray-drying parameters on physicochemical properties of powdered fruits

Liew Phing Pui*, Lejaniya Abdul Kalam Saleena

UCSI University, Kuala Lumpur, Malaysia

* e-mail: puilp@ucsiuniversity.edu.my

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Abstract:
This review features different powdered fruits with optimal storage stability and physiochemical parameters. Spray-drying parameters, such as temperatures and flow rate, can affect the physical properties of powders. Carrier agents provide powders with various favorable qualities, e.g. good flow rate. Commercial spray-drying of fruit juice knows different carrier agents.

The review involved scientific and methodological publications, conference papers, patents, regulatory papers, and Internet resources. They were subjected to grouping, categorization, comparative analysis, and consolidation.

Inlet temperature, maltodextrin concentration, and air flow rate of spray-drying increased the powder yield but decreased the moisture content. Inlet temperature, maltodextrin concentration, and feed flow rate affected the solubility. Effects of atomization rate, air flow rate and free flow rate were assessed in terms of yield, moisture content, hygroscopicity, and solubility.

The article introduces the fundamentals of spray-drying and describes the effect of each spray-drying parameter on the powder quality. The list of parameters included inlet air temperature, atomization rate, air flow, and feed flow rate. We also evaluated the impacts of various carrier agents on the powder quality. The article contributed to a better understanding of how variable parameters affect the quality of food powders. The results provide the food industry with better choice options to adopt certain parameters for specific production needs.

Keywords: Temperature, atomization rate, flow rate, maltodextrin, powder properties

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INTRODUCTION

Dehydration of food allows extending its shelf life by reducing the chemical and microbial activities [1]. Drying reduces the moisture content of powder, which guarantees a long and safe storage [2]. High-water content makes fruit juices highly perishable products with high transportation costs. In this regard, powdered fruit juices are an attractive option for the food business: they are stable, space-effective, and easy to transport [3]. Atomization, droplet-hot air interaction, and moisture evaporation are the three essential processes of spray-drying [4].

Fruits usually undergo such procedures as open sun-drying, hot air drying, solar drying, microwave-drying, freeze-drying, and spray-drying. However, these methods have some disadvantages. For example, hot air drying is time-consuming, and freeze-drying is rather expensive [5, 6]. Spray-drying is a highly suitable process for heat-sensitive products producing powders with good quality [7–9]. Spray-dried powders have good dispersion characteristics and are easy to incorporate into food products [10]. Some resent studies introduced spray-dried powders from cempedak jackfruit and kuini mango [11–13].

Spray-drying is an effective means of making inhalable powders [3]. The list of physicochemical parameters that affect powders during spray-drying includes such process factors as viscosity, particle size, liquid feed flow rate, temperature and pressure of the drying air, the kind of atomizer, etc. As a result, optimizing the drying process is critical for obtaining goods with improved sensory and nutritional properties, as well as for increasing process yield. Studies that feature surface characteristics of powder particles can provide better knowledge of the production process and optimize the powder composition [4].

Effective spray-drying requires a careful selection of operating conditions. For particles ≤ 2 μm, spray-drying has a poor cyclone collection efficiency. A common spray-dryer has an average output of 20–50%, but a new high-performance cyclone developed by the Swiss company BÜCHI increased it to ≥ 70%. Another significant problem with spray-drying is the lack of control over the mean droplet size. As a result, droplets come in a wide range of sizes, and pneumatic nozzles can cause clogging. Ultrasonic nozzles produce more consistent droplets and more uniform size distribution of the powder [7, 8].

Some difficulties, such as stickiness, hygroscopicity, and solubility, can be overcome by introducing the carrier agents before atomization. Biopolymers and gums are the most popular carrier agents. These compounds are typically associated with microencapsulation. They can minimize powder hygroscopicity, protect delicate food components from unfavorable ambient circumstances, reduce food component volatility and reactivity, and improve the appearance of the finished product [10].

Fruit storage provides their off-season supply. However, some fruits tend to rot during storage and lose their nutritional content. The benefits of a dried extract over traditional liquid forms include cheaper storage costs, increased concentration, and active component stability. Spray-drying can produce powders with precise quality criteria in a continuous process [14]. It is a one-stage technology that turns liquid meals or suspensions into powder form. Spray-drying is also used in pharmacy for tablet coating. Spray-drying has three primary steps: atomizing the liquid feed, creating and drying the droplets, and droplet motion.

Problem statement. Spray-dried fruit juice powders have high sugar solids content and usually assume amorphous state [14]. Some recent studies describe the advances in the spray-drying of sugar-rich foods, including fruit juices, pulp, and honey with or without carriers [15]. Products with low molecular weight sugars, e.g. fructose, sucrose, and glucose, have a very low glass transition temperature. Sucrose, glucose, and fructose have the glass transition temperature of 62, 32, and –5°C, respectively. They reduce the glass transition temperature of sugar-rich foods, which are prone to caking during storage [16]. The hygroscopic and thermoplastic nature of dried materials, such as fruit juice powders, are known to cause adhesion to dryer walls, reduce the drying yield, increase stickiness, and decrease solubility [17]. These sugars are very hygroscopic, which increases their stickiness and tendency to agglomeration [18].

Organic lactic, malic, tartaric, and citric acids also make spray-drying difficult. When tartaric, citric, and malic acids were applied at concentrations of ≥ 10% dry matter, they reduced the powder recovery. As a result, spray-drying of fruits with high acid content required more maltodextrin [19]. Spray-drying below +20°C of glass transition temperature helped avoid stickiness but was not economically feasible [20]. Spray-dried blood fruit powder was found to have high solubility and good retention of resveratrol content [21]. This work features the effect of different spray-drying parameters, e.g. temperature, flow rate, flow rate, and carrier concentration, on food powders.

STUDY OBJECTS AND METHODS

The study was carried out at UCSI University in Malaysia's Faculty of Applied Sciences, Department of Food Science and Nutrition. It featured scientific and methodological literature, publications in scientific journals, conference papers, patents, regulatory papers, and Internet resources. The data were grouped, categorized, compared, and consolidated. Because 1995 was the year that the topic of spray-drying was first highlighted, the review includes high-quality peer-reviewed English-language papers published between 1995 and 2021. Most publications were Scopus indexed. The conference papers were chosen based on their citation quantity and keywords. The review did not include books and non-academic resources.

RESULTS AND DISCUSSION

Basic principles of spray-drying. Spray-drying involves five major stages [22, 23]:

1) Concentration. The feed is concentrated before being pumped into the spray-dryer;

2) Atomization. The fluid products are dispersed into fine droplets and pumped into the drying chamber via an atomizer;

3) Droplet-air contact. The atomized feed comes in contact with the hot gas. Water evaporates, leaving a dry product. The contact time between spray-droplets and the hot air is very short, which provides an efficient drying process of heat sensitive materials without thermal decomposition;

4) Droplet drying. It occurs in two sub-stages. The first sub-stage happens at a relatively constant rate. During this sub-stage, the surface of the droplets is quickly moisturized by the water trapped inside the droplets. The second sub-stage happens when the surface of the droplets runs out of moisture. This sub-stage yields a dried product;

5) Separation. The dried powder passes through the cyclone and is then collected in the collection vessel. The air is exhausted from the top of the cyclone and passes through the bag filter.

Main properties of spray-dried powders. Primary powder properties include hygroscopicity, moisture content, solubility, particle density, particle size distribution, appearance, color bulk density, particle morphology, and surface composition [24]. In addition to moisture content, some important characteristics of spray-dried powders also include particle porosity, size, and rehydration [20]. As a result, scientific publications concentrate mostly on the effect of feed qualities and drying conditions on the physical properties of powder, although the results are sometimes confusing [25]. The spray-dried powders are analyzed in a few common tests (Table 1).

The powder yield depends on the kind of fruit and the carrier agent. For example, orange juice powder has a big range of yield, from 25 to 85% [49]. However, acai juice powder yield was reported as 48.49% [26]. The moisture content is one of the main characteristics of powder which affects mainly solubility and bulk density [24]. Moisture content of spray-dried tomato powder was reported as 3.11–9.30%, whereas watermelon juice powder obtained by the same method had 1.47–2.48% moisture content [50, 51].

Fruit juice powder has a high hygroscopic feed and thermoplastic nature. As a result, it sticks to the dryer walls, which is one of the major problems in spray-drying [52]. The other reason might be its low melting point temperature, high water solubility, and low glass transition temperature [53]. Stickiness normally occurs if particles are not dry enough when they come in contact with one another or with the drying wall and thus stick to the drying chamber [19]. Stickiness causes operational issues and lowers the yield [16, 14].

Reported hygroscopicity of 12.48–15.79 for acai powder, while Rodrigues-Hernandez *et al.* stated 36.32–48.93 for cactus pear juice powder [26, 54]. According to Fitzpatrick *et al.*, particle size and particle distribution eventually have significant impact on the powder flowability, handling, and processing [43, 55].

Solubility is another important property of powders [49, 50]. It can be affected by compressed air flow rates, carrier agents, and low feed rates [24]. The water solubility index increased when maltodextrin reached 96% [56]. According to Mahendran, 30% of maltodextrin produced a guava powder with 95% solubility, whereas 60% of maltodextrin added to guava juice decreased the solubility to 86% [38]. Bulk density is an important powder property as it determines the size of containers, which eventually affect the handling and transportation costs.

Consumers prefer it when the powder is reconstituted well and can be instantly dissolved in water [20, 57]. Mango powder showed a good reconstitution property: it completely dissolved in warm water at 40°C with no suspended particles in the solution [52]. Reconstituted pineapple powder was found to have a lower lightness but a higher redness and yellowness, probably, as a result of the non-enzymatic browning reaction that occurred during spray-drying [58].

Youssefi *et al.* measured the color change in the pear cactus juice powder and its reconstituted solution. The slight changes in the color (ΔE) ranged from 6.7 to 9.8 [17]. L* was affected neither by the drying conditions nor by the color change, only by the maltodextrin concentration. The L* values of the reconstituted samples (13.00–16.00) were similar to those of the untreated juice (13.02), which meant that the spray-drying process did not darken the finished product.

Factors affecting the properties of spray-dried powder. Table 2 shows the production of different fruit powders obtained by spray-drying. Spray-drying parameters are important and must be controlled as they affect the quality and quantity of powder. Some parameters of spray-drying include inlet and outlet temperature, air flow rate, feed flow rate, atomizer, carrier agents, and concentration. Different parameters affect such powder properties as bulk density, solubility, hygroscopicity, particle size, flowability, and glass transition temperature [50].

Inlet air temperature and outlet temperature. Table 2 demonstrates the effects of inlet air temperature on the physicochemical properties of spray-dried fruit powders. Such powder properties as moisture content, bulk density, particle size, hygroscopicity, and morphology are all affected by the initial settings of inlet air temperature [61]. Inlet air temperature proved a more important factor than maltodextrin content, judging by bulk density, caking, and water solubility index [62].

Inlet air temperature can range from as low as 80°C for red beet to as high as 205°C in for pear cactus [54, 63]. However, the normal range for spray-drying is 110–160°C [50, 64]. Nevertheless, Phisut reported that the inlet air temperature of 150–220°C is commonly used for food spray-drying [61]. Some recent studies of spray-drying of guava, pineapple, and bael powder revealed the inlet air temperature of 148, 160, and 166°C, respectively [65–67].

Quek *et al.* found that the moisture content of spray-dried powder decreased as inlet air temperature and outlet temperature grew higher [51]. The outlet temperature should be the same to maintain the product quality. For every 2–3°C increase in the inlet air temperature, the outlet air temperature is usually increased by 1°C. According to [49, 51, 68], a higher inlet air temperature reduced the residual moisture content. When the inlet air temperature was increased, the moisture content fell down because the heat transfer happened at a faster rate between the product and the drying air [61].

The inlet air temperature can also affect the hygroscopicity of powder [61]. Similarly, powders produced at higher inlet air temperatures were more hygroscopic [24, 26]. Higher inlet air temperatures lowered the moisture content in the powder, causing the powder to absorb moisture from the environment [61]. Inlet air temperature can also affect bulk density. In particular, increasing the inlet air temperature caused the bulk density to drop [49]. For instance, the bulk density of acai juice powder decreased as the inlet air temperature increased [26].

When temperature increased during spray-drying, case-hardening appeared at the outer layer of atomized powder [61]. Particle size was reported to increase together with temperature. Higher drying temperatures resulted in faster drying rates, triggering an early structural formation and preventing the particles

Table 1 Spray-drying conditions in fruit powder production

Powder	Initial sample	Total solids	Inlet temperature, °C	Outlet temperature, °C	Aspirator rate/air velocity	Feed rate	Atomization rate/ compressor pressure	Analysis	References
Acai	Pulp	–	138–202	82–114	73 m^3/h, 0.06 MPa	5–25 g/min	–	Process yield, moisture content, hygroscopicity, anthocyanin retention, outlet temperature	[26]
Amla	Juice	–	120–200	81–119	75 m^3/h	13–15 mL/min	0.12 mPa	Moisture content, hygroscopicity, bulk density, water solubility index, surface morphology, DPPH, total phenolic content	[27]
Andes berry	Juice	9°B	12	70	10 m^3/h	485 mL/h	4 bar	Particle morphology, size, thermal analysis, volatile compounds, anthocyanin activity	[28]
Bayberry	Juice	11°B	150	80	100% (35 m^3/h)	–	439 L/h	Product recovery, moisture content, water activity, glass transition temperature, surface composition	[29]
Ber	Juice	–	170–210	–	40–80 m^3/h	1 L/h 9–21%	–	Color, bulk density, hygroscopicity, packed density, outlet temperature	[30]
Black currant	Extract	Final 35°B	150, 160, 180, 205	70, 70, 85, 100	–	–	–	Total polyphenol, antioxidant activity	[31]
Black mulberry	Juice	–	110–150	–	800 L/h	150 mL/h	4.65 bar	Yield, moisture content, bulk density, solubility, surface morphology, glass transition temperature, particle size	[32]
Blackberry	Pulp	–	140–180	99–115	35 m^3/h	0.49 kg/h	0.36 m^3 air flow	Moisture content, hygroscopicity, anthocyanin content, color, surface morphology, particle size	[33]
Blueberry	Extract	30% total solids	160	70	–	–	23 000 rpm	Particle size, true density, water-binding capacity, anthocyanin content	[34]

Continuation of Table 1

Powder	Initial sample	Total solids	Inlet temperature, °C	Outlet temperature, °C	Aspirator rate/air velocity	Feed rate	Atomization rate/ compressor pressure	Analysis	References
Cantaloupe	Juice	–	170–190	75–77	–	–	–	Moisture content, water activity, vitamin C, β-carotene content, dissolution, surface morphology	[35]
Elderberry	Juice	10–13°B	70–120	–	–	180 & 300 mL/hr	–	Total phenolic content, color	[36]
Gac	Aril	–	120–200	83–125	56 m^3/h	12–14 mL/min	0.06 mPa	Moisture content, water activity, bulk density, antioxidant activity, color total carotenoid, water solubility index	[37]
Guava	Concentrate	10.5°B	160	80	–	–	40 000 rpm	Moisture content, pH, titratable acidity, total sugars, vitamin C, total soluble solids	[38]
	Slurry	–	170–185	80–85	4 kg/m^2	18–20 rpm	–	Moisture content, solubility, dispersibility, vitamin C	[39]
Indian gooseberry	Juice	19%	120/160	80	–	1.2 mL/min	2.4×10^2 kPa	Moisture content, water activity, vitamin C, dissolution	[40]
Lime	Juice	9.5	140–170	–	–	1.75 g/min	5 bar	Powder recovery, bulk density, surface morphology color	[41]
Orange	Juice	56–57%	160	65	–	–	–	Color, moisture content, titratable acidity, water activity, particle size, bulk density, glass transition temperature	[42]
Pitaya	Juice	50%	145–175	–	–	400 L/h	4.5 bar	Moisture content, water activity, color, true density, bulk density, tap density, Carr Index, Hausner ratio, glass transition temperature, particle size, surface morphology, betacyanin content	[43]
Pomegranate	Juice	20–44°B	110–140	–	0.53 m^3/min	7 mL/min	–	Moisture content, hygroscopicity, anthocyanin content, color, solubility, bulk density, yield, total phenolic content, antioxidant activity	[44]

Continuation of Table 1

Powder	Initial sample	Total solids	Inlet temperature, °C	Outlet temperature, °C	Aspirator rate/air velocity	Feed rate	Atomization rate/compressor pressure	Analysis	References
Red beet	Concentrate	20%	150, 165, 180, 195, 210	87–115	56 m^3/h	390–560 g/h	–	Moisture content, hygroscopicity, drying ratio, drying rate, productivity, bulk density, color, Tg, betayanin content	[45]
Red pitaya peel	Puree	–	155–175	75–85	900 m^3/min	–	15 000 rpm	Color, hygroscopicity, moisture content, solubility, water activity, betacyanin retention	[46]
Satureja Montana L.	Extract	–	135–140	60–70	–	–	20 000–21 000 rpm	Yield, moisture content, bulk density, hygroscopicity, water solubility index, total phenolic content, total flavonoid, sensory evaluation	[47]
Sea buckthorn	Juice	–	148.79–191.21	65–9	2.1 kg/cm^3	30 rpm	50 Hg	Moisture content, dispersibility, vitamin C, overall color change	[48]

The table is based on the findings of this study

from shrinking during drying [69]. A higher inlet air temperature produced powder with larger particles and greater swelling [70]. A lower inlet air temperature resulted in shrunk and smaller particles.

The moisture content in the powder was reported to improve solubility: the solubility of spray-dried raisin extracts and tomato concentrates increased together with the moisture content [18, 24, 50, 51]. The solubility of spray-dried roselle and tomato powder decreased as the drying temperature fell [24, 71]. A larger spray-dryer affected the beetroot powder color changes, namely increased the *a** value and decreased the *b** value [72].

Quek *et al.* focused on the color of spray-dried watermelon powder [51]. When the inlet air temperature increased, the *b** value increased. However, the *a** values increased at 145–165°C and started to decrease at 175°C. The lightness of the powders decreased when the temperature grew higher. At a higher inlet air temperature, the color of the powders turned darker. Red color decreased when the inlet air temperature rose [51]. The stability of heat sensitive pigment depended on the inlet air temperature. The lycopene content in watermelon juice powder decreased at a higher inlet air temperature, which was in agreement with another publication on tomato pulp [50]. The reduction of lycopene content was likely due to thermal degradation and oxidation. On the other hand, Tonon *et al.* also reported that the inlet air temperature affected the anthocyanin content in acai juice powder [68]. A higher inlet air temperature also decreased the amount of pigments in powder [61].

Atomization rate and air flow rate. Tables 3 and 4 illustrate the effects of atomization rate and air flow rate, respectively. As for atomization rate, spray-drying uses different ranges of speed. Atomization rate had a positive effect on sirih powder yield [73]. Amla and

Table 2 Effects of inlet air temperature on physicochemical properties of spray-dried fruit powders

Powder	Inlet air temperature, °C	Yield/ recovery, %	Moisture content	Water activity	Hygroscopicity	Density	Porosity	Particle size	Caking	Solubility	Color	Pigment	Antioxidant activity	Vitamin C	References
Acai	138–202	+ve	–ve	–	+ve	–	–	+ve	–	–	–	–ve	–	–	[26]
Acerola pomace	170–200	–	–ve	–	–ve	–	–	–	–ve	+ve	–	–	–	–	[59]
Amla	100–200	–	–ve	–	–ve	–ve	–	–	–	NS	L*+ve	–	–ve	–	[27]
Ber	170–210	–	–	–	+ve	–ve	–	–	–	–	–	–	–	–	[30]
Black mulberry	110–150	+ve	–ve	–	–	–ve	–	–	–	+ve	–	–	–	–	[32]
Blackberry	140–180	–	–ve	–	–ve	–	–	NS	–	–	L*+ve	–ve	–	–	[33]
Cantaloupe	170–190	–	–ve	–	–	–	–	–	–	–	L*–ve a*+ve b* NS	–	–	–	[35]
Gac	120–200	–	–ve	–ve	–	–ve	–	–	–	–	L* NS TC NS	–ve	–ve	–	[37]
Guava	170–185	–	–ve	–	–	–	–	–	–	+ve	–	–	–	+ve	[39]
Jujube	140–160	–	NS	–	+ve	–	–	–	–	–	L*–ve TC +ve	–	–	+ve	[60]
Lime	140–170	+ve	NS	–	+ve	–	–	–	–	–	–	–	–	–	[41]
Orange juice	110–170	–	–ve	–	NS	–	NS	–	–	–	–	–	–	–	[49]
Pitaya	145–175	–	–ve	–	–	–	–	–	–	–	LNS	NS	–	–	[43]
Pomegranate	110–150	NS	–ve	–	NS	+ve	–	–	–	+ve	TC +ve a*–ve	–ve	+ve	–	[44]
Red pittaya peel	155–175	–	–ve	–ve	–ve	–	–	–	–	+ve	L* +ve a*–ve	–ve	–	–	[46]
Watermelon	145–175	–	–ve	NS	–	–ve	–	–ve	CI NS HR NS	+ve	L*–ve a* NS b*+ve	–ve	–	–	[51]

+ve – positive effect; –ve – negative effect; NS – no significant effect; – – not reported

orange powder with greater moisture content resulted from an increase in atomization rate [27, 49]. However, Tee *et al.* stated that raising the atomization rate by 80–100% produced sirih powder with low moisture content and low hygroscopicity [73].

As for the air flow rate, Fazeli *et al.* and Goula and Adamopoulos applied air flow rate of 400–800 and 500–800 L/h, respectively, to produce black mulberry and tomato powders [32, 74]. Fazeli *et al.* reported that the powder yield increased with faster air flow rate, producing a powder of lower moisture content and higher solubility [32]. Greater air flow rates reduced the moisture content and increased the density [32, 74]. However, as the air flow rate increased, the solubility of black mulberry fell down while that of tomato increased [32, 74].

Feed solid content and flow rate. Table 5 summarizes the effects of feed flow rate on the physicochemical properties of spray-dried powdered fruits. Most of the initial sample used for spray-drying were in the form of juice [36, 51, 76]. Two types of value were reported for Brix sample solids. Moßhammer *et al.*, used pear cactus juice with 65% of total solids while Roustapour *et al.* reported lime juice with 12% total solids as spray-drying feed [75, 76]. The Brix value also depended on the fruit. For instance, bayberry juice spray-dried into powder had Brix of 7–17°, whereas for pomegranate juice it was 20–44° [65].

Different rates of spray-drying feed have also become subjects of scientific research. Elderberry juice was spray-dried into powder at the feed rate of 180 and 300 mL/h [36]. However, Ferrari *et al.* spray-dried blackberry pulp at the feed rate of 0.49 kg/h [33]. Bazaria and Kumar utilized feed flow rate of 400 mL/h to obtain high-quality spray-dried powdered beetroot [78]. Ribeiro *et al.* used different levels of intake temperature (110, 140, and 170°C), feed flow (0.36, 0.60, and 0.84 L/h), maltodextrin quantity (14–26%), and maltodextrin dextrose equivalent (DE) as independent variables (5, 10, and 15 DE) [79].

Table 3 Effects of atomization rate on physicochemical properties of spray-dried powders

Powder	Atomization rate	Yield/recovery, %	Moisture content	Hygroscopicity	Density	Particle size	Solubility	References
Amla	30–50	–	+ve	NS	NS	–	NS	[27]
Sirih	80–100%	+ve	–ve	–ve	–	–ve	–	[73]
Orange	10 000–25 000 rpm	–	+ve	–	NS	NS	–	[49]

+ve – positive effect; –ve – negative effect; NS – no significant effect; – – not reported

Table 4 Effects of air flow rate on physicochemical properties of spray-dried powders

Powder	Air flow rate	Yield/recovery, %	Moisture content	Density	Solubility	References
Black mulberry	400–800 L/h	+ve	–ve	+ve	–ve	[32]
Lime	47.1–57.8 m^3/h	+ve	NS	NS	–	[41]
Tomato	500–800 L/h	–	–ve	+ve	+ve	[74]

+ve – positive effect; –ve – negative effect; NS – no significant effect; – – not reported

Table 5 Effects of feed flow rate on physicochemical properties of spray-dried fruit powders

Powder	Feed flow rate	Yield/ recovery, %	Moisture content	Water activity	Hygro-scopicity	Density	Particle size	Solu-bility	Color	Pigment content/ retention	References
Acai	5–25 g/min	–ve	+ve		NS	–	–	–	–	–	[26]
Jujube	3–5 m^3/h	–	+ve		–ve	–	–	–	*L**–ve TC +ve	–	[60]
Orange	150–450	–	–ve		–	NS	NS	–	–	–	[49]
Water-melon and carrot	2–5 mL/min	–	+ve		–	–	–	+ve	–	–ve	[77]

+ve – positive effect; –ve – negative effect; NS – no significant effect; – – not reported

Tonon *et al.* observed that high feed flow rates resulted in a lower yield [26]. This correlation was related to the slow heat and mass transfer. Higher feed flow rates triggered wall deposit, which reduced the yield [80]. Feed flow rate also had an adverse effect on the powder moisture content [77]. High feed flow rate shortened the time of contact between the feed and the drying air, thus decreasing the effectiveness of the heat transfer. An increment in feed flow rate also affected the evaporating intensity, which lowered the inlet air temperature and increased the water content in the powder [81]. Chen *et al.* reported that higher feed flow rate resulted in low-hygroscopicity jujube powder [60]. In addition, higher feed flow rates increased the particle size [80]. Higher feed flow rates increased the solubility of fermented carrot-and -watermelon juice powder [82].

Type and concentration of carrier agents. Selecting the best drying aids is one of the most important steps in spray-drying of fruits and vegetables. Drying aids, or wall materials, or carriers, are mostly used to increase the glass transition temperature of the feed. They can improve the recovery by decreasing the stickiness which causes the product to stick together or to the drying chamber [16]. An ideal spray-drying carrier has a high solubility, bland taste, and good emulsifying and drying properties. Its limited solution viscosity is at 35–45% solids content; it is nonhygroscopic, nonreactive, and cheap [83]. Maltodextrin, alginate, Arabic gum, modified starch, inulin, and their combinations served as carriers for spray-drying of carotenoid-rich goldenberry (*Physalis peruviana* L.) juice, while cellobiose was used as control [84].

Table 6 demonstrates different carrier agents in fruit powder production, the most common carrier agents being maltodextrin and Arabic gum. Arabic gum had a high glass transition temperature and proved efficient in flavor retention [85]. Arabic gum is expensive because its supply from Middle East and Africa is as unpredictable as its quality. Maltodextrin is not only neutral in color and taste but also relatively cheap, which makes is the most common carriern commercial spray-drying [7, 16]. Maltodextrin consists of β-D-glucose units that are linked by glycosidic bonds (1→4), with dextrose equivalency (DE) that indicates its reducing capacity [86]. Lee *et al.* studied the use of additives as carriers in spray-drying, as well as the impact on such physicochemical parameters as hygroscopicity, flavor retention, and color indexing [87].

Table 6 Applications of different carrier agents in spray-drying of fruit powders

Powder	Initial sample	Carrier agent	Concentrations/ percentage	Analyses	References
Acai	Pulp	Matodextrin (DE 20) & Arabic gum	6%	Process yield, moisture content, hygroscopicity, anthocyanin retention, outlet temperature	[8]
Amla	Juice	Maltodextrin	3–9% (w/v) juice	Moisture content, hygroscopicity, bulk density, water solubility index, surface morphology, DPPH, total phenolic content	[38]
Bayberry	Juice	Maltodextrin (DE 12 & 19)	1:1 (fruit juice)	Moisture content, color	[64]
		Maltodextrin DE 10	10–50%	Product recovery, moisture content, water activity, glass transition temperature, surface composition	[29]
Black mulberry	Juice	Maltodextrin DE 6, 9, 20	8–16%	Yield, solubility, bulk density, moisture content	[32]
Blackberry	Pulp	Maltodextrin (DE 20)	5–25%	Moisture content, hygroscopicity, anthocyanin content, color, surface morphology, particle size	[33]
Blackcurrant	Extract	Maltodextrin (DE 11, 18, and 21)	Total °B 35	Total polyphenol and antioxidant activity	[31]
Blueberry	Extract	Maltodextrin (DE 18.5)	Total solids 30% (blueberry solids 20%)	Particle size, true density, water-binding capacity, anthocyanin content	[34]
Cantaloupe	Juice	Maltodextrin (DE 9–13)	10%	Moisture content, water activity, vitamin C, carotene content, dissolution, surface morphology	[35]
Elderberry	Juice	Acacia gum & maltodextrin (DE 4–7)	5:1–5:4; 1:1 (juice)	Total phenolic content, color	[36]
Gac	Fruit aril	Maltodextrin DE 12	10–30%	Moisture content, water activity, pH, color, water solubility index, bulk density, carotenoid, antioxidant	[37]
Gooseberry	Juice	Maltodextrin	19% TSS	Moisture content, water activity, vitamin C, dissolution time	[40]
Guava	Juice	Maltodextrin 500 RM1249	7–12%	Moisture content, solubility, dispersibility, vitamin C	[39]
Jucara	Pulp	Arabic gum, Maltodextrin, Gelatin	Arabic gum and Maltodextrin (5–55%), Gelatin (5–15%)	Anthocyanin content, moisture content, water activity, hygroscopicity, solubility, total color change, bulk density	[88]
Lime	Juice	Maltodextrin (DE 5)	10–30%	Moisture content	[76]
Mango	Juice	Maltodextrin, arabic gum, starch wax, crystalline cellulose		Surface morphology, stickiness, solubility, powder diffraction	[14]
Orange	Concentrate	Maltodextrin (DE 6-21)	–	Glass transition temperature, residue formation	[74]
	Juice	Maltodextrin and liquid glucose	–	Particle size, wettability time, insoluble solids, bulk density, moisture content	[49]
Pineapple	Juice	Maltodextrin (DE 10)	10–12.5%	Moisture content, color, bulk density, solubility	[7]
Pitaya	Juice	Maltodextrin	20 and 30%	Moisture content, water activity, color, true density, bulk density, tap density, Carr’s Index, Hausner ratio, glass transition temperature, particle size, surface morphology, betacyanin content	[43]

Continuation of Table 6

Powder	Initial sample	Carrier agent	Concentrations/ percentage	Analyses	References
Pitaya	Juice	Maltodextrin DE 10	8–22% w/w	Color, hygroscopicity, moisture content, water activity, solubility, betacyanin content	[46]
Pomegranate	Juice	Maltodextrin, arabic gum, starch wax	8 and 12%	Yield, solubility, color, total anthocyanin, antioxidant	[17]
Seabuckthorn fruit	Juice	Maltodextrin DE 20	20–49 g in 100 mL	Moisture content, solubility, dispersibility, vitamin C, overall color difference	[48]
Strawberry	Juice	Maltodextrin	10–30%	Vitamin C loss, solubility, anti-caking, sensory	[89]
Watermelon	Juice	Maltodextrin (DE 9–12)	3 and 5%	Moisture content, water activity, dissolution, color, carotene content, sugar	[51]

Table 7 Effects of maltodextrin concentration on physicochemical properties of spray-dried powder

Powder	Maltodextrin concentrations, %	Yield/ recovery, %	Moisture content	Water activity	Hygroscopicity	Density	Particle size	Caking	Solubility	Color	Pigment content/ retention	Antioxidant activity	Vitamin C	References
Acai	10–30	–	NS	–	+ve	–	+ve	–	–	–	–	–	–	[26]
Amla	3–9	–	–ve	–	–ve	NS	–	–	NS	L^*+ve	–	–ve	–	[27]
Black mulberry	8–16	+ve	–ve	–	–	–ve	–	–	+ve	TC–	–	–	–	[32]
Blackberry	5–25	–	–ve	–	–ve	–	–	–			–ve	–	–	[33]
Guava	5.95–13.03	–	+ve	–ve	–	–	–	–	+ve	–	–	–	–ve	[39]
Pineapple		–	–	–	–	–ve BD	–	–	–ve	NS	–	–	–	[7]
Pitaya	20 30	–	–ve	NS		+ve	–	NS		L^*+ve	–ve	–	–	[43]
Pomegranate	44.1–59.1	+ve	–ve	–	–ve	+ve BD	–	–	+ve	TC+ve a^*_{RP} –ve	+ve	–	–	[44]
Red pittaya	8–22	–	+ve	+ve	+ve	–	–	–	+ve	L^*–ve a^*–ve	–ve	–	–	[46]

BD – bulk density; TC – total color changes, +ve – positive effect; –ve – negative effect; NS – no significant effect; – – not reported

Maltodextrin has been used to spray-dry sticky products, e.g. orange, tamarind, blackcurrant, raspberry, and apricot juice, honey, mango pulp, raisin juice, lime juice, watermelon pulp, and sweet potato puree because it facilitates the drying process [25]. The percentage of carrier agents incorporated ranges from 3% for watermelon juice powder to 40–64% for pomegranate juice powder [44, 51]. The concentration of maltodextrin was 15, 20, and 25%, respectively, in the production of spray-dried cempedak, papaya, and terung asam powder [90–92]. However, Henao-Ardila *et al.* reported 22.62% maltodextrin concentration as optimal for spray-drying of feijoa pulp, while Dantas *et al.* used 23% of malto-dextrin to produce powdered avocado drink [93, 94]. The flowability, color, antioxidant activity, and phenol content of barberry powder were optimal at 13% (w/w) of maltodextrin [95].

Table 7 shows the effects of maltodextrin concentration on the physicochemical properties of spray-dried powder. Maltodextrin reduced the moisture content, which might be explained by the increment in feed solids and the low amount of free water [38, 50, 51, 96]. With the use of it, the yield was 18–35% but there was more deposit on chamber wall [49]. Maltodextrin increased the yield up to 18–35% but the deposit on the chamber wall reached 65–82% [49]. Yet the concentration of maltodextrin is important in controlling the quality of the powder. For instance, a higher amount of maltodextrin dextrose equivalent made it possible to obtain low-hygroscopicity liquorice [97]. Leyva-Porras *et al.* investigated the effect of spray-drying

Table 8 Applications of Response Surface Methodology (RSM) in spray-drying of fruits

Powder	Starting material	Independent variables	Response variables	Optimization	Design	Software	References
Acai	Juice	Inlet air temperature, feed flow rate, maltodextrin concentration	Process yield, moisture content, hygroscopicity, anthocyanin retention, outlet temperature	RSM	Rotatable central composite design	Statistica 5.5	[26]
Acerola	Juice	Inlet air temperature, Drying aid/acerola, percent replace of maltodextrin by crystalline cellulose	Moisture content, hygroscopicity, water solublity, flowability	RSM	Central composite design (CCD)	Minitab 15	[59]
Blackberry	Pulp	inlet air temperature, maltodextrin concentration	Moisture content, anthocyanin retention, hygroscopicity, particle size, color parameters	RSM	Central composite rotatable design	Statistica 8.0	[33]
Cashew apple	Juice	Drying aid/juice, percent replace of maltodextrin by crystalline cellulose	Ascorbic acid retention, hygroscopicity, flowability, water solubility	RSM	RSM with 11 runs	Minitab 15	[85]
Guava	Slurry	Inlet air temperature, maltodextrin concentration	solubility, moisture content, dispersibility, vitamin C	RSM	CCRD	–	[39]
Jujube	Juice	Inlet air temperature, maltodextrin concentration, feed flow rate	Moisture content, vitamin C, color, hygroscopicity	RSM	Box Behnken	–	[60]
Orange	Juice	Inlet air temperature, atomization rate, flow rate	Particle size, wettability time, insoluble solids, bulk density, moisture content	Full factorial design	Complete random design	–	[49]
Pineapple	Juice	Atomization rate, maltodextrin concentration	Apparent and true density, color, moisture content, solubility	Complete factorial design	3 repetition at center point	–	[7]
Pomegranate	Juice	Inlet air temperature, maltodextrin concentration, feed/mix concentration	Moisture content, hygroscopicity, anthocyanin content, color, solubility, bulk density, yield, total phenolic content, antioxidant activity	RSM	CCD	Design expert 6.0	[44]
Red pitaya peel	Puree	Inlet air temperature, outlet temperature, maltodextrin concentration	Color, hygroscopicity, moisture content, water activity, solubility, betacyanin content	RSM	CCD	–	[46]

settings on the microencapsulation of bioactive components and the physicochemical qualities of strawberry juice with maltodextrin as a transporting agent [98].

Reduction in maltodextrin generally improved the solubility [7]. Similar observation was reported by Moreirra *et al.*, who used a drying assistance ratio of cashew apple juice dry weight (5:1) and cashew tree gum substituting maltodextrin in 50% of spray-drying of cashew apple juice generated with high solubility (> 90%) [59]. The solubility of spray-dried mango powder decreased as the cellulose concentration grew. At 9% of cellulose, the solubility values of mango powder were 72, 71, and 31% using maltodextrin, arabic gum, and waxy starch, respectively [14]. Quek *et al.* studied watermelon powder production and discovered that adding maltodextrin in greater quantities than 10% led to color loss [51]. These results confirmed those obtained by Farimin and Nordin, who studied roselle-and-pineapple powder [96]. Papadakis *et al.* reported that the exact color of each powder depended on the ratio of raisin juice solids:maltodextrin solids [18].

Optimization of spray-drying process. Response surface methodology is applied to determine the optimum condition of spray-drying because this procedure is comprehensive, simple, and highly efficient [82, 99]. The central composite design builds a quadratic model for the response variable without a complete three level factorial experiment. Only by optimizing the spray-drying process, food producers can obtain better powder properties and yield [26].

Table 8 summarizes the use of response surface methodology as optimization for spray-drying of fruit powder. The main independent variables are inlet air temperature, maltodextrin concentration, and feed or flow rate [20, 26, 100]. Moisture content and water solubility are the most important properties of food powder [19]. However, yield and hygroscopicity proved to be the common response variables [26, 59]. Consequently, optimization of the amount of carrier is an important step in making a commercial product [16]. Li *et al.* applied the Box-Behken method to obtain the optimal condition of 142.8°C, 23.7% core material, and 11.7% feed solid in spray-drying of plum [101]. Pandey *et al.* reported the inlet temperature of 166.64°C and 9.26% maltodextrin concentration as optimal conditions for fruit slurry spray-drying process [102].

CONCLUSION

This review covered the basic principles of spray-drying while determining the effects of each spray-drying parameter on powder properties. These parameters included inlet air temperature, atomization rate, air flow rate, and feed flow rate. The article also summarized the effects of different carrier agents on the powder. Inlet temperature of spray-dryer and carrier concentration were found to increase the product yield and solubility, as well as to decrease the moisture content, pigment, and antioxidant content.

However, inlet temperature proved to be the main factor that affected the powder density. On the other hand, atomization rate had little effect on powder properties. Certain powder properties depended on the type of fruit and the range of parameters applied. The review showed that the impact of additives and encapsulation on the physicochemical parameters of fruit extract powder is critical. Changing the spray-dryer settings can solve the technical obstacles in spray-drying of fruit extracts. In addition, spray drying is a newer and cheaper method of turning fruit extracts into powder.

CONTRIBUTION

Liew Phing Pui gathered data, donated data and analysis tools, conducted the study, wrote the manuscript, and submitted it. Abdul Kalam Saleena Lejaniya was in charge of data collection and data contribution, formatted the manuscript and proofread the article.

CONFLICT OF INTEREST

The authors note that they have no known conflicting financial or personal interests that might have impacted the findings of this study.

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ORCID IDs
Liew Phing Pui https://orcid.org/0000-0001-5305-4334
Abdul Kalam Saleena Lejaniya https://orcid.org/0000-0001-7852-8073