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Top-Spray Agglomeration Process Applications in Food Powders: A Review of Recent Research Advances

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ABSTRACT

There is a rising demand for improving instant properties of powders which increase consumer appreciation, reduce losses during production and facilitate the processability of these powders. Fluidized bed agglomeration is used to produce large and porous dry agglomerates with improved instant properties. In this review, the applications of the wet agglomeration process for different food powder types were optimally scrutinized. Food powders were categorized in milk and milk products, cereals, fruits and vegetables and gum powders. The major findings of the studies and improved powder properties were emphasized in the review. This review is a supplementation to the adoption of this technique for the development of food powders with optimally instant properties.

1. Introduction

Converting foods into powder form provides advantages such as easy and economical transportation as a result of a decrease in volume and long shelf life (Forny, Marabi, & Palzer, 2011; Jinapong, Suphantharika, & Jamnong, 2008). Spray drying technology is one of the techniques commonly used in the drying of liquid foods. The short contact time of the product with hot air causes a high evaporation rate and the heat damages of the powders are minimized. However, spray drying is not the only solution in instant powder production. Powders obtained from the single-stage spray dryer show low reconstitution due to high cohesion forces between the particles (Chen, Yang, Dave, & Pfeffer, 2009). Agglomeration process is defined as the size enlargement process in which fine particles join other particles, resulting in a porous structure and increase in instant properties of powders. Agglomeration process can be subdivided into wet or dry agglomeration depending on whether the binder liquid is added or not (Dhanalakshmi, Ghosal, & Bhattacharya, 2011). Wet agglomeration applied as binderless (using water) or using binder solutions. Agglomeration is widely used in the pharmaceutical and chemical field as well as its use in the food industry is known to gradually become widespread. In the food industry, it is used in the production of instant milk powders, soup mixes, instant chocolate mix, beverage powders and compressed cubes (bouillon), flour, instant coffee, cocoa powder, sweeteners, juice powders and herbal extracts within the scope of instant product production (Dhanalakshmi et al., 2011).

Wetting agglomeration technology provides higher instant properties such as dispersibility, wettability and sinkability as well as obtains high particle size and porous morphology enables the production of desired high quality. Powders with improved instant properties increase consumer appreciation, reduce powder losses during processing and facilitate the processability of these powders in the industry.

The agglomeration of the particles consists of three stages that repeat continuously. In the initial stage, the powder acquires fluency on hot air and the binder solution is sprayed on the surface of the powders. Spraying the binder makes the particles moist. Liquid bridges form and adhesion occurs when the adhesive particles collide with each other (Barkouti, Turchiuli, Carcel, & Dumoulin, 2013; Turchiuli, Smail, & Dumoulin, 2013). With the drying process in hot air, wet particles are partially dried and stabilized.

2. Principle of Wet Agglomeration Technique

In principle, the agglomeration process is carried out by making the powders flow upward with airflow and spraying the binder solution with the powder in motion (Bernard Cuq, Mandato, Jeantet, Saleh, & Ruiz, 2013). While it may be sufficient to use pure water for amorphous water-soluble powders, viscous lactose, mannitol, or hydrocolloid solutions are as binder solutions used for crystalline water-soluble particles (Palzer, 2011). The selection of a suitable binder type is an important parameter that affects particle enlargement and shapes. These differences occur from binder types' chemical composition, viscosity and interactions

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between particles. The concentration of binder is also another important parameter as well as binder type. Different concentrations of binder led to different agglomerate sizes and morphology, porosity and density (Jeong, Bak, & Yoo, 2019; Jinapong et al., 2008).

Mechanisms such as wetting, development, consolidation, fraction and drying occur spontaneously during the fluidized bed agglomeration process (Turchiuli, Eloualia, El Mansouri, & Dumoulin, 2005). The air supplied from the bottom of the system in a fluid state and acts as a carrier of heat and moisture. Agglomerates obtained with fluidized bed systems show highly porous and irregular shape distribution. To obtain spherical agglomerates, it is necessary to use low viscosity binders or increase fluid air velocity and bed height (Cuq et al., 2013).

Spraying the liquid binder in the fluid bed process wet the particle surface and make the particles sticky due to the binder forming a film or modifying the particle surface viscosity (Turchiuli et al., 2005). This is especially observed when the amorphous components convert into the elastic phase due to the decrease in glass transition temperatures with the increase of water content of the carbohydrate-containing powders (Turchiuli et al., 2013). Adhesion occurs with liquid bridges or agglomerations by the collision of sticky particles. Afterward, the new structure formed by hot air drying process becomes stronger. Although the steps such as strong mixing, hot air drying and wetting occur simultaneously throughout the fluidized bed process, there are three different regions where these processes are concentrated (Jiménez et al., 2006).

The first zone is the wetting active zone where is the upper part of the bed and is near the nozzle. It is the region with high humidity and low temperature, and wetting of the particles causes humidity and temperature transitions to the dust. The second zone is the isothermal zone is the region near the bed walls, where the heat and mass transfer are balanced and the air temperature is homogeneous. The last zone is heat transfer zone is just above the air distributor. The temperature of the air entering this zone decreases due to the cold particles coming from the upper regions absorbing energy. The agglomeration of the particles takes place in the active zone, where the surfaces are wetted with binder liquid. The size of this region and the duration of the particles in this region are very important parameters in terms of particle development (Turchiuli et al., 2013). Many parameters are affecting the agglomeration growth kinetics in the spray agglomeration system. Parameters such as air velocity, air inlet temperature, spray rate, amount and type of binder, atomization pressure, water holding capacities of the powders, fluidity properties and size of the conical cell (the area where the agglomeration process takes place) are the process conditions need to be optimized to complete the agglomeration process. Especially, air temperature and velocity are the major process parameters that affect agglomeration growth. Low temperature and air velocity can cause particles to get wet and can cause powder to collapse on the fluidized bed and adhere to the bed walls. The high temperature and air velocity cause excessive drying in agglomerates, causing the wetting stage to disappear and the dispersion of agglomerates due to friction. If both cases occur, agglomeration is considered unsuccessful. Unless these conditions are properly adjusted, the powders can reach the filters with excessive drying, or if they remain too humid, stickiness occurs at the heat transfer area and powder show less fluidity.

As the agglomeration process continues, polydisperse particle size agglomerates are formed. Small and light particles frequently enter the wetting active zone, while heavy particles remain in the isothermal zone for a longer period. As the agglomerates develop, large particles in the porous structure are formed and the density decreases (Ji, Cronin, Fitzpatrick, Fenelon, & Miao, 2015). Bed height decreases as the agglomeration process progress by keeping the air velocity constant and the height should be controlled by increasing the velocity of air.

3. Top Spray Wet Agglomeration Process Applications in Food Products

In that section, the application of the top spray wet agglomeration process in foods is divided into four groups as milk and milk product powders, fruit and vegetable powders, cereal powders and gums (Table 1). The process parameters, the major findings of the studies were discussed.

3.1. Milk and milk product powders

The production of dairy powders is growing rapidly worldwide. Especially direct consumption by rehydration, utilization in different food formulas increase the importance of instant properties of these powders. The wet agglomeration process was applied to different milk and milk product's powders. Ji et al. (2015) agglomerated milk protein isolates with water, lactose, and sucrose (15%) binders and determined that the structural and physical properties of the powders changed significantly with the fluidized bed agglomeration process. The agglomeration process decreased the bulk density while the porosity of the powders increased. Agglomerated particles showed low sphericity and convexity, while elongation properties were found to be high. The type of binder has affected the particle shape. The use of water resulted in more uneven particle formation than other sugar binders. As a result, the wettability of powders in which hydrophilic sugars are used as binders has improved. Szulc & Lenart (2013) agglomerated milk-derived multi-component powders with top-sprayed fluidized bed agglomeration technique by using distilled water, 15% lactose and sucrose solutions and 2% lecithin solutions as binding solutions. The average particle size value of the non-agglomerated powder increased from 146 μm to 217 μm with the agglomeration process. The highest particle size and porosity ratio were obtained by using 15% sucrose solution as binder. The loose and compacted bulk density of the agglomerated powders was found to be significantly lower compared to the non-agglomerated powders. It has been revealed that the wet agglomeration process causes modifications on the surfaces of the particles. No improvement in the wetting ability of powders has been observed in both agglomeration and coating processes. This situation is attributed to the presence of starch and protein on the surface of the powders and it was determined that they prevent the powders from fully wetting as they form a thin layer when contacting with water. Barkouti et al., (2013) agglomerated fatty and non-fat milk powders and it was found that significant changes were observed in the particle size and powder structure of the milk powders with the fluidized bed agglomeration process and the wettability and fluidity properties were also improved. Turchiuli et al. (2013) agglomerated skim milk powders with distilled water. With the agglomeration process, powders with an initial particle size of 128 μm were reached up to 618 μm. The loose and compacted bulk density value decreased compared to the control sample. At the same time, the wetting time of the powders that had poor wetting properties at the beginning was

Table1. Summary of the studies about the top-sprayed agglomeration process of food powders

Dairy-Based Milk Powders

Application	Top-Spraying Process Parameters	Agglomerated Powder Properties	References
Skim and whole milk powders	Total sprayed wetting material: 55g/100g particle Air flow rate: 75kg/h Inlet air temperature: 49 ºC Used wetting material: Distilled water	- Large particle size (from 200 µm to 640-700 µm) - Improved wettability (from poor to very good). - Improved flowability	(Barkouti, Turchiuli, Carcel, & Dumoulin, 2013)
Whey Protein Isolate Powder	Total sprayed wetting material: 50g/100g particle Airflow rate: 70 L min^{-1} Pump rate: 1 mL min^{-1} Inlet air temperature: 50 ºC Used wetting material: Lecithin aqueous solution (0.5%, 2% and 5%, w/v)	- Large granules - Higher porosity - Lower bulk density - More irregular shape	(Ji, Cronin, Fitzpatrick, & Miao, 2017)
Milk protein isolates Whey protein isolates Micellar casein Sodium caseinate Calcium caseinate	Total sprayed wetting material: 10-25g/50g particle Airflow rate: 30 L min^{-1} to 250 L min^{-1} Inlet air temperature: 50 ºC Used wetting material: Lactose solution binders (15% w/v) Atomization pressure: 1 bar	- Droplet penetration improved for WPI and MPI powders - MPI and MC have better wettability - Dispersibility not changed	(Ji et al., 2016)
Milk protein isolate powder	Total sprayed wetting material: 150g/200g particle Airflow rate: 100 L min^{-1} to 200 L min^{-1} Inlet air temperature: 50 ºC Pump rate: 1 mL min^{-1} Used wetting material: Lactose solution binders (15% w/v) Atomization pressure: 1 bar	- Large particle sizes - Loose and porous structures - No difference in water adsorption measurements	(Ji, Fitzpatrick, Cronin, Fenelon, & Miao, 2017)
Milk protein isolate powder	Total sprayed wetting material: 100g/200g particle Airflow rate: 100 L min^{-1} to 200 L min^{-1} Inlet air temperature: 50 ºC Pump rate: 1 mL min^{-1} Used wetting material: Distilled water; Lactose and sucrose solutions (15% w/v) Atomization pressure: 1 bar	- Decreased bulk density - Increased porosity - Lower circularity and convexity - Higher elongation values - Improved wettability - No difference in solubilization	(Ji, Cronin, Fitzpatrick, Fenelon, & Miao, 2015)
Dairy-based multi-component powders	Total sprayed wetting material: 30 ml/300g particle Inlet air temperature: 50 ºC Pump rate: 4 mL min^{-1} Used wetting material: Distilled water; lactose and sucrose solution (15% w/v), lecithin solution (2%, w/v) Atomization pressure: 1 bar	- Lower bulk density - Higher porosity - Irregular shape - No improvement in wettability	(Szulc & Lenart, 2013)
Skim Milk Powder	Total sprayed wetting material: 160 ml/300g particle Airflow rate: 1 kg·h^{-1} Inlet air temperature: 70 ºC Pump rate: 4.9 mL min^{-1} Used wetting material: Distilled water Atomization pressure: 1 bar	- Large particles (from 64 to 354 µm) - Porous structure (from 0.62 to 0.86 µm) - Irregular shape - Good instant properties - Reduced bulk and tapped density	(Turchiuli, Smail, & Dumoulin, 2013)
Yoghurt Powder	Total sprayed wetting material: 50-80 g/150g particle Airflow rate: 8–9m^3/h Inlet air temperature: 50-80 ºC Pump rate: 2.11 mL min^{-1} Used wetting material: Distilled water Atomization pressure: 0.5-1.5 bar	- Optimum conditions: 62 ºC inlet temperature, 0.9 bar atomizing pressure and 68 g sprayed amount of water - Increasing atomizing pressure cause lower average particle size and porosity - Atomizing pressure and amount of sprayed binder affected reconstitution properties of powders - Inlet air temperature affected moisture content	(Atalar & Yazici, 2018)

Yoghurt Powder	Total sprayed wetting material: 68 g/150g particle Airflow rate: 8–9 m^3/h Inlet air temperature: 62 ºC Pump rate: 2.11 mL min^{-1} Used wetting material: Distilled water, lactose, sucrose, and maltodextrin solutions (15% w/v) Atomization pressure: 0.9 bar	- Increase in porosity, particle density, elongation, flowability and solubility - Decrease in bulk and tapped densities, lightness index, circularity, and cohesiveness values - The highest porosity and particle size were observed when lactose binder was used - Sugar binders improved wettability	(Atalar & Yazici, 2019)
	Fruit and Vegetable Powders		
Soymilk Powder	Total sprayed wetting material: 200 mL/200g particle Inlet air temperature: 50 ºC Pump rate: 11-12 mL min^{-1} Used wetting material: Maltodextrin DE 14 (0%, 5%, 10%, 15%, and 20% w/v) Atomization pressure: 1.5 bar	- Larger particles (from <25 µm to 260 µm) - 10% was found as optimum binder concentration - Wettability value decreased 42 s - Dispersibility value found as 61%	(Jinapong, Suphantharika, & Jamnong, 2008)
Cocoa Powder	Total sprayed wetting material: 1 g Metarin /200g particle Airflow rate: 50–80 m^3/h Inlet air temperature: 65ºC Pump rate: 11-12 mL min^{-1} Used wetting material: Water-soluble lecithin (Metarin) Atomization pressure: 0.2 MPa Cocoa powder fat content: 10-12 g/100 g fat and 16-18 g/100 g fat	- Cocoa powder agglomerates with higher fat content exhibited poorer wettability - Cocoa powder with low-fat content exhibited better solubility - Sauter diameter values for cocoa powder agglomerates with cocoa low and high-fat content ranged from 43.43 to 152.65 mm and from 51.37 to 170.21 mm, respectively	(Benković et al., 2015)
Bayberry powders	Inlet air temperature: 50ºC Used wetting material: Water	- Reduced wetting time (from 2 min to 15s) - Increased particle size (from 74 µm to 200 µm) - Decreased bulk density - Dispersibility not changed	(Gong, Zhang, Mujumdar, & Sun, 2008)
Spinach powder	Kg powder/kg binder rates: 1:0:1, 1:0:2, 1:0:3 Airflow rate: 1.6 m/sec Inlet air temperature: 60 ºC Used wetting material: Maltodextrin, gum Arabic, whey protein isolate	- Morphological structure not changed - Increased glass transition temperature - Larger particle size - Increased zeta potential - Maltodextrin had better physical properties - Containing GA in the ratio of 1:0.3 were found to have some of the best powder properties such as shortest wettability and solubility times	(Yuksel & Dirim, 2020)
Carrot concentrate powder	Powder amount: 3 kg Agglomeration time: 40 min Inlet air temperature: Increased during the process Used wetting material: Water	- Improved dissolution and flow properties - Fast dissolution - Non-uniform density distribution - Irregular structures - Decreased loose and compressed bulk density - Improved flowability (from poor to fair)	(Haas et al., 2020)
Green banana flour	Total sprayed wetting material: (1, 4, 5 and 8) g/100 g powder Airflow rate: 50–80 m^3/h Inlet air temperature: 35 and 50 ºC Pump rate: 3 mL min^{-1} Used wetting material: Aqueous solution of sodium alginate Atomization pressure: (100-150) kPa	- Chemical structure not changed - Larger particle size - Enhanced instant properties - Porous surface - Irregular shapes - High flowability with lower cohesiveness	(Rayo et al., 2015)
Acerola powder	Powder amount: 250 g Liquid atomization was fixed at 20 min. Air flow rate: 0.13–0.57 m/s Inlet air temperature: 55-85 ºC Pump rate: 0.6 ml min^{-1} Used wetting material: Water Atomization pressure: 1 bar	- Porous structure - Irregular shape - Enhanced wettability - Improved product solubility	(Dacanal & Menegalli, 2009)

Cereal Powders			
Durum wheat semolina	Powder amount: 2 kg Airflow rate: 1.67 x 10^{-2} m^3 s^{-1}. Inlet air temperature: 80 ºC Pump rate: 1.56 mL s^{-1}. Used wetting material: Tap water	- Fluidization velocity and bed height affect the friction conditions - Higher friction causes spherical agglomerates - Irregular shapes - Increased swelling capacity - Increased water solubility index	(Hafsa et al., 2015)
Corn, manioc, amaranth, buckwheat, and quinoa flours	Powder amount: 100 g Pump rate: 2 mL/min Used wetting material: Water	- Larger particle size - Agglomeration yields were very high especially with corn (98.33 g/100 g) and amaranth (84.84 g/100 g) flours that have larger particle size distributions.	(Chemache, Lecoq, Namoune, & Oulahna, 2019)
Durum wheat semolina	Total sprayed wetting material: (0, 5, 10, 15 and 20%, dry solid basis) Airflow rate: 0.70 m3/min Inlet air temperature: 25 ºC Pump rate: 11.0 ± 0.9 g /min Used wetting material: Water	- Larger particle size (1000-2000 µm with mass fraction of about 40%) - Decreased compactness (from 0.43 to 0.36) - High sphericity (0.82–0.87)	(Bellocq et al., 2018)
Gum Powders			
Xanthan gum	Total sprayed wetting material: 1000 mL /1.5 kg Inlet air temperature: 73 ºC Pump rate: 20 mL/min Used wetting material: Sorbitol, lactose, sucrose, glucose aqueous solutions (10% (w/w)) Atomization pressure: 1.5 bar	- Sugar binders had a major influence on the dissolution time - Larger particle size - Increased porosity - Glucose produced larger and more irregular-shaped particles - Lactose showed a synergistic effect on the elastic properties	(Lee & Yoo, 2020a)
Xanthan gum	Total sprayed wetting material: 900 mL/1.5 kg Inlet air temperature: 45 ºC Pump rate: 15 mL/min Used wetting material: HPMC aqueous solutions (2, 4 and 6% w/w) Atomization pressure: 1.2 bar	- HPMC produced larger, porous, and irregularly shaped particles - Improved flowability and cohesiveness - HPMC at higher concentrations result in viscoelastic properties with higher dynamic moduli - HPMC binder would be useful in developing formulation of XG-based food thickeners for patients with dysphagia	(Jeong, Bak, & Yoo, 2019)
Xanthan gum/guar gum Xanthan gum/guar gum/ carboxymethyl cellulose	Total sprayed wetting material: 1000 mL/1.5 kg Inlet air temperature: 53 ºC Pump rate: 20 mL/min Used wetting material: Guar gum (0.1% w/ w) Atomization pressure: 1.2 bar	- The addition of guar gum and carboxymethyl cellulose improved powder flow characteristics - Xanthan gum-based food thickeners with desirable rheological properties of thickened liquids used for the treatment of dysphagia.	(Park & Yoo, 2020)
Guar gum and Locust gum powders	Total sprayed wetting material: 1000 mL/1.5 kg Inlet air temperature: 53 ºC Pump rate: 20 mL/min Used wetting material: Maltodextrin (0–40% w/w) Atomization pressure: 1.5 bar	- Larger particle size - 40% MD produced larger, more porous, and irregularly shaped agglomerates - Improved flowability, cohesiveness, and dispersibility - Guar gum powders were found to have a relatively larger size and porosity, and a more irregular shape when compared to LBG	(Lee & Yoo, 2020b)

reduced to 3.4 seconds. In line with the findings of the study, modifications were made in the particle size and structural properties of skimmed milk powders by fluidized bed agglomeration. Large, porous and irregularly shaped agglomerates showed good instant properties. Atalar & Yazici (2018) agglomerated spray-dried yoghurt powders by applying wet agglomeration process with distilled water. The control sample has a small particle size (57 mm) and the higher cohesiveness and agglomeration process increased particle size and lowered the cohesive forces. The authors optimized the process conditions in terms of the high-quality reconstitution properties of yoghurt powder. The optimum process conditions were found as 62.5 ºC inlet air temperature, 0.9 bar atomizing pressure and 68 g sprayed water amount. In another study, the effect of binder types on the agglomeration conditions of yoghurt powder was investigated. The results indicated that sugar-based binders resulted in large particle size and porous structure compared to water binders. Sugar binders also improved wettability properties of powders. Protein and stretching vibration of N–H groups were affected by the acidity of water and resulted in changes in powder solubility. The circularity of particles decreased with the usage of sugar binder solutions while elongation increased (Atalar & Yazici, 2019). Ji et al. (2016) agglomerated milk protein isolates, whey protein isolates, micellar casein, sodium caseinate and calcium caseinate by fluidized bed granulation and comparison was made with their non-agglomerated forms. The results of the study indicate that high protein dairy powders generally had poor wettability due to forming an impermeable layer that separates the water surface and powders. It was found that agglomeration process only reasoned the external structural modification and showed no beneficial effect on dispersibility because it does not impact the structure of the primary particles. The micellar structure of powders inhibits the release of materials into the liquid phase and it caused extent rehydration time.

3.2. Fruit and vegetable powders

Fruit and vegetable powders are used in the food product to improve colour, flavour, bioactive and nutritional value of food products. For improving the instant properties, agglomeration process was applied to different fruit and vegetable powders. Jinapong et al. (2008) agglomerated soy milk powder by top spray fluidized bed with maltodextrin binders. Particle sizes of the powders obtained from the spray dryer are very small (<25µm) and the existing cohesion forces caused them to show poor flow properties. Agglomeration of the powders increased particle size to 260 µm and reconstitution properties of powders were improved. It has been emphasized that the wetting time of agglomerated powders can be reduced to 42 s. In the study where the effect of the binder concentration was investigated, the optimum binder concentration at which the highest particle size and the lowest cohesion force were obtained was determined as 10%. Benković et al. (2015) investigated the effect of agglomeration process parameters on the physical and chemical properties of cocoa powder mixtures using the artificial neural networks (ANN) method. Water-soluble lecithin solution, commercially known as Metarine, was used as the binder. Agglomeration conditions (water amount and process time) and mixture composition (fat, sweetener and bulking agent content) were selected as input variables, and physical (Sauter diameter, bulk density, porosity, Chroma wettability and solubility) and chemical (total phenolic content and antioxidant capacity) properties of cocoa powders were chosen as output variables. The amount of sprayed water during the agglomeration affected both the physical and chemical properties of the cocoa powder mixtures significantly. Artificial neural networks successfully applied for connecting the changes in different properties of agglomerated cocoa powder with agglomeration process parameters. Bayberry powder was agglomerated by a sprayed fluidized bed granulator. With the agglomeration of the powders, the wetting time of spray-dried bayberry powders was reduced from 2 minutes to 15 seconds. Particle size increased from 74 µm to 200 µm. While bulk density decreased, no significant change was observed in dispersibility. A slight increase has been observed in the flowability properties of the powders (Gong, Zhang, Mujumdar, & Sun, 2008). Yuksel & Dirim (2020) agglomerated spray-dried spinach powders by fluidized bed equipment with distilled water, maltodextrin, whey protein isolate, and gum Arabic binder solutions. The agglomeration process increased the mean particle size and decreased the wettability and solubility times of spinach powders. The agglomeration also improved the cohesiveness, flowability, porosity, and hygroscopicity properties of powders. The microstructure of powders showed differences depending on binder type. Authors suggest that the agglomeration process by using a fluidized bed system can be applied successfully in the production of instant spinach powders Haas et al. (2020) agglomerated spray-dried carrot concentrate powders by fluidized bed agglomeration and spout fluidized bed spray granulation. Agglomeration and spray granulation processes caused a high encapsulation efficiency (96–99%), oxidation stability and flowability of powders improved compared to spray-dried powders. Dissolution of agglomerated powders in water increased and lump formation was prevented. It was stated that the best flowability, the highest encapsulation efficiency (92–93%) and the lowest carotenoid degradation were observed for spray granulated powders. Rayo et al. (2015) agglomerated the green banana flour by using a pulsed fluidized bed with an aqueous solution of sodium alginate. Agglomeration process resulted in increased mean particle diameter, high flowability and porosity with an irregular shape. Agglomeration led to obtaining a porous surface, irregular shape with lower cohesiveness and densities. Agglomeration process provides to improving the transport and handling properties of powders with lower flowability. Wettability of particles increased with the agglomeration process. Agglomeration also did not influence the starch gelatinization transition of green banana flour. The turmeric powder samples with different moisture contents (10–28%) and steaming time (0–60 min) are subjected to agglomeration process with distilled water. An increase in moisture content and steaming time causes a decrease in the wetting and sinking times of powders. While non-agglomerated turmeric powders showed spheroids and ellipsoids shape, the agglomerated powders shape changes from spheroid to elongated ellipsoids. The mean diameter of the particles increased with the increase in moisture content of the powder (Dhanalakshmi & Bhattacharya, 2014). Dacanal & Menegalli (2009) granulated the acerola powder by using a conical fluid bed system. Spraying water as a binder resulted in wetted sticky surface and particle coalescence. During the drying stages of these particles, consolidation of the structure cause particle enlargement. The lower fluidizing air temperature and velocity decreased the drying of particles efficiently and caused wall incrustation of powders. Agglomeration process forms porous and irregular acerola powder particles and formed granules can penetrate a liquid surface to become wet compared to the non-agglomerated powder. The formed bridges led to solids dissolve easily and resulting in improved product solubility. The agglomeration led to an improvement in the instant properties of acerola powder.

3.3. Cereal Powders

The end-use properties of different cereal product powders were modified by using agglomeration process and usability in different purposes like for the preparation of couscous investigated. Bellocq et al. (2018) agglomerated durum wheat grain with fluidized bed technology. It was found that the dried agglomerated grains obtained using the fluidized bed were less compact than the traditional couscous grains manufactured using low shear mixers. Fluidized bed granulation produced agglomerates with a diameter between 1000-2000 µm. By using the hydrotextural diagram, the interparticle arrangements related to the expansion and densification of the wet agglomerates were explained. The wet agglomeration mechanisms occurring during the wetting/

mixes process of durum wheat semolina were studied. During the wetting and mixing stages, structural changes were occurred in composing the bed bulk. These changes were investigated at the bed bulk and the agglomerate scales in a hydro-textural diagram. The evolution of the solid volume fraction concerning the water content includes expansion, densification and dilution stages at the bed bulk scale. For the agglomerate scale, the evolution in the solid volume fraction includes a fractal formation. The formed equation made it possible to predict the characteristics of the structures during the wetting process (Saad, Barkouti, Rondet, Ruiz, & Cuq, 2011). Wet agglomerates of gluten-free cereals such as corn, manioc, amaranth, buckwheat, and quinoa flours were produced by a high- shear granulator system for examing the suitability for the preparation of couscous grains. In this system, except for manioc flour, all flours can be granulated. Corn flour possesses better uniformity in size distribution. The highest agglomeration yields of flours were found as corn (98.33 g/100 g) and amaranth (84.84 g/100 g) flours. It is possible to produce gluten-free couscous grains based on new cereals, and it gives an option to the people suffering from celiac about the selection of the different couscous types (Chemache, Lecoq, Namoune, & Oulahna, 2019). The agglomeration process of durum wheat semolina with different techniques such as mechanical mixing, steaming, and drying (process 1), mechanical mixing and drying (processes 2–3), or by pneumatic mixing (processes 4–5) were investigated. In fluidized bed agglomeration chamber, segregation occurs and small particles flow with the air toward the recycling cyclone before participating in the agglomeration mechanisms. This situation was not observed when using the mechanical mixers and all the native semolina particles contribute to the structure of the agglomerates. The agglomerates that were prepared by using the fluidized bed have an irregular and rough shape, whilst, the agglomerates that were prepared by using spray drying are more spherical. The authors indicated that the differences in the shape can be reasoned from fluidization rate and bed height that affect the friction conditions during the pneumatic processes. A functional model was also formed to describe the agglomeration mechanisms by considering the reversible and irreversible changes (Hafsa et al., 2015). Chen et al. (2009) agglomerated corn starch powder with a particle size of 15 μm by precoating with 0.5% nano-silica by fluidized bed agglomerator system with PVP (polyvinylpyrrolidine) aqueous solution. The effects of binder concentration, binder spray rate and nozzle pressure on powder properties were studied. The use of larger amounts of the binder led to an increase in granule size. Authors indicated that increasing binder concentration while keeping the sprayed binder amount constant resulted in larger particles until the concentration reaches 8 wt.%.

3.4. Gums

Different gum powder types were agglomerated to improve their instant and rheological properties and increase usability as an additive for different purposes in food formulas. Jeong et al. (2019) agglomerated xanthan gum (XG) by using a fluidized bed agglomeration process with different concentrations of hydroxypropyl methylcellulose binder (HPMC). It was found that agglomeration of XG powders using HPMC binder had a better flowability and higher porosity than the agglomerated powder without using binder solution. Rheological parameters of all samples were compared and it was found that dynamic moduli (G′ and G”) of agglomerated XG powders at 2% and 4% HPMC were significantly higher than other powders. Using HPMC as a binder improved the elastic behavior. It was suggested that the agglomeration process increases the flow characteristics and rheological properties of XG powders. In another study, XG powders were agglomerated with water and sugar (glucose, lactose, sucrose, and sorbitol) solutions. It was found that particle size and porosity values of xanthan gum powders agglomerated with different sugar binders were much higher than those agglomerated with water binder and dissolution times of sugar binder used powders were shorter. Flowability properties of powders showed differences due to the type of sugar binder. In a rheological aspect, agglomeration with water caused to increase in consistency index compared to the sugar binders and using caused to highest storage modulus. Sugar binders also decrease the tan δ values compared to the water and affected the elastic behavior of powders. Among the sugar binders, using glucose resulted in larger and more irregular-shaped particles with a porous surface and using lactose caused a synergistic effect on the elastic properties of agglomerated XG powder (Lee & Yoo, 2020). Kim, Kim, & Yoo (2017) agglomerated XG powders with maltodextrin binder. It was found that storage (G’) and loss modulus (G”) of agglomerated XG powders were significantly higher than those of non-granulated XG and granulated XG without binder (0 % MD). Agglomeration caused to decrease in tan δ values and G’ and G” values at 10 % maltodextrin concentration were much higher than other concentrations. Park & Yoo (2020) agglomerated gum mixture powders: xanthan gum (XG) /guar gum (GG) and xanthan gum/guar gum/ carboxymethyl cellulose (CMC) powders by a fluidized bed agglomerator. Better flowability was observed for xanthan gum/guar gum mixture. For assessing the thickening effect of gums, powders are incorporated in different beverage types like water, milk, orange juice and sports beverage. The highest viscosity in the beverages, except for water, was obtained with agglomerated xanthan gum/guar gum powder. Elastic characteristics of the thickened beverages (milk, orange juice, and sports drink) were improved due to the strong interactions between beverage constituents and agglomerated gum powders.

4. Conclusions

Agglomeration of food powders and improving their instant properties have a significant role in their processability in food industries and consumer acceptance on market shelves. In the top spray agglomeration technique, the fine powders adhering to one another via spraying a binder directly on the fluidized bed, resulting in a porous aggregate structure. During the agglomeration process, there are a lot of factors that affect the agglomeration growth and different powder types can show different agglomerate growth behaviors even if the same process condition is used. For these reasons, it is critical to optimize the process conditions, the types of binder and concentration to obtain high-quality instant powders.

References

Atalar, I., & Yazici, F. (2019). Effect of different binders on reconstitution behaviors and physical, structural, and morphological properties of fluidized bed agglomerated yoghurt powder. *Drying Technology*, *37*(13), 1656-1664. https://doi.org/10.1080/07373937.2018.1529038

Atalar, I., & Yazici, F. (2018). Influence of top spray fluidized bed agglomeration conditions on the reconstitution property and structure modification of skim yoghurt powder. *Journal of Food Processing and Preservation*, *42*(1), e13414. https://doi.org/10.1111/jfpp.13414

Barkouti, A., Turchiuli, C., Carcel, J. A., & Dumoulin, E. (2013). Milk powder agglomerate growth and properties in fluidized bed agglomeration. *Dairy Science and Technology*, *93*(4–5), 523–535. https://doi.org/10.1007/s13594-013-0132-7

Bellocq, B., Cuq, B., Ruiz, T., Duri, A., Cronin, K., & Ring, D. (2018). Impact of fluidized bed granulation on structure and functional properties of the agglomerates based on the durum wheat semolina. *Innovative Food Science and Emerging Technologies*, *45*, 73–83. https://doi.org/10.1016/j.ifset.2017.09.001

Benković, M., Tušek, A. J., Belščak-Cvitanović, A., Lenart, A., Domian, E., Komes, D., & Bauman, I. (2015). Artificial neural network modelling of changes in physical and chemical properties of cocoa powder mixtures during agglomeration. *LWT - Food Science and Technology*, *64*(1), 140–148. https://doi.org/10.1016/j.lwt.2015.05.028

Chemache, L., Lecoq, O., Namoune, H., & Oulahna, D. (2019). Agglomeration properties of gluten-free flours under water addition and shearing conditions. *LWT-Food Science and Technology*, *110*, 40–47. https://doi.org/10.1016/j.lwt.2019.04.058

Chen, Y., Yang, J., Dave, R. N., & Pfeffer, R. (2009). Granulation of cohesive Geldart group C powders in a Mini-Glatt fluidized bed by pre-coating with nanoparticles. *Powder Technology*, *191*(1–2), 206–217. https://doi.org/10.1016/j.powtec.2008.10.010

Cuq, B., Gaiani, C., Turchiuli, C., Galet, L., Scher, J., Jeantet, R., … Ruiz, T. (2013). *Advances in Food Powder Agglomeration Engineering*. *Advances in Food and Nutrition Research* (1st ed., Vol. 69). Copyright © 2013 Elsevier Inc. All rights reserved. https://doi.org/10.1016/B978-0-12-410540-9.00002-8

Cuq, Bernard, Mandato, S., Jeantet, R., Saleh, K., & Ruiz, T. (2013). *Agglomeration/granulation in food powder production*. *Handbook of Food Powders: Processes and Properties*. Woodhead Publishing Limited. https://doi.org/10.1533/9780857098672.1.150

Dacanal, G. C., & Menegalli, F. C. (2009). Experimental study and optimization of the agglomeration of acerola powder in a conical fluid bed. *Powder Technology*, *188*(3), 187–194. https://doi.org/10.1016/j.powtec.2008.04.076

Dhanalakshmi, K., & Bhattacharya, S. (2014). Agglomeration of turmeric powder and its effect on physico-chemical and microstructural characteristics. *Journal of Food Engineering*, *120*(1), 124–134. https://doi.org/10.1016/j.jfoodeng.2013.07.024

Dhanalakshmi, K., Ghosal, S., & Bhattacharya, S. (2011). Agglomeration of food powder and applications. *Critical Reviews in Food Science and Nutrition*, *51*(5), 432–441. https://doi.org/10.1080/10408391003646270

Forny, L., Marabi, A., & Palzer, S. (2011). Wetting, disintegration and dissolution of agglomerated water soluble powders. *Powder Technology*, *206*(1–2), 72–78. https://doi.org/10.1016/j.powtec.2010.07.022

Gong, Z., Zhang, M., Mujumdar, A., & Sun, J. (2008). Spray drying and agglomeration of instant bayberry powder. *Drying Technology*, *26*(1), 116–121. https://doi.org/10.1080/07373930701781751

Haas, K., Dohnal, T., Andreu, P., Zehetner, E., Kiesslich, A., Volkert, M., … Jaeger, H. (2020). Particle engineering for improved stability and handling properties of carrot concentrate powders using fluidized bed granulation and agglomeration. *Powder Technology*, *370*, 104–115. https://doi.org/10.1016/j.powtec.2020.04.065

Hafsa, I., Mandato, S., Ruiz, T., Schuck, P., Jeantet, R., Mejean, S., … Cuq, B. (2015). Impact of the agglomeration process on structure and functional properties of the agglomerates based on the durum wheat semolina. *Journal of Food Engineering*, *145*, 25–36. https://doi.org/10.1016/j.jfoodeng.2014.08.005

Jeong, G. Y., Bak, J. H., & Yoo, B. (2019). Physical and rheological properties of xanthan gum agglomerated in fluidized bed: Effect of HPMC as a binder. *International Journal of Biological Macromolecules*, *121*, 424–428. https://doi.org/10.1016/j.ijbiomac.2018.10.048

Ji, J., Cronin, K., Fitzpatrick, J., Fenelon, M., & Miao, S. (2015). Effects of fluid bed agglomeration on the structure modification and reconstitution behaviour of milk protein isolate powders. *Journal of Food Engineering*, *167*, 175–182. https://doi.org/10.1016/j.jfoodeng.2015.01.012

Ji, J., Fitzpatrick, J., Cronin, K., Maguire, P., Zhang, H., & Miao, S. (2016). Rehydration behaviours of high protein dairy powders: The influence of agglomeration on wettability, dispersibility and solubility. *Food Hydrocolloids*, *58*, 194–203. https://doi.org/10.1016/j.foodhyd.2016.02.030

Jiménez, T., Turchiuli, C., & Dumoulin, E. (2006). Particles agglomeration in a conical fluidized bed in relation with air temperature profiles. *Chemical Engineering Science*, *61*(18), 5954–5961. https://doi.org/10.1016/j.ces.2006.05.007

Jinapong, N., Suphantharika, M., & Jamnong, P. (2008). Production of instant soymilk powders by ultrafiltration, spray drying and fluidized bed agglomeration. *Journal of Food Engineering*, *84*(2), 194–205. https://doi.org/10.1016/j.jfoodeng.2007.04.032

Kim, Y. H., Kim, S. G., & Yoo, B. (2017). Effect of maltodextrin on physical properties of granulated xanthan gum prepared by fluidized-bed granulator. *International Journal of Food Engineering*, *13*(8). https://doi.org/10.1515/ijfe-2017-0069

Lee, H., & Yoo, B. (2020). Agglomerated xanthan gum powder used as a food thickener: Effect of sugar binders on physical, microstructural, and rheological properties. *Powder Technology*, *362*, 301–306. https://doi.org/10.1016/j.powtec.2019.11.124

Palzer, S. (2011). Agglomeration of pharmaceutical, detergent, chemical and food powders - Similarities and differences of materials and processes. *Powder Technology*, *206*(1–2), 2–17. https://doi.org/10.1016/j.powtec.2010.05.006

Park, J., & Yoo, B. (2020). Particle agglomeration of gum mixture thickeners used for dysphagia diets. *Journal of Food Engineering*, *279*, 109958. https://doi.org/10.1016/j.jfoodeng.2020.109958

Rayo, L. M., Chaguri e Carvalho, L., Sardá, F. A. H., Dacanal, G. C., Menezes, E. W., & Tadini, C. C. (2015). Production of instant green banana flour (Musa cavendischii, var. Nanicão) by a pulsed-fluidized bed agglomeration. *LWT - Food Science and Technology*, *63*(1), 461–469. https://doi.org/10.1016/j.lwt.2015.03.059

Saad, M. M., Barkouti, A., Rondet, E., Ruiz, T., & Cuq, B. (2011). Study of agglomeration mechanisms of food powders: Application to durum wheat semolina. *Powder Technology*, *208*(2), 399–408. https://doi.org/10.1016/j.powtec.2010.08.035

Szulc, K., & Lenart, A. (2013). Surface modification of dairy powders: Effects of fluid-bed agglomeration and coating. *International Dairy Journal*, *33*(1), 55–61. https://doi.org/10.1016/j.idairyj.2013.05.021

Turchiuli, C., Eloualia, Z., El Mansouri, N., & Dumoulin, E. (2005). Fluidised bed agglomeration: Agglomerates shape and end-use properties. *Powder Technology*, *157*(1–3), 168–175. https://doi.org/10.1016/j.powtec.2005.05.024

Turchiuli, C., Smail, R., & Dumoulin, E. (2013). Fluidized bed agglomeration of skim milk powder: Analysis of sampling for the follow-up of agglomerate growth. *Powder Technology*, *238*, 161–168. https://doi.org/10.1016/j.powtec.2012.02.030

Yuksel, H., & Dirim, S. N. (2020). Application of the agglomeration process on spinach juice powders obtained using spray drying method. *Drying Technology*, 1–16. https://doi.org/10.1080/07373937.2020.1832515