powders

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Review

Factors Influencing Food Powder Flowability

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Abstract: The flowability of food powders is a critical determinant of their processing efficiency, product quality, and overall operational success. This review delves into the intricacies of powder flowability, elucidating the factors that govern it and exploring various methods for its evaluation and enhancement. Particle size and distribution, particle shape, surface properties, moisture content, and storage conditions stand as the key determinants of powder flowability. Finer powders, with their increased interparticle cohesive forces, tend to exhibit poorer flowability. Particle shape also plays a role, with irregular or elongated particles flowing less readily than spherical ones. Surface properties influence interparticle friction, thereby impacting flow behavior. Moisture content significantly affects flowability, as increased moisture can lead to liquid bridge formation, hindering powder movement. Storage temperature, on the other hand, generally enhances powder flow due to reduced interparticle cohesive forces at higher temperatures. This highlights the need to understand the factors influencing food powder flowability and to employ appropriate evaluation strategies for optimizing food powder processing efficiency, product quality, and overall production success.

Keywords: powder rheology; particle size; food powder flow; cohesion; angle of repose

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1. Introduction

The flowability of food powder refers to the property of powdered materials to flow smoothly during various stages of processing, handling, and manufacturing. This characteristic is pivotal in ensuring efficient and cost-effective production processes within the food industry. As consumers increasingly demand powdered food products for their convenience and longer shelf life, optimizing powder flow becomes a critical factor for manufacturers [1]. The ability of powders to flow seamlessly through equipment not only influences the overall manufacturing efficiency but is also involved in affecting the consistency and quality of the final product. Inadequate flowability can lead to issues such as uneven mixing, blockages in processing equipment, and challenges in packaging, impacting the overall integrity of the final product [2,3].

The flowability of food-grade powders, designed for use in food products, may differ from that of non-food-grade powders used in industrial or technical applications. Food-grade powders contain additives approved for food use, such as anti-caking agents or flow aids like silica or calcium compounds, which prevent clumping and enhance flowability. These powders undergo specialized milling techniques to achieve a uniform particle size distribution and have controlled moisture content to optimize flowability while maintaining product stability. In contrast, non-food-grade powders may prioritize properties such as chemical reactivity or mechanical strength over flowability and may not require additives for flow enhancement. Processing methods, such as spray drying or agglomeration, can also differ, affecting flow behavior. Regulatory requirements ensure that additives and processing aids in food-grade powders meet safety and quality standards, whereas non-food-grade powders may have more flexibility in formulation and processing.

The measurement of food powder flowability is a nuanced process that has evolved with technological advancements. Conventional methods, such as the angle of repose, Carr

index, Hausner ratio, and powder flow function, have provided fundamental insights into basic flow properties. These methods serve as benchmarks for assessing the foundational aspects of powder behavior [4–6]. However, recent strides in technology have ushered in a new era of precision. Powder rheometers have emerged as powerful tools, allowing for detailed analyses of flow behavior under varying conditions [7,8]. This enables researchers and manufacturers to gain a more sophisticated understanding of how powders respond to external forces, aiding in the development of tailored processing strategies.

Numerous factors intricately contribute to the flowability of food powders, necessitating a holistic examination for effective optimization. Moisture content, shape, particle size, and cohesiveness collectively shape the flow behavior of powders. The importance of studying these factors lies in their direct impact on manufacturing efficiency, product quality, and consumer satisfaction. For instance, understanding how variations in particle size influence flow properties allows for tailored processing strategies. Similarly, the interplay of particle shape, moisture content, and cohesiveness is crucial for preventing issues such as uneven mixing, blockages in processing equipment, and challenges in packaging [9–12].

In 2010, Juliano et al. [4] reviewed the theory of powder flowability and discussed conventional methods to assess it. More recently, Enriquez et al. [13] reviewed the influence of water on food powder flowability. However, food powder flowability is influenced by multiple factors, and there have been developments in methods to study it. Therefore, this review aims to discuss the various factors that influence the flowability of food powders and explore advancements in measuring methods, with a major focus on literature from the last 10 years. By providing a comprehensive perspective on measurement techniques and the intricate factors influencing flowability, the review aims to guide both current practices and future research directions. Practical implications extend beyond theoretical insights, encompassing improved manufacturing efficiency, enhanced product quality, and continued innovation in the development and production of powdered food products. This review serves as a valuable resource for researchers, industry professionals, and practitioners seeking to navigate the intricate landscape of food powder flowability, facilitating informed decision-making and advancements in this critical aspect of food science.

2. Advances in Measuring Food Powder Flowability

Numerous extensively documented conventional techniques are readily accessible (Figure 1), such as flow meters (critical orifice diameter), tapped density tests (Carr's index/Hausner ratio), and the angle of repose. Despite their cost-effectiveness, speed, and simplicity, these methods exhibit high dependence on the operator, limited repeatability, and a lack of significant differentiation [14]. Shear cell analysis is another recognized approach. Despite its well-established principles, this method was originally conceived to analyze the initial flow behavior of continuous, cohesive powders under high stress conditions. Several unit operations and processes, however, happen at low to moderate stress. An advantageous aspect of shear cell analysis is its applicability to hopper designs. The discussed methodologies present two key drawbacks. First, they fail to capture the entire spectrum of powder flowability and cohesion. Angle of repose and flow meters rely on granular or powdery material flowing through a funnel, making them unsuitable for cohesive powders. Tapped density tests are also proven to be ineffective for highly cohesive materials since the tapping force is inadequate to break the strong interparticle cohesive bonds, preventing the complete repacking or consolidation of the powder bed upon tapping. Additionally, when applied to granular materials, this test method encounters further challenges, given that the heavier and denser particles tend to pack more efficiently due to their own weight, resulting in inaccurately low outcomes [15]. In contrast, shear cell analysis is often less discerning for free-flowing powders and may overlook subtle changes in powder properties that influence process performance. Moreover, because of limitations related to particle size, instruments commercially available currently often lack the capacity to handle the larger particle sizes associated with many granular materials. The second significant limitation of these methods is their inability to accurately represent the range of

processing conditions to which grains and powders undergo during the manufacturing process. Notably, there is a lack of standardized test to assess powder flow across all four flow regimes: plastic, inertial, entrained flow, and fluidized [16,17].

Recent advancements in powder rheometers have successfully addressed these limitations, gaining widespread recognition and acceptance [18–21]. While originally designed for powder measurement under dynamic conditions, integrated design and adaptability of this technology allow for the convenient measurement of both bulk properties (such as permeability and compressibility) and shear properties (including shear cell and wall friction). Consequently, this technique is proficient in evaluating a broad spectrum of materials, ranging from free-flowing to highly cohesive, and can handle larger particle sizes. This capability not only facilitates direct comparisons between different materials, such as distinct raw components but also enables a single instrument to monitor the entire processing journey from raw ingredients to the final products [15].

Recently, Hausmann et al. [12] highlighted the power of powder rheology as a quick and effective method to track how humidity affects powder flow behavior, including the influence of electrostatics and deliquescence (solid-to-liquid phase transition). Their findings demonstrated that varying humidity levels impacted the flow energy of sodium chloride powder, particularly during downward cycle, autoturn, and upward cycle stages. These alterations were attributed to humidity-induced variations in tip speed and the resulting shifts in powder shear forces. While autoturn and upward cycle experiments highlighted sodium chloride's humidity-induced deliquescence behavior, downward flow energy indicated shifts in the powder's electrostatic properties. The mode of aeration and humidity control also impacted experiment reproducibility. The implementation of a dependable humidification technique enhances the capability of powder flow rheology, transitioning it from a routine test method to a powerful research tool for in-depth investigations. This work highlights the previously neglected importance of upward cycle data and underscores the necessity to move beyond the traditional analysis confined to downward cycle measurements. The humidity-controlled FT4 represents a significant advancement with the potential to revolutionize the characterization of moisture-sensitive powders.

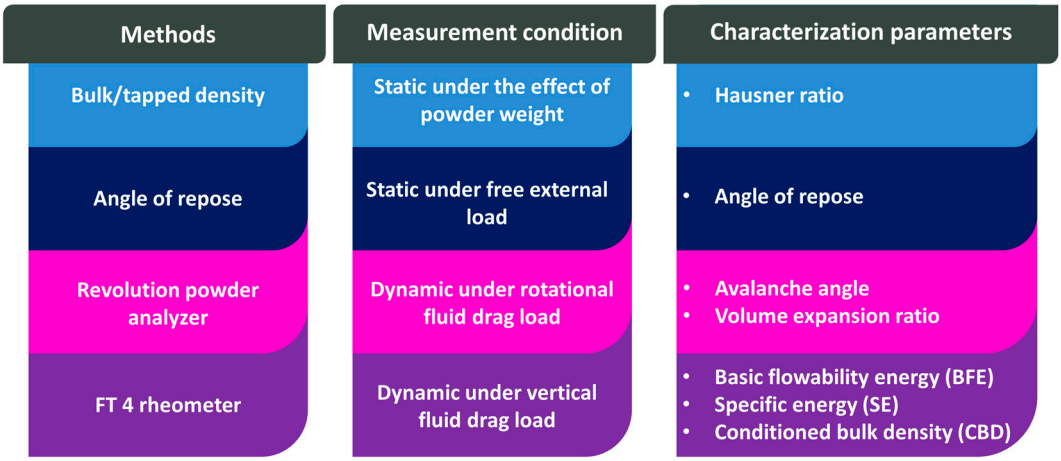

Figure 1. Methods to measure powder flowability. Reproduced from [22] with permission from Elsevier, 2020).

The quantification of the rheological properties of powders or granular systems involves measuring their resistance to flow. FT4 Powder Rheometer (Freeman Technology, Tewkesbury, UK) expresses resistance as flow energy. This method utilizes a novel measurement technique that quantifies the resistance encountered by a rotating blade as it traverses a predefined path within a precisely controlled sample volume. Recorded torque and force measurements exerted during blade movement are translated into a single value representing the material's flow energy (Figure 2). This principle was successfully modeled

using discrete element modeling, with the computer model's results showing close agreement with experimental data [14,23]. Easy adjustment of stress and strain rates is possible by modifying tip speed and helix angle, while vessels and blades of various dimensions facilitates the comprehensive characterization of powders spanning a wide range, encompassing particles from a few nanometers to millimeters [20]. In contrast to conventional approaches, sample conditioning is a dynamic test method which helps eliminate operator variability and consolidation history. This involves displacing the entire sample to loosen and slightly aerate the powder, aiming to achieve a standardized packing state. Simplifying the workflow, the conditioning cycle(s) are often embedded within the overall test routine. Nevertheless, when investigating consolidation/storage history, the sample may undergo preliminary conditioning before storage. The consistent sample volume guaranteed by the vessel's separation mechanism directly translates to enhanced repeatability and reliability of data [15].

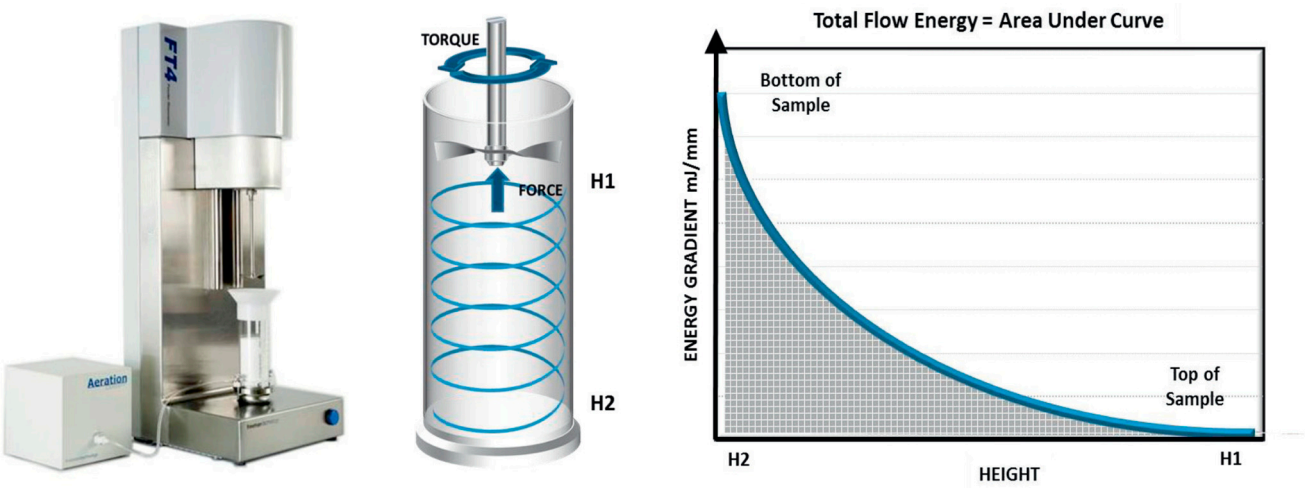

Figure 2. Measurement of flow energy using the FT4 Powder Rheometer® (Freeman Technology Tewkesbury, UK) (Reprinted from [21] under the CC BY-NC-ND license).

Unlike other dynamic systems that measure only axial force by assuming a powder bed as a continuous, uniform body, the system described acknowledges the presence of air pockets and channels, particularly in highly cohesive powders. If blade-moved particles fill voids instead of displacing surrounding particles, the axially positioned load cell receives less energy, impacting the overall measurement. Force, when compared to torque, exhibits substantially lower values, frequently differing by an order of magnitude. This inherent limitation compromises the discriminatory power of force measurements and potentially yields misleading assessments and rankings, especially for cohesive powders [14,23]. Beyond assessing properties in a "poured" condition, incorporation of regulated air feed enables measuring the flow energy correlated with air velocity. This proves particularly valuable for comprehending powder attributes in a low-stress, aerated/fluidized condition, as observed during pneumatic conveying. The inability of certain powders to fully fluidize necessitates the exploration of alternative rheological techniques or adaptations to existing methods to accommodate non-fluidizable materials [15]. Conversely, for characterizing dynamic properties under higher stress conditions, researchers can employ external forces like vibration or compaction. Recent developments have highlighted the utility of rheological measurements in quantifying caking behavior in powders, particularly for non-homogeneous caking [21,24].

Dynamic flow properties used to describe powder flowability include:

- Basic Flowability Energy (BFE) signifies the energy required during the seventh test cycle to displace a conditioned powder sample during the downward movement of the blade. It is primarily influenced by the compressibility, consolidation level, and

density of the powder bed [25]. A low *BFE* indicates easy-flowing behavior, while poorly flowing powders typically exhibit a high BFE.

- Specific Energy (SE) represents the energy required to displace a conditioned powder bed during upward testing (Equation (1)). It is influenced by various factors, including particle shape, powder cohesion, surface roughness, surface composition, and particle size distribution. Additionally, chemical and physical interactions between particles play a significant role in determining *SE* [25,26].

$$SE = \frac{\frac{(Up\ energy\ cycle\ 6 + Up\ energy\ cycle\ 7)}{2}}{mass\ of\ powder} \quad (1)$$

  The *SE* value can be used to classify powder flow behavior into the following categories:

  - Low cohesion: SE < 5 mJ/g.
  - Moderate cohesion: 5 mJ/g < SE < 10 mJ/g.
  - High cohesion: SE > 10 mJ/g.

- Stability Index (SI) serves as an indicator of a powder's tendency to expand, compact, or remain at a constant volume throughout the test cycles. *SI* value close to 1.0 suggests that the powder retains its volume, while values greater or less than 1.0 indicate a propensity for expansion or compaction, respectively (Equation (2)) [27].

$$SI = \frac{BFE\ required\ during\ test\ cycle\ 7}{BFE\ required\ during\ test\ cycle\ 1} \quad (2)$$

3. Factors Preventing Food Powder Flow

Powder flow is an intricate phenomenon influenced by both the system's physical and chemical properties, and the powder's inherent characteristics. Flowability is also contingent upon the powder bulk properties, including particle size distribution, moisture content, composition, density, and shape. These properties can undergo alterations due to handling-related impact, changes in storage time conditions, temperature fluctuations, and air relative humidity. While extensive research has been conducted in this area, it is crucial to recognize that the reported flowability values are highly specific to the inherent properties of a particular food powder, the experimental conditions employed, and the specific method and equipment utilized. Beyond factors such as particle size, powder composition, and moisture content, flowability is also influenced by surface and material properties, particle shape, ruggedness, hardness, and the presence of surface lubrication resulting from water or fat. However, the impact of surface properties on descriptors of food powder flow remains relatively unexplored [4,28]. Figure 3 summarizes some of the prominent variables affecting powder and system characteristics, contributing to the characterization of food powders as among the most unpredictable materials concerning flowability due to the multitude of factors that can significantly alter their rheological properties.

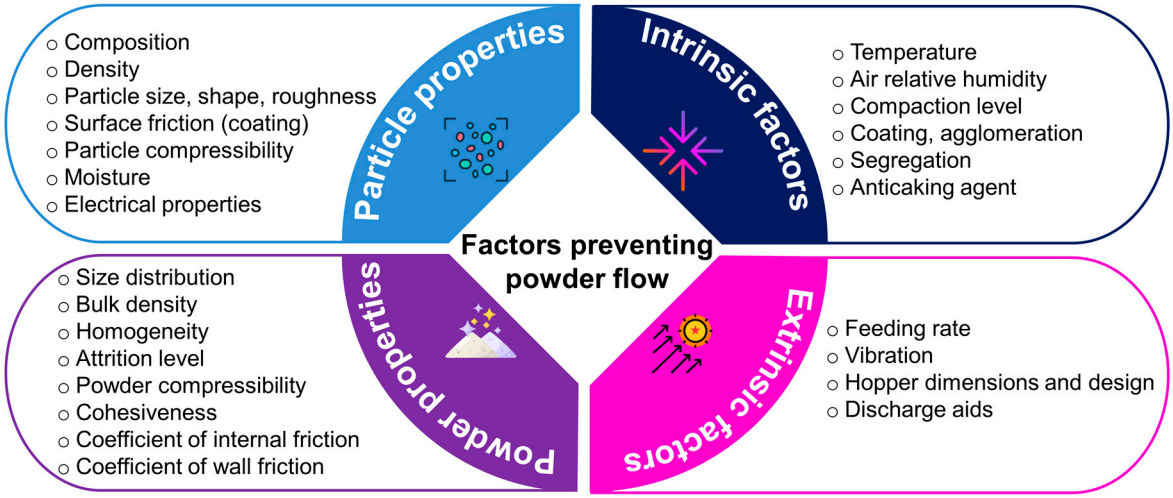

Figure 3. Factors preventing food powder flow (Reproduced from [29] with permission from Elsevier, 2008).

3.1. Moisture and Water Activity

Managing the water content of powders poses a challenge due to its dynamic equilibrium with ambient conditions. Consequently, water in powders emerges as a critical control point for optimizing flowability. Even subtle changes in water content can determine whether powders flow effectively or not, with significant implications for their storage and transportation [13].

The physical structure and chemical composition of dry powders influences their ability to absorb water from surrounding humid environments. This property is known as powder hygroscopicity, which quantifies the extent to which a powder can take up water from ambient moisture [29]. Callahan et al. [30] devised a classification system for hygroscopic powders relying on the quantity of water absorbed by the powder over one week at a specified relative humidity. Subsequently, Murikipudi et al. [31] validated an expedited water vapor sorption method for classifying the hygroscopicity of food and pharmaceutical powders. This method can be completed within 24 h, compared to the conventional method's one-week timeframe for reaching equilibrium conditions. Both methods classify powders as non-hygroscopic, slightly hygroscopic, moderately hygroscopic, or very hygroscopic materials (Table 1).

Table 1. Classification of hygroscopic powders.

Classification	Mass Change Criteria		Observations
	Conventional Method	Vapor Sorption Method	
Non-hygroscopic	<20% (w/w) in MC at 90% RH	<0.2% (w/w)	No moisture uptake < 90% RH
Slightly hygroscopic	<40% (w/w) in MC at 90% RH	0.2–2% (w/w)	No moisture uptake < 80% RH
Moderately hygroscopic	<60% (w/w) in MC at 90% RH	2–15% (w/w)	No moisture uptake < 60% RH
Very hygroscopic	>60% (w/w) in MC at 90% RH	>15% (w/w)	Moisture uptake < 50% RH

MC—moisture content; RH—relative humidity. (Reproduced from [32] with permission from Taylor & Francis, 2013).

Water activity and moisture content, both interconnected variables at a constant temperature, share a function defined by the sorption isotherm [32]. At first glance, it might seem that either of these variables could adequately portray the influence of water content on powder flowability; the non-linear relationship of sorption isotherms between moisture content and water activity suggests that one of these variables must correlate linearly in a better way with powder flowability than the other [33].

In general, increasing moisture content tends to decrease the flowability of powders. However, this relationship is not always consistent when assessed using the Hausner ratio,

Carr index, angle of repose, and flow factor. Literature suggests that flow indices like the Hausner ratio, Carr index, and angle of repose are relatively insensitive to variations in moisture content. In contrast, the flow factor appears to be more responsive to changes in powder moisture content [13]. Several studies have investigated the relationship between moisture content and flow factor using various food powders. For example, oregano powder exhibited a linear decrease in flowability as the moisture content increased from 1.9% to 8.8% [34]. Similarly, skim milk, sodium caseinate, whey protein concentrate, and rennet casein powders demonstrated a consistent trend of decreasing flowability with increasing moisture content [35,36]. However, it is worth mentioning that this linear relationship does not always hold true for all food powders. A second-order equation adequately described the flowability of paprika and aspartame, with moisture content ranging from 1.67% to 17.48%. For paprika, flowability was represented by an exponential function, indicating a high flow factor at low moisture content. In contrast, aspartame exhibited an inverse quadratic flowability function across a moisture content range of 0.45% to 8.23%, with a maximum flow index at 4.57% [34].

Furthermore, as previously mentioned in this section, moisture content refers to the quantity of water adsorbed by a powder, although it does not provide insight into the distribution of water molecules within the powder matrix. In contrast, water activity describes how water is bound within the powder structure. Water activity is an inherent characteristic of powders that signifies the availability of water. Accordingly, Juarez-Enriquez et al. [29] studied the changes in flow factor of maltodextrin, starch, and pectin powders under varying water activities or moisture contents. Linear models using absolute moisture as the independent variable inadequately reflected the observed variations in the flow factor for starch and maltodextrin ($R^2 < 0.75$). Conversely, employing water activity as the independent variable to model the impact of water content on the flowability of starch and maltodextrin powders accurately represented their flow factor behavior ($R^2 > 0.90$). For pectin powder, a comparable trend was observed, where both absolute moisture and water activity effectively predicted the influence of water content on flow behavior ($R^2 > 0.93$). The improved fitting of models using water activity as the independent variable in linear models could be attributed to water activity's ability to capture the interaction between solids and water, not just their mass relationship [29]. Water activity values below 0.20 indicate that water molecules are tightly bound to the biomolecule structure as a monolayer, preventing interference with powder flow [37]. At water activity values above 0.60, water molecules tend to bind to other water molecules [38]. At higher water contents, free water may form liquid bridges, reducing powder flowability [39].

3.2. Particle Size

Particle size and particle size distribution have been recognized as crucial factors that impact not only flowability but also other properties, such as bulk density, angle of repose, and compressibility of bulk solids. Even slight alterations in particle size have been observed to result in significant alterations in flowability. Notably, a decrease in particle size often leads to a decrease in the flowability of a given granular material due to the increased surface area per unit mass [36,40]. Finer particle sizes and a broader particle size distribution both increases cohesive strength and reduce flowability [41]. This reduction in particle size augmented the contact area between particles, thereby strengthening the cohesive forces [28].

Reducing particle size significantly impacts the cohesion of low-fat milk powders, while the effect on high-fat milk powders is less pronounced. For 26% and 1% fat milk powders, decreasing the particle size from 239 to 59 μm and from 170 to 92 μm, respectively, led to substantial decreases in the flow index from over 10 (free-flowing) to just below 2 (highly cohesive) and from 6.3 to 3.6, respectively. This was attributed to the increased surface area available for interparticle contact, fostering stronger cohesive interactions. In the case of 50% fat milk powder, reducing the particle size from 199 to 96 μm exhibited no impact on interparticle cohesion, suggesting that the cohesiveness derived from the high fat

content likely overrides the effect of particle size reduction within the investigated range. Furthermore, 1% fat milk powder exhibited a higher wall friction coefficient in comparison to milk powders with higher fat content. Particle size did not significantly impacted the wall friction of any of the powders, whereas the effective angle of internal friction increased with particle size [40].

Studies have also investigated the effect of particle size on dynamic flow properties of several plant powders. BFE exhibited a positive correlation with particle size for *Dichostachys glomerata* fruits and *Hibiscus sabdariffa* calyxes powders, while an inverse relationship was observed for *Boscia senegalensis* seeds powder [42]. Defatted soybean flour demonstrated an increase in both BFE and CBD values as particle size increased. Analyzing trends in interparticle forces could elucidate the specific mechanisms driving the observed SE increase with decreasing particle size [43]. In another study, surprisingly, non-cohesive *foufou* flour, characterized by large angular particles, exhibited a higher BFE compared to *foutou* flour. Contrary to expectations, *foutou* flour, with its relatively higher proportion of fine particles, displayed low BFE values, suggesting good flowability [44].

Rivera et al. [45] examined the flowability of both soft and hard red winter wheat flour. They found that the type of wheat significantly impacted the BFE values, with hard red winter wheat samples showing higher BFE values compared to soft red winter flours. Interestingly, particle size did not affect the BFE values. However, it did influence the cohesion values, with cohesion increasing as particle size decreased. This variation in cohesion was attributed to differences in surface roughness, which decreased with increasing particle size. Furthermore, large particle sizes (>53 µm) exhibited increased flow function, indicating easy flowing powder. Soft red winter wheat flour showed lower flow function values, suggesting poorer flow properties.

Particle size and shape of defatted soybean flour were demonstrably affected by the chosen milling technique. Jet milling, in particular, lead to the formation of smaller and more spherical particles compared to hammer milling. The different particle sizes and shapes caused by milling methods significantly impact flow behavior. Specifically, jet-milled flour exhibited greater compressibility and lower permeability compared to hammer-milled flour. While similar cohesion and flow properties were observed in defatted soybean flours with particle sizes between 42.0 and 108.1 µm, a significant decrease in flowability was seen in the much smaller 9.5 µm size fraction [43].

Nkurikiye et al. [7] explored the flow properties of lentil, yellow pea, and chickpea flours in comparison to wheat flour. Chickpea flour exhibited higher BFE values, which remained consistent across various particle sizes, consequent upon their inherent cohesiveness. Particle size influenced the flow behavior of yellow pea and lentil flour, whereas for chickpea flour, it was postulated that higher fat content increased the resistance to flow, necessitating additional energy for movement initiation. Among the tested flours, small-sized lentil flour demonstrated superior flowability (402.52 mJ), while large-sized lentil flour exhibited poorest flowability (953.01 mJ). The smaller particle size of lentil flours likely contributed to their lower BFE, due to increased particle displacement by the blades compared to larger-sized flours.

BFE is considered as a crucial parameter for powder flowability in low-stress environments [14]. Generally, powders characterized by low BFE values exhibit a favorable flowability, while those with poor flowability often exhibit high BFE values. Consequently, although there seems to be a correlation between powder fineness and flowability, this relationship is not always straightforward. For poorly flowing and highly cohesive particles, the blade might displace only a small quantity of powder in its immediate surroundings, leading to a deceptively low BFE [44,46]. Variations in CBD can significantly impact BFE [47], and evaluating flowability solely based on high or low BFE may not be appropriate under conditions where CBD varies markedly with particle size [43].

3.3. Surface Composition

The surface composition of the powder plays a significant role in shaping the differences in flow patterns [27]. This composition is considerably influenced by the feed concentrates used in the process. During the spray-drying of milk powders, lipids tend to gather at the surface of milk droplets due to their buoyant nature (arising from density differences between water and lipids), strong hydrophobic properties, and slow diffusion in water. This accumulation leads to an overabundance of lipids on the particle surface. Meanwhile, milk proteins, though diffusing slowly in water, move faster than lipids, leading to a lower protein content at the particle surface. Lactose and minerals, with their effective water diffusion and hydrophilic characteristics, are primarily found within the particle core. In low-fat powders, such as skim milk powder, proteins are overrepresented on the particle surface due to their role as the most surface-active components of skim milk [26,48].

Fat content had a notable impact on powder cohesion. The cohesion observed in the skim-milk powder (0.9% fat) was considerably lower than that of whole-milk powder (26% fat). The whole-milk powder and high-fat powder (73% fat) exhibited similar flow functions and were classified as highly cohesive powders based on their flow indices. Skim-milk powder was categorized as an easy-flow powder, making whole-milk powder and high-fat powder substantially more prone to cohesive arching than skim-milk powder. Despite having a much higher fat content than whole-milk powder, high-fat powder exhibited similar cohesiveness [35]. According to Kim et al. [49], the surface fat content of industrial spray-dried milk powders, including skim milk powder with 1% fat, whole milk powder with 26.5% fat, and a cream powder with 71.5% fat, significantly exceeded their bulk average compositions. Specifically, the surface fat contents of skim milk powder, whole milk powder, and cream powder were 18%, 98%, and 99%, respectively. The substantially lower surface fat content of skim milk powder compared to whole milk powder and cream powder could explain its reduced cohesiveness. Moreover, Fitzpatrick et al. [40] studied the flowability of 26% fat milk powders with varying free fat content from 12.6 to 74.2%. They observed no correlation between free fat content and powder cohesion, with the 12.7% free fat powder exhibiting the least cohesion. Therefore, they concluded that free-fat content within the range of 13–74% had no significant impact on the cohesion of 26% fat powder at 20 °C.

3.4. Storage and Handling Conditions

Powder flowability is also influenced by storage and handling conditions. Elevated temperatures within the range of 10–30 °C, where the majority of fat melting takes place, can enhance the cohesiveness of powders containing significant fat content by creating liquid fat bridges between particles. However, the influence of increasing temperature between freezing and 30 °C is unpredictable. While increasing temperature tends to make components more plastic and thus more cohesive, it may also vaporize moisture, reducing powder cohesiveness. Furthermore, a sharp increase in powder cohesiveness and adhesion to surfaces occurs when the temperature exceeds the "sticky" temperature [50]. This temperature is moisture-dependent and can be directly linked to glass transition temperature [51]. Cooling milk powder can lead to lumping and caking. Furthermore, Foster et al. [52] demonstrated that heating and subsequent cooling of powders with a total fat content of at least 41% resulted in significant lumping and caking issues.

Fitzpatrick et al. [40] observed a minor increase in the cohesiveness of skim milk powder at 25 °C, likely due to the enhanced thermoplasticity of components, particularly lactose, at higher temperatures. The impact of temperature on whole milk powder cohesiveness was more pronounced. Given the high fat content of high fat milk powder (73% fat), a more significant effect of temperature was initially anticipated. Increasing the temperature from 5 to 20 °C enhanced the cohesiveness of high fat milk powder; however, a further increase in temperature to 30 and 40 °C unexpectedly produced the opposite effect.

4. Conclusions

In conclusion, powder flowability is a multifaceted property influenced by a complex interplay of factors, including particle size, shape, surface properties, moisture content, and temperature. Understanding these factors and their impact on flow behavior is essential for optimizing food powder processing and handling. The methods discussed in this review provide valuable tools for evaluating and improving powder flowability, allowing manufacturers to select appropriate powders and optimize process conditions to ensure consistent product quality and efficient operations. Further research is warranted to elucidate the intricate mechanisms governing powder flow and to develop advanced methods for flowability enhancement, particularly in complex food powder systems.

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