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Properties and Fractal Analysis of High-Protein Milk Powders

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Abstract: (1) Background: Optimization of production and evaluation of the quality of preparations containing milk proteins facilitates their use in various branches of the food industry. The aim of this study was to produce and characterize high-protein milk powders (MCC, SPC) obtained by membrane techniques, and to compare them with industrially produced powders (WPC, CH, WPH, WPI). (2) Methods: The composition, reconstitution and flow properties, particle size, and microstructure of milk powders were determined, and fractal analysis was performed. (3) Results: MCC and SPC produced by the membrane separation of skim milk and industrially produced powders were characterized by a wettability of >180 s and a high solubility (0.10–0.85 cm^3), excluding MCC (10.75 cm^3 of insoluble particles). Flowability expressed as the Carr index was very good in CH (<15%), good in MCC (15–20%), and fairly good in the remaining powders (20–25%). All powders were moderately cohesive, excluding CH, which was characterized by low cohesiveness. The analyzed preparations differed in the values of fractal dimension. (4) Conclusions: The reconstitution and rheological properties of high-protein milk powders were affected by their composition, particle size, porosity, and surface properties. The fractal approach to the microstructure of milk particles enabled the unambiguous detection of subtle differences in the microstructure of the analyzed samples, which could not be identified during a visual assessment.

Keywords: membrane filtration; micellar casein concentrate; serum protein concentrate; commercial high-protein milk powders; reconstitution properties; flowability; cohesiveness; microstructure; fractal analysis

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1. Introduction

Milk and dairy products contain complete proteins that are the source of all essential amino acids [1,2], and they are abundant in bioactive peptides [3,4], which enhance metabolic processes and deliver health benefits for consumers [2]. In addition to their high nutritional value, powdered milk protein products also improve the functional properties of dairy foods, such as their ability to form gels, foams, or emulsions and bind water [5–7]. These properties determine the suitability of dairy powders as functional ingredients in dairy and food production. Therefore, dairy powders, depending on their composition, are increasingly used in the food processing industry, including bakery and confectionery products, meat products, ready-made foods, and dairy products such as ice-cream, yoghurt, and cheese [8].

A knowledge of the properties of innovative preparations containing milk proteins facilitates their application in various branches of the food industry. Due to their functional and nutritional properties, whey proteins are valuable ingredients in various food products. They are used to improve properties such as dispersibility, water binding, foaming, whipping, emulsifying, gelling, and buffering capacity [9,10]. The physical properties of dairy powders are usually determined by their composition and the surface properties of powder particles, which can be modified during technological processes [10].

The quality of dairy powders is determined by their properties, including reconstitution properties such as wettability, solubility, and loose and tapped density. The

reconstitution properties of these powders consist of a number of complex processes such as wettability, water absorption, sinkability, dispersibility, and solubility. On the other hand, loose and tapped densities determine the flowability and cohesiveness of powder particles. The flowability and cohesiveness of particles have to be evaluated for rheological analyses of powders [11]. Both reconstitution and rheological properties are affected by particle size and particle porosity, defined as the fraction of void space. The bulk density of dairy powders is highly dependent on packing density, namely the compressibility of the powder bed. Loose bulk density denotes the volume of a powder, including the volume of void spaces between particles, whereas tapped density is the density of a powder where small particles enter the voids between large particles, decrease the powder's volume and increase its density. The cohesiveness and compressibility of a powder are determined by its flowability, which, in turn, is affected by particle shape, size, hygroscopicity, and porosity. Similar factors are responsible for the reconstitution properties of a powder. Wettability, i.e., the ability of milk powder particles to absorb water initially on their surface and then in the interior, and water absorption, i.e., the susceptibility of the powder mass to water penetration into the interparticle pores (capillaries). The presence of fine particles and low bed porosity, as well as hydrophobic substances on the surface, make it difficult for water to penetrate their interior [10].

Particle properties such as particle size, size distribution, and shape determine the desired functional properties and hence the quality of milk powders. The degree of surface irregularity of the particles can be determined using fractal analysis. The fractal dimension can be a useful parameter for describing milk powder particles [12]. Fractals are self-similar, and the fractal dimension is not an integer. In classical Euclidean geometry, points, lines, planes, and volumes are objects with 0, 1, 2, and 3 dimensions, respectively. In Euclidean space, the dimension of objects with fractal features is not limited to an integer and theoretically can range from 0 to 3 [13]. The mass and size of a fractal object are bound by a linear relationship which can be expressed as $M\ (R) \sim R\hat{}d$, where M is mass, R is size, and d is the fractal dimension of the object [13,14]. These properties determine the applicability of dairy powders as functional additives in dairy and food production.

High-protein milk powders are an additional ingredient used in a wide range of food products, intended for specific groups of consumers with specific nutritional requirements. The use of high-protein preparations as additives to non-fermented milks is one of the methods of modifying the nutritional value and sensory attributes of the end products [15]. The aim of this study was to produce high-protein milk powders (micellar casein concentrate, MCC; serum protein concentrate, SPC) and characterize their physicochemical properties. The obtained powders were then compared with industrially produced powders (whey protein concentrate, WPC; casein hydrolysate, CH; whey protein hydrolysate; WPH; whey protein isolate, WPI). Another research objective was to perform image analysis combined with the determination of the fractal dimension in order to compare the microstructure of the tested powders and its impact on their functional properties.

2. Materials and Methods

2.1. Materials

The experimental material comprising high-protein milk powders was produced experimentally on a pilot scale with the use of membrane techniques and the following: micellar casein concentrate (MCC) and serum protein concentrate (SPC), and commercial products—whey protein concentrate (WPC), casein hydrolysate (CH), whey protein hydrolysate (WPH), and whey protein isolate (WPI) (Superior Sp. z o.o., Olsztyn, Poland).

Production of Micellar Casein Concentrate and Serum Protein Concentrate

Raw whole milk originated from a dairy farm administered by the University of Warmia and Mazury in Olsztyn. Cream and skim milk were separated by centrifugation at the University's dairy plant. Raw skim milk was pasteurized with the use of a plate heat exchanger at 72 °C; the holding time was 16 s. The milk was then cooled to 4 °C, and refrigerated overnight (≤4 °C) until processing [16].

After pasteurization, skim milk was microfiltered three times (three-stage process, 50 °C) in a pilot-scale ceramic microfiltration system (described below) in continuous feed-and-bleed mode with a 3× concentration factor (CF) to produce MF retentate and MF permeate. A two-stage diafiltration (DF) process was carried out on the same day, to complete the three-stage microfiltration process [16].

Skim milk was microfiltered in a pilot-scale microfiltration system (Figure 1) equipped with graded permeability (GP) 0.1-µm ceramic Membralox membranes (model EP1940GL0.1µAGP1020, alumina, Pall Corp., East Hills, NY, USA). The membranes had a pore diameter of 0.1 µm, and a surface area of 0.72 m^2 (three membrane elements with an area of 0.24 m^2 each). They consisted of 19 channels (4 mm in diameter, 1.02 m in length) in each of the tubular stainless-steel modules. The channels were installed vertically in the system; the permeate and retentate streams passed from the bottom to the top of the module. The GP MF unit featured a feed pump (LKH-10-155-FSS-DIN 3.0 kW) and a retentate recirculation pump (LKH-10-155-FSS-DIN 4.0 kW), which were supplied by Alfa Laval (Kansas City, MO, USA).

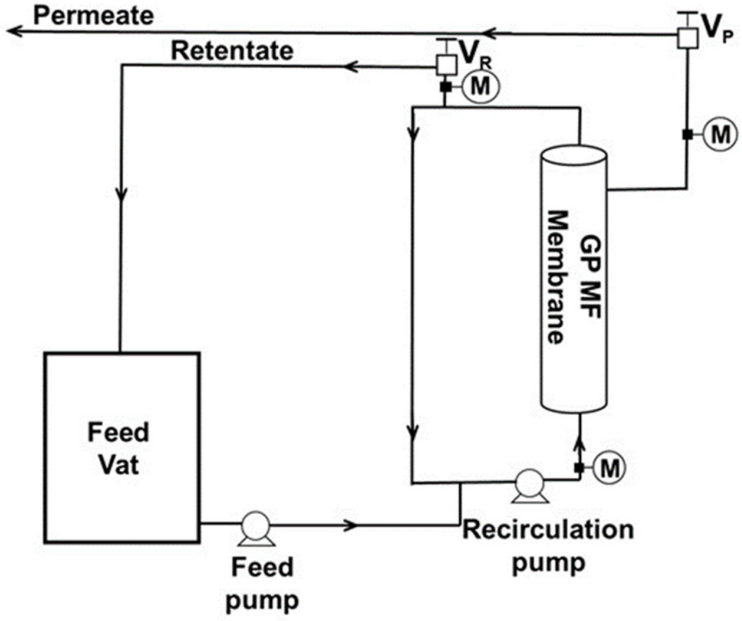

Figure 1. Simplified diagram of the MF system used in the study: M—manometer, V_R—retentate outlet valve, V_P—permeate outlet valve.

Skim milk was poured into the system's feed tank; only the retentate valve was opened, and all other valves were closed. Feed and retentate recirculation pumps were activated, and their working capacities were set at 40% and 30%, respectively. After five-minute recirculation, the permeate valve was gradually opened to achieve the fully open position. Subsequently, the setting of the retentate outlet valve was slowly adjusted to stabilize the flow of the retentate and permeate streams and achieve 3× CF. The actual CF was calculated based on the volume of the retentate and the permeate collected in 30 s. When the removal rates of the retentate and the permeate were below 3× CF (i.e., 2 kg of the permeate was removed per kg of the retentate), the retentate outlet valve/recirculation diaphragm valve was adjusted to achieve and maintain 3× CF. The removal rates of the retentate and the permeate were monitored and adjusted at 30 min intervals to maintain 3× CF.

Throughout microfiltration, the retentate and the permeate were continuously discharged into separate stainless-steel tanks, where they were immediately cooled down to 4 °C. The retentate stream was then returned to the feed vat to increase permeate yields and obtain a final CF of 3×. Typical inlet pressure was 2.5 bar, and retentate outlet pressure was 1.4 bar with the permeate valve fully open to maintain atmospheric pressure on its side. The flux (kg/m^2 per hour) was measured at 30 min intervals, and the permeate and the retentate were sampled for analysis. The composition of retentate and permeate samples was analyzed using a MilkoScan™ FT2 infrared milk analyzer (Foss, Hillerød, Denmark) for process control. At the end of the MF run, the retentate and the permeate collected during the processing run were combined and sampled. The MF experiment was performed in three replicates.

The MF retentate was subjected to DF twice, in order to produce native micellar casein concentrate with reduced serum protein (SP) content. The MF retentate (obtained in the first stage) was diluted by weight to 1× CF by reverse osmosis (2 kg of pasteurized RO water per kg of the retentate, DF factor of 3), and it was used in the first DF process. The retentate was combined with water before heating to 50 °C, and it was processed in the MF system to achieve 3× CF under identical conditions as in the first stage. The third and last MF stage (second DF) was identical to the second MF stage (first DF); the retentate from the second stage was diluted with RO water, and it was used as the feed. All retentates and permeates were collected, cooled, combined, and sampled [16].

The final MF retentate (liquid MCC) was spray-dried after cooling and storing overnight (4 °C). SP removed from milk by MF was further purified and concentrated by ultrafiltration to obtain SPC. Both MF permeates and the DF permeate from the first DF were cooled to 4 °C and stored overnight before SPC production.

One day after MCC production, MF permeates and the DF permeate from the first DF were weighed, combined, heated to 50 °C, ultrafiltered (UF stage 1 with 5× CF) and diafiltered (DF stage 2 at 8× CF) to produce 60% liquid SPC. The final UF retentate (liquid SPC) was spray-dried after cooling and storing overnight (4 °C).

The feed for the ultrafiltration process was fractionated in a pilot-scale UF system (continuous bleed-and-feed recirculation mode). The system was equipped with a semipermeable polyethersulfone (PES) spiral wound membrane (model: 3838 HFK-131, Koch Separation Solutions, Wilmington, MA, USA) with a nominal pore size of 10,000 Da and a surface area of 6.7 m^2. Ultrafiltration was caried out under the following conditions: feed temperature—around 50 °C; retentate inlet pressure—around 4.2 bar for UF and around 3.8 bar for DF, with no back pressure on the permeate side.

At the beginning of the UF process, before the retentate and the permeate were redirected to the feed tank, approximately 10 to 15 L of the feed was collected and discarded to flush water out of the system. Next, the retentate and the permeate were returned to the feed vat, and retentate and permeate outlet valves were adjusted to the indicated CF values.

Before DF, RO water was added to the UF retentate in an amount corresponding to the amount of permeate obtained during UF. When the desired CF was achieved, the permeate and retentate streams were directed to cooling and storage tanks. When the process was completed, the final UF retentate and permeate were combined and sampled for analysis in the MilkoScan™ FT2 infrared milk analyzer (Foss, Hillerød, Denmark).

The final MCC and SPC retentates were spray dried with a Production Minor Spray Dryer (Niro Atomizer, Søborg, Denmark). The feed was kept at or below 7 °C; the feed rate was approximately 15 kg/h; the inlet temperature was 180 °C and the outlet temperature was 80 °C. The dried product was collected, packaged in hermetically sealed plastic bags, and weighed after the run. Powder samples intended for physicochemical analyses were stored in a shaded place, at 21 °C [17].

2.2. Analysis of High-Protein Milk Powders

2.2.1. Composition of High-Protein Milk Powders

High-protein milk powders were analyzed to determine their dry matter content (AOAC International, method 990.20; 33.2.44) and total nitrogen content (by the Kjeldahl method, AOAC International method 991.20; 33.2.11) [18]. Fat and ash content was determined with the NIRS DS2500 analyzer (Foss, Hillerød, Denmark). All analyses were performed in duplicate.

2.2.2. Properties of High-Protein Milk Powders

The following parameters were determined in the tested powders: wettability [19], insolubility index [20] and loose and tapped bulk density [21]. Flow properties were assessed by calculating the Hausner ratio and the Carr index based on loose and tapped bulk density. Both density values were used to calculate flowability coefficients: the Carr index (CI) according to Equation (1), and the Hausner ratio (HR) according to Equation (2) [22]:

$$CI = [(\varrho T - \varrho L)/\varrho T] \times 100 \quad (1)$$

and

$$HR = \varrho T/\varrho L \quad (2)$$

where

ϱT—tapped bulk density;
ϱL—loose bulk density.

2.2.3. Microstructure of High-Protein Milk Powders

Microscopic observations of high-protein milk powder particles were performed under a QUANTA 200 scanning electron microscope (FEI Company, Hillsboro, OR, Thermo Fisher Scientific, Waltham, MA, USA). Samples were prepared as described by Smoczyński [12]. Micrographs were observed and recorded at 200× and 800× magnification.

2.2.4. Particle Size Analysis of High-Protein Milk Powders

The size of high-protein milk powder particles was measured by laser diffraction with a Mastersizer 3000 particle size analyzer with the Aero S disperser (Malvern Instrument, Malvern, UK). The results were expressed in the following units: particle size distribution (SPAN), span = $(d_v90 - d_v10)/d_v50$; surface-weighted mean diameter, Sauter mean diameter (d_{32}), $d_{32} = \Sigma\, Sd_i^3\, n_i/Sd_i^2\, n_i$; volume-weighted mean diameter, De Brouckere mean diameter (d_{43}), $d_{43} = \Sigma\, Sdi^4\, n_i/Sdi^3\, n_i$, where n_i is the number of particles with diameter d_i.

2.2.5. Fractal Image Analysis of High-Protein Milk Powder Particles

The microstructural images of milk powder particles were analyzed using Nis-Elements Basic Research software (Nikon Corporation, Tokyo, Japan). The original micrographs were converted to high-contrast images based on the predefined contrast parameters. The perimeter (P) and area (A) of 200–250 small, medium, and large particles were measured. The analyzed objects were self-similar, and their fractal dimension D was calculated from the slope of the corresponding lg A = f (lg P) line [23,24].

2.3. Statistical Analysis

A statistical analysis of high-protein milk powders was performed in triplicate. The results were checked for normal distribution and the homogeneity of variance. The significance of differences between means was determined by the LSD test. The analyses were carried out at a significance level of 0.05. Linear relationships between particle size and powder properties were analyzed. Data were processed in Statistica v. 13.0 (StatSoft Inc., Tulsa, OK, USA).

3. Results and Discussion

The composition of high-protein milk powders is presented in Table 1. The protein content of high-protein milk powders was as follows: MCC—76.66 ± 0.35, SPC—67.75 ± 0.33, WPC—60.92 ± 0.22, CH—68.12 ± 0.23, WPH—68.21 ± 0.23, and WPI—91.43 ± 0.35.

Table 1. Proximate composition of high-protein milk powders.

Product	Fat, %	Protein, %	Water, %	Ash, %
MCC	1.46 ± 0.08 ^{e}	76.66 ± 0.35 ^{c}	5.67 ± 0.04 ^{d}	7.11 ± 0.14 ^{d}
SPC	0.78 ± 0.06 ^{b}	67.75 ± 0.33 ^{b}	5.11 ± 0.03 ^{c}	3.71 ± 0.05 ^{b}
WPC	1.46 ± 0.17 ^{e}	60.92 ± 0.22 ^{a}	5.17 ± 0.04 ^{c}	4.08 ± 0.09 ^{c}
CH	1.05 ± 0.09 ^{d}	68.12 ± 0.23 ^{b}	4.13 ± 0.08 ^{a}	12.23 ± 0.33 ^{e}
WPH	0.99 ± 0.09 ^{c}	68.21 ± 0.23 ^{b}	4.17 ± 0.04 ^{a}	2.98 ± 0.17 ^{a}
WPI	0.44 ± 0.07 ^{a}	91.43 ± 0.35 ^{d}	4.89 ± 0.05 ^{b}	3.85 ± 0.26 ^{b}

Results are expressed as means ± standard deviation. Mean values with different superscripts in columns differ at $p < 0.05$.

The values of wettability and the insolubility index were determined to evaluate the reconstitution properties of high-protein milk powders. The wettability of all powders was generally >180 s (Table 2). When the powders were wetted, a sticky coating or lumps were formed on the surface, which hindered water absorption by powder particles. Poor wettability could also be attributed to the relatively small size of powder particles and small voids between particles. The low solubility of MCC could be attributed to the cross-linking of casein micelles on the surface of powder particles by non-covalent bonds (e.g., hydrophobic interactions and/or hydrogen bonds). Moreover, the low lactose content of high-protein milk powders contributes to their lower solubility since the interactions between proteins in the presence of lactose result in a different spatial configuration. Micelle agglomeration through non-covalent bonding and high micelle packing were observed due to the low lactose content of the insoluble portion that remained after powder reconstitution. Both phenomena, i.e., the cross-linking of micelles on the powder surface and impeded water transfer into the powder structure are responsible for the poor solubility of MCC [25,26].

Table 2. Properties of high-protein milk powders.

Product	Wettability, s	Insolubility Index, cm^3	Loose Bulk Density, g/cm^3	Tapped Bulk Density, g/cm^3	Carr Index, %	Hausner Ratio
MCC	>180	10.75 ± 0.12 ^{b}	0.16 ± 0.01 ^{a}	0.20 ± 0.01 ^{a}	20.03 ± 0.82 ^{b}	1.25 ± 0.01 ^{b}
SPC	>180	0.10 ± 0.01 ^{a}	0.11 ± 0.01 ^{a}	0.14 ± 0.01 ^{a}	21.09 ± 1.78 ^{b}	1.27 ± 0.03 ^{b}
WPC	>180	0.35 ± 0.03 ^{a}	0.33 ± 0.01 ^{b}	0.42 ± 0.02 ^{b}	21.03 ± 0.37 ^{b}	1.27 ± 0.01 ^{b}
CH	>180	0.10 ± 0.02 ^{a}	0.30 ± 0.01 ^{b}	0.33 ± 0.01 ^{b}	9.10 ± 0.23 ^{a}	1.10 ± 0.01 ^{a}
WPH	>180	0.85 ± 0.04 ^{a}	0.30 ± 0.02 ^{b}	0.39 ± 0.03 ^{b}	23.84 ± 1.24 ^{b}	1.31 ± 0.02 ^{b}
WPI	>180	0.10 ± 0.01 ^{a}	0.33 ± 0.02 ^{b}	0.45 ± 0.04 ^{b}	26.56 ± 1.23 ^{c}	1.36 ± 0.02 ^{c}

Results are expressed as means ± standard deviation. Mean values with different superscripts in columns differ at $p < 0.05$.

In food powders, solubility is one of the most important attributes which influences other functional properties, such as thickening, gelling, foaming, and emulsifying properties. MCC was characterized by an exceptionally high volume of insoluble particles (>10 cm^3), whereas SPC was 99.08% soluble. In the tested group of high-protein milk powders, MCC and SPC were characterized by the lowest loose bulk density (0.11–0.16 g/cm^3) as well as the lowest tapped bulk density (0.14–0.20 g/cm^3), while the loose and tapped bulk densities of commercial powders achieved higher values. The bulk density of dairy powders is highly dependent on packing density, namely the compressibility of the powder

bed. Loose bulk density denotes the volume of a powder, including the volume of void spaces between particles, whereas tapped density is the density of a powder where small particles enter voids between large particles, decrease the powder's volume and increase its density [10].

Flow properties were assessed by calculating the Hausner ratio and the Carr index based on loose and tapped bulk density (Table 2). High-protein milk powders were classified based on the calculated values of the Carr index (CI) and the Hausner ratio (HR) [22]. Powders with a higher Hausner ratio were more cohesive, whereas powders with a lower Carr index were more flowable (free-flowing). An analysis of Carr index values revealed that MCC and SPC had fairly good flow properties (20–35%). Commercial whey protein powders were fairly flowable, whereas CH was characterized by very good flowability. In turn, the calculated values of the Hausner ratio demonstrated that all analyzed high-protein milk powders were moderately cohesive (1.2–1.4), except CH, which was characterized by low cohesiveness. These results confirmed that increased protein content and reduced lactose content contribute to strong intermolecular interactions in dairy powders, and enhance cohesive forces that determine flowability [27]. According to Sharma et al. [10], the cohesiveness, flowability, and reconstitution properties of powders are determined by, among other things, particle shape, surface, size, hygroscopicity, and porosity.

The results of particle size measurements revealed that the MCC preparation was characterized by the largest particles (d_{32}, 52 µm). The remaining high-protein milk powders were divided into two groups based on particle size. The first group was characterized by larger particles (≥35 µm), and it included CH, WPC, and SPC. The second group was characterized by smaller particles (≤20 µm), and it comprised WPH and WPI (Table 3). Despite a high particle dispersion, the WPH was characterized by greater differences in particle size, as indicated by high SPAN values and differences between d_{32} and d_{43}. Particle size distribution was more uniform in the remaining high-protein milk powders (Table 3). The large particle sizes of high-protein milk powders result from the size of the concentrate drops dispersed during spray drying, and are also related to their cohesiveness. This is particularly evident in the case of MCC, which is larger in size and has higher values of cohesiveness and flowability than the commercial CH preparation.

Table 3. Diameter and particle size distribution of high-protein milk powders.

Product	D32, µm	D43, µm	SPAN
MCC	52.04 ± 3.96 ^{d}	83.96 ± 4.14 ^{d}	2.00 ± 0.07 ^{b}
SPC	37.48 ± 2.48 ^{c}	81.59 ± 3.00 ^{d}	1.74 ± 0.46 ^{ab}
WPC	36.95 ± 1.95 ^{c}	67.40 ± 3.60 ^{c}	1.73 ± 0.10 ^{a}
CH	35.61 ± 1.61 ^{c}	81.33 ± 3.33 ^{d}	2.07 ± 0.06 ^{b}
WPH	10.25 ± 1.75 ^{a}	55.49 ± 1.90 ^{b}	3.75 ± 0.12 ^{c}
WPI	18.99 ± 1.50 ^{b}	39.15 ± 3.85 ^{a}	2.11 ± 0.09 ^{b}

Results are expressed as means ± standard deviation. Mean values with different superscripts in columns differ at $p < 0.05$.

The micrograph analysis confirmed the results of particle size measurements and demonstrated that most of the examined high-protein milk powders, regardless of protein type, contained particles with a smooth surface (Figure 2).

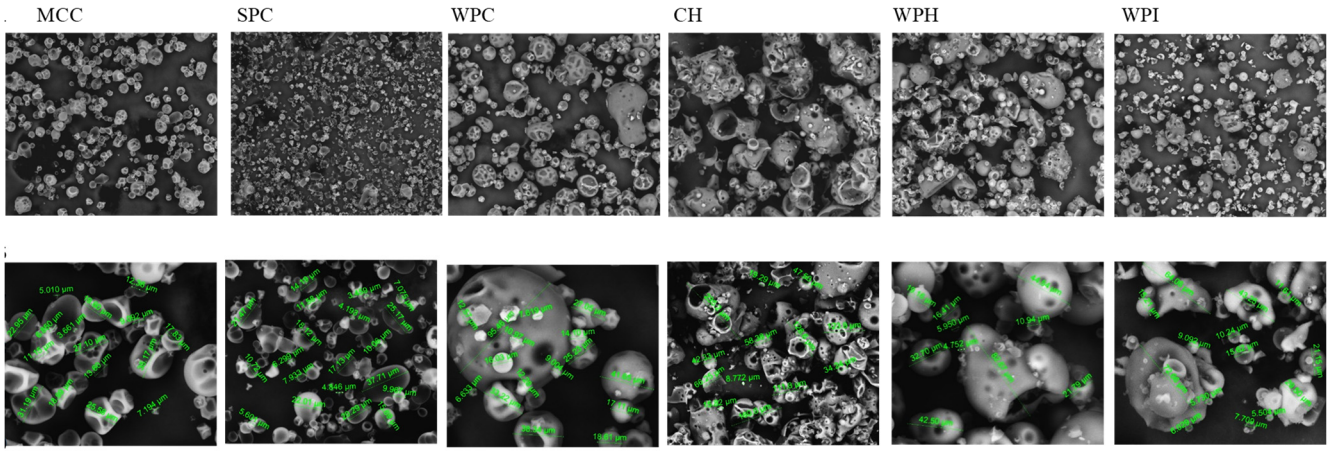

Figure 2. Micrographs of high-protein milk powders at 200× (**upper row**) and 800× (**bottom row**) magnification.

The morphology of powder particles influences a powder's reconstitution characteristics and flowability. The size and the shape of powder particles (including internal porosity) and the size of void spaces between particles significantly affect wettability and solubility. The measured differences in the microstructure of the analyzed samples can be reflected in various functional properties, such as powder solubility. Therefore, a direct relationship can be observed between the microstructure and functional properties of the tested powder samples. The presence of fine particles and low powder porosity make it difficult for water to penetrate their interior [10]. Agglomerated powders contain larger particles with irregular shapes and a porous surface. According to Domian [28], the flowability of powders is determined mainly by the size of agglomerates, whereas changes in powder composition have no significant effect on flow characteristics. However, the results of this study indicate that the reconstitution properties of high-protein milk powders depend not only on the powder's microstructure, but also (to a large extent) on the concentration and type of protein in the concentrate. In the present study, a moderate correlation (r = 0.4–0.7) was observed between the size of powder particles described by D32, D43, and the insolubility index (positive values of r) vs. density, the Carr index, and the Hausner ratio (negative values of r) (Table 4).

Table 4. Correlation coefficients (*r*) denoting the strength of the linear relationships between particle size and powder properties.

Diameter	Insolubility Index	Loose Bulk Density	Tapped Bulk Density	Carr Index	Hausner Ratio
D32	0.62	−0.58	−0.65	−0.44	−0.47
D43	0.41	−0.66	−0.79	−0.69	−0.72

The weak correlations between particle size and the analyzed properties of milk powders are explained by the relationship between the mass and size of fractal objects. The fractal dimension, calculated as the relationship between the perimeter and the surface area of a particle, describes surface roughness and supports precise and unbiased comparisons of particle microstructure (Figure 3).

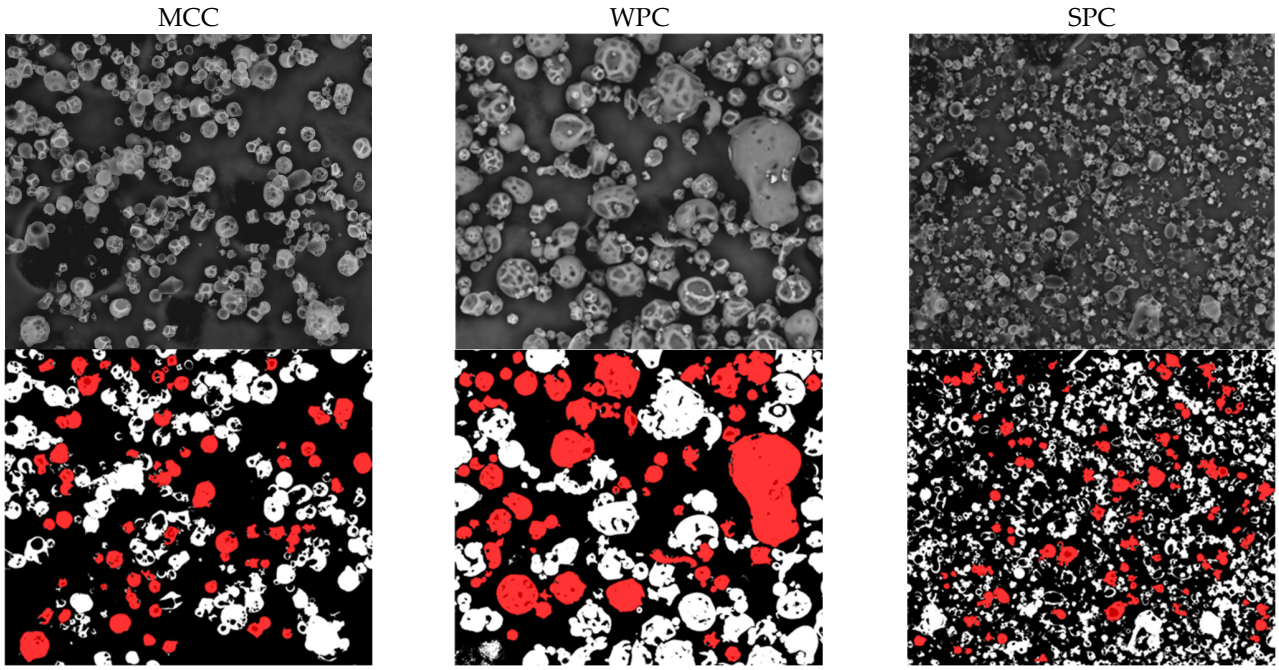

Figure 3. Examples of micrographs for fractal dimension calculations.

The results of the image analysis are presented in Table 5, and an example of the logarithmic relationship between the perimeter and surface area of the analyzed particles is shown in Figure 4.

Table 5. Fractal dimensions and determination coefficients for high-protein milk powders.

Product	D_L	R^2
MCC	1.29	0.92
SPC	1.40	0.87
WPC	1.18	0.91
CH	1.28	0.93
WPH	1.25	0.93
WPI	1.24	0.93

D_L—fractal dimension, R^2—coefficient of determination.

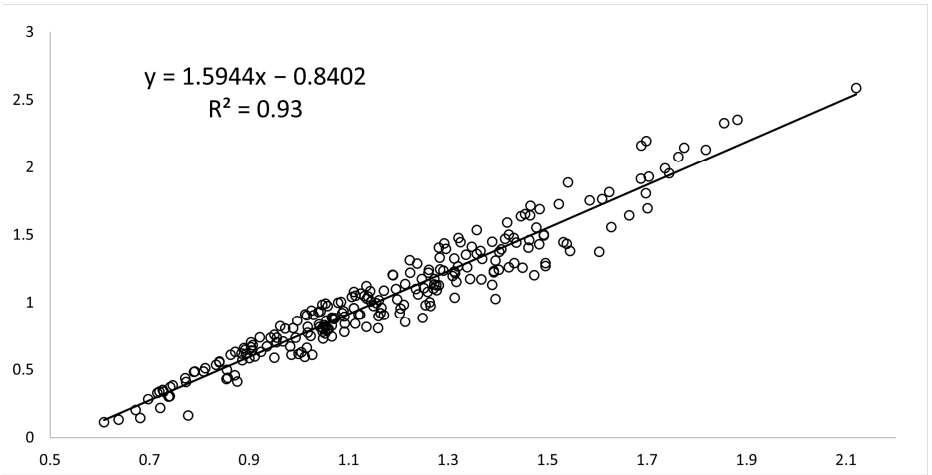

Figure 4. Logarithmic plot for image analysis of whey protein hydrolysate.

The calculated fractal dimensions point to minor differences in the microstructure of milk powders. The calculated fractal dimension was highest in SPC and lowest in WPC, which implies that WPC particles had smoother and less ragged contours (Table 5, Figure 3). The observed differences in the microstructure of the analyzed powders may affect their functional properties, including solubility. For this reason, the relationships between the microstructure and the properties of the tested powders were analyzed. An analysis of the linear relationship between the fractal dimension and powder properties revealed that the fractal dimension was correlated with bulk density (r = 0.73). The fractal dimension was not correlated with the remaining properties of milk powders. However, the fractal dimension characterizes only the surface properties of powders, and their functional properties are influenced by other parameters, such as chemical composition and internal porosity. Nevertheless, the fractal dimension can be used as an additional parameter characterizing the microstructure of milk powders, thus contributing to a more comprehensive analysis of their attributes.

4. Conclusions

The size and morphology of powder particles determine the performance characteristics of powders, including their behavior during the rehydration process. Particle size influences the flowability and cohesiveness of powders. Powders composed of small particles are classified as cohesive, whereas powders containing larger particles are more flowable. In this study, experimentally produced powders containing the largest particles (MCC and SPC) were characterized by relatively low cohesiveness and high flowability.

The microstructure of milk powder particles was determined in a micrograph analysis combined with a fractal analysis. Such a mathematical approach promotes objective assessment and enables unambiguous detection of even subtle differences in the microstructure of the analyzed samples, which could not be captured during a visual evaluation. High values of the coefficients of determination indicate that the values predicted by the mathematical model were close to the obtained results. In view of the diverse applications of high-protein milk powders, a robust knowledge about their reconstitution properties is becoming increasingly important in industrial-scale production. The information that these properties are affected not only by the powder's morphology may set the direction for further improvement and modification of the functional properties of high-protein milk powders.

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Abbreviations

MCC—micellar casein concentrate; SPC—serum protein concentrate; WPC—whey protein concentrate; CH—casein hydrolysate; WPH—whey protein hydrolysate; WPI—whey protein isolate.

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