e-ISSN: 2757-8836
ORIGINAL ARTICLE
J. Raw Mater. Process. Foods vol.6(2), (2025), 68-78

Recieved: 07/07/2025 Revised: 03/11/2025 Accepted article published: 10/12/2025 Published online: 30/12/2025

Influence of Carriers on the Physicochemical Properties of Freeze-Dried Purple Sweet Potato

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DOI: https://doi.org/10.57252/jrpfoods.2025.6

Abstract

Purple sweet potato (*Ipomoea batatas* L.) is a valuable source of bioactive compounds, particularly antioxidants; however, their stability and handling properties can be limited in powder form. The aim of this study was to investigate the effect of different carrier materials on the physicochemical and hydration properties of freeze-dried purple sweet potato powders using a matrix-type encapsulation approach. Purple sweet potato extracts were freeze-dried in the presence of carboxymethyl cellulose (CMC), maltodextrin (MD), whey protein isolate (WPI), and gum arabic (GA), and compared with a carrier-free control sample. Bulk density, tapped density, Carr Index, Hausner Ratio, wettability, water absorption capacity, and water solubility index were evaluated. The results showed that the type of carrier material significantly influenced powder properties. MD exhibited the highest bulk density and the best flowability, whereas CMC resulted in lower density and poorer flow characteristics. In terms of hydration behavior, MD and GA showed faster wettability, while WPI displayed delayed water uptake. Overall, freeze-drying with appropriate carrier materials improved the physical functionality of purple sweet potato powders, demonstrating the potential of matrix-type encapsulation for developing functional food ingredients with tailored properties.

Keywords: Microencapsulation, freeze drying, purple sweet potato, wall material, physicochemical properties

1.INTRODUCTION

Purple sweet potato (*Ipomoea batatas* L.) is a food crop that has attracted increasing attention due to its high nutritional value and associated health benefits. It is particularly rich in anthocyanins and other phenolic compounds, which contribute to its strong antioxidant capacity. Anthocyanins derived from purple sweet potato have been reported to effectively scavenge free radicals and reduce oxidative cellular damage (Rahman and Nurdin, 2023). Purple sweet potato is cultivated across a wide range of geographical regions, including Asia, South America, and Africa. In Turkey, the Eastern Anatolia and Black Sea regions possess suitable climatic and soil conditions for its cultivation (Saputri and Utami, 2020).

Although studies specifically focusing on purple-fleshed sweet potato cultivation in Turkey are limited, several peer-reviewed studies have demonstrated that *Ipomoea batatas* can be successfully grown under Turkish agro-climatic conditions. Çalışkan et al. (2007) reported that different sweet potato cultivars exhibited satisfactory growth, yield, and quality characteristics in the Mediterranean and Southeastern Anatolia regions of Turkey. Similarly, Karan and Şanlı (2021) evaluated various sweet potato genotypes in the Middle Black Sea region and confirmed their adaptability and production potential. These findings provide a scientific basis for considering the feasibility and future expansion of colored and purple-fleshed sweet potato varieties under Turkish conditions.

Despite its nutritional advantages, the application of purple sweet potato in powdered or processed forms may be limited by the instability of its bioactive compounds, which are sensitive to environmental factors such as oxygen, moisture, light, and temperature. To overcome these limitations, encapsulation-based strategies have been widely employed in food systems to improve the stability, handling, and functionality of bioactive-rich ingredients. In this context, encapsulation refers to the entrapment of active compounds within a protective matrix or carrier material, thereby reducing degradation and improving functional performance in food applications.

In this study, encapsulation refers to a matrix-type encapsulation approach achieved by freeze-drying in the presence of carrier materials. Unlike classical microencapsulation methods that form distinct core–shell structures, the applied method embeds bioactive compounds within a solid carrier matrix, improving powder stability and functional properties. This matrix-based approach has been increasingly reported in food and bioprocessing studies as an effective strategy for stabilizing plant-derived bioactives while enhancing powder characteristics such as flowability, wettability, and rehydration behavior.

Freeze-drying (lyophilization) is a dehydration process that involves freezing the product followed by sublimation of ice under reduced pressure. This method is particularly advantageous for heat-sensitive materials, as it allows for high retention of nutritional and physicochemical quality. In the case of purple sweet potato, freeze-drying has been shown to effectively preserve anthocyanins and other phenolic compounds while producing powders with low moisture content and extended shelf life (Laveriano-Santos et al., 2022). Compared to conventional drying methods, freeze-drying results in products with superior texture, color retention, and solubility, making them suitable for direct consumption or incorporation into functional food formulations (Ungu et al., 2018; Gumul et al., 2018).

The incorporation of carrier materials during freeze-drying plays a critical role in determining the final properties of the resulting powders. Carrier materials contribute to the formation of a stabilizing matrix that immobilizes bioactive compounds and modifies powder behavior during handling and storage. Commonly used carrier materials in matrix-type encapsulation include maltodextrin (MD), gum arabic (GA), whey protein isolate (WPI), and carboxymethyl cellulose (CMC). Maltodextrin is widely applied due to its low cost, high water solubility, and ability to improve powder flowability and reduce hygroscopicity (Turkiewicz et al., 2020; Mishra et al., 2015; Zhang et al., 2020). Similarly, GA, WPI, and CMC have been reported to enhance the stability and functional performance of freeze-dried food powders when used individually or in combination with other biopolymers (Chew et al., 2018).

Although several studies have examined the effects of freeze-drying on purple sweet potato, limited information is available regarding the comparative influence of different carrier materials on the physicochemical and hydration properties of freeze-dried purple sweet potato powders. Therefore, the objective of this study was to investigate the effects of various carrier materials (MD, WPI, CMC, and GA) on the physicochemical properties—including moisture content, water activity, color parameters, bulk density, tapped density, flowability, and adhesion—of carrier-assisted freeze-dried purple sweet potato powders.

2. MATERIAL AND METHODS

2.1. *Material*

Purple sweet potatoes (*Ipomoea batatas* L.) were harvested in September 2024 from the Hatay region (Türkiye). After harvesting, the tubers were washed thoroughly, boiled (water/sweet potato ratio 1:5, w / w; cooking temperature 80 °C; cooking time 15 min), and manually peeled. The cooked samples were homogenized using a waring blender (Waring 8011 EB SET2) to obtain a uniform purple sweet potato puree. The dry matter content of the fresh puree was determined gravimetrically by oven drying at 105 °C until constant weight and was found to be 25.00 ± 0.96 % (w / w). The prepared puree was transferred into polyethylene bottle and stored at −18 °C until further processing. The carrier materials used in this study were maltodextrin (MD), gum arabic (GA), whey protein isolate (WPI), and carboxymethyl cellulose (CMC), all supplied by Alfasol (Türkiye).

2.2. *Preparation of the samples*

Frozen purple sweet potato puree was thawed at room temperature prior to sample preparation. For carrier-added samples, MD, GA, WPI, or CMC were incorporated at a concentration of 16 g carrier per 100 g total dry matter of the puree, calculated on a dry basis. Based on the determined dry matter content, this corresponded to 4 g of carrier per 100 g of fresh puree. The mixtures were homogenized using a homogenizer (Ultra-Turrax T18, IKA, Germany) operating at 10,000 rpm for 5 min under ambient conditions to ensure uniform dispersion of the carrier materials within the puree matrix. For the control sample, no carrier material was added. The control consisted solely of purple sweet potato puree with the same dry matter content and underwent identical processing conditions as the carrier-added samples. All samples (control and carrier-added) were frozen at −80 °C for 72 h and subsequently freeze-dried at a constant shelf temperature of −72 °C under a vacuum pressure of 0.01 mPa using a laboratory-scale lyophilizer (Biobase BK-FDI8). Drying was carried out under these conditions for 72 h to allow complete sublimation of ice. Drying was continued until the final moisture content of the powders reached below 3 % (w / w), as determined by gravimetric analysis. The freeze-dried samples were then ground and sieved through a 100-mesh sieve to obtain a uniform powder. The resulting powders were packed in aluminum bags, vacuum sealed, and stored at 4 °C until further analyses.

2.3. *Moisture content and water activity*

The moisture content of the powder samples was determined according to AOAC (2000) moisture determination method. The device directly gave the % moisture value. At least three parallel measurements were taken from each sample and the average value was calculated. The water activity values of the powder samples were analysed at 25°C using a water activity meter (Novasina Lab-swift).

2.4. *Color values*

The color properties of powdered samples were determined by HunterLab ColorFlex EZ color meter. Measurements were made according to the CIELAB color system; L (lightness), a* (green-red), and b* (blue-yellow) parameters were reported and three repetitions were taken for each sample. Average L, a*, b* values were recorded via the device software.

2.5. *Bulk density and compacted density*

Bulk density and compacted density values were determined to evaluate the flow properties of the powder samples. Bulk density was calculated from the mass to volume ratio of 2 g sample in a measuring cylinder (Jinapong et al., 2008). The compressed density of powder samples is calculated by compressing the mass of powder material in a volumetric container with a specific number of strokes (Saifullah ve ark., 2016).

2.6. *Flowability*

Flowability properties were determined by Carr Index (CI) and Hausner Ratio (HR). CI and HR were calculated according to Equations 1 and 2 (Islam et al., 2017).

CI = (ρcompacted- ρbulk /ρbulk) ∗100
Equation (1)

HR = ρcompacted /ρbulk
Equation (2)

2.7. *Wettability*

The wettability values of microcapsules were determined by recording the time s (seconds) it took for them to completely settle in 100 ml of distilled water at 25°C (Gong et al., 2008).

2.8. *Water absorption capacity (WAC)*

1 g of powder sample was mixed with 10 mL of water in centrifuge tubes, stirred and incubated, then centrifuged at 3000 × g for 25 minutes using a laboratory centrifuge (Hettich Universal 320R, Germany). The supernatant was discarded and the remaining material was weighed, and the results were given as the amount of water retained in g / g of dry powder (Michalska-Ciechanowska et al., 2025).

2.9. *Water solubility index (WSI)*

The sample (0.5 g) was suspended in 50 mL of distilled water and the suspension was incubated at 60 °C for 1 hour. The suspension was centrifuged at 1431 × g for 30 minutes using a laboratory centrifuge (Hettich Universal 320R, Germany), the insoluble residue was recovered, and it was dried at 60 °C until a constant weight was obtained (Budnimath et al., 2023)

WSI (%) = Insoluble residue weight (g) / Original sample weight (g) × 100

2.10. *Statistical Analysis*

To identify significant differences between samples, a one-way ANOVA test was performed using SPSS 22 software (IBM Corp., Armonk, NY, USA). Mean comparisons were conducted using Duncan multiple comparison test at a significance level of $p<0.05$.

RESULTS AND DISCUSSION

3.1. *Moisture content and water activity*

The moisture content and water activity of freeze-dried purple sweet potato powders are critical parameters governing microbial stability, storage behavior, and rehydration performance. As shown in Table 1, significant differences were observed between the control sample and powders produced with different carrier materials ($p<0.05$), confirming that the drying matrix strongly influenced water–solid interactions. The control sample exhibited a moisture content of 2.69 % and a water activity of 0.09, which is consistent with previous reports for freeze-dried potato and tuber-based powders processed without carrier agents (Akintomide and Antai, 2012; Kemal et al., 2022). Such low aw values indicate limited availability of free water, contributing to improved shelf stability. In contrast, maltodextrin-containing powders showed the highest moisture content (2.95 %) and water activity (0.11). This behavior can be mechanistically explained by the low molecular weight and highly hygroscopic nature of maltodextrin, which contains numerous hydroxyl groups capable of binding water molecules through hydrogen bonding. Similar increases in moisture retention and aw in maltodextrin-based systems have been reported by Mujaffar and Dipnarine (2020), who emphasized that carbohydrate carriers tend to retain physically adsorbed water even after freeze-drying.

Table 1. Water content and activity in microencapsulated purple potato using different wall materials

	Moisture Content (%)	Water Activity (aw)
Control	$2.69±0.25^{cd}$	$0.09±0.00^{c}$
MD	$2.95±0.06^{d}$	$0.11±0.00^{d}$

WPI	0.64±0.11^{a}	0.03±0.00^{a}
CMC	1.95±0.69^{bc}	0.05±0.00^{b}
GA	1.41±0.07^{ab}	0.04±0.01^{b}

Results are the mean value of three replication and standart deviation (SD) of microencapsulated purple potato
Different lowercase letters (a-d) in the same column are statistically significant (*p*<0.05)

Conversely, whey protein isolate (WPI) resulted in the lowest moisture content (0.64 %) and water activity (0.03). This outcome is likely associated with protein denaturation and aggregation during freezing and sublimation, leading to a compact matrix with reduced water mobility. Comparable trends have been observed in protein-enriched dried powders, where structural rearrangements limit free water retention (Buzera et al., 2024). This reduced a_w is advantageous for microbial stability but may negatively affect rehydration kinetics.

CMC and gum arabic exhibited intermediate moisture and water activity values, reflecting their polymeric network structures, which immobilize water within the matrix rather than retaining it as free water. The high viscosity and water-binding. capacity of CMC may entrap water in a bound state, resulting in relatively low a_w despite moderate moisture levels. This observation aligns with findings by Zhang et al. (2011), who reported that bound water within polysaccharide-rich matrices does not significantly contribute to water activity but still affects functional behavior.

Overall, these results demonstrate that differences in moisture content and water activity are governed not only by total water content but also by the physicochemical state of water and carrier-specific molecular interactions, as also suggested by Hidayat and Setyadjit (2019). Therefore, carrier selection plays a decisive role in optimizing the stability and functionality of freeze-dried purple sweet potato powder.

3.2 Color values

Color parameters (L*, a*, b*) are quality indicators for purple sweet potato powders and presented in Table 2. Significant differences in color values were observed among samples produced with different carrier materials ($p<0.05$), demonstrating that the formulation matrix played a key role in color preservation during freeze-drying.

The L* value, representing lightness, ranged from 56.82 in the CMC-treated sample to 63.72 in the control, indicating that the incorporation of CMC resulted in a darker powder. This reduction in lightness can be mechanistically attributed to the high viscosity and dense polymeric network of CMC, which increases particle compactness and reduces surface light reflectance. Similar decreases in L* values for polysaccharide-rich matrices have been reported in dried vegetable powders, where enhanced light absorption and reduced scattering lead to darker appearances (Truong et al., 2012).

In contrast, samples containing maltodextrin and gum arabic exhibited relatively higher L* values, suggesting improved color brightness. This behavior may be explained by the glass-forming and film-forming properties of these carriers, which promote a more uniform encapsulation of anthocyanins and reduce pigment aggregation during drying. Comparable protective effects of maltodextrin and gum arabic on color retention have been reported by Ginting et al. (2021), who observed improved lightness and color stability in encapsulated plant powders.

The a* values, which indicate the red–green axis, did not differ significantly among samples, suggesting that freeze-drying effectively preserved the red–purple chromophores of anthocyanins regardless of carrier type. This stability supports previous findings that low-temperature drying methods minimize anthocyanin degradation compared to conventional thermal drying (Santiago et al., 2016).

In terms of chromaticity indicators, the a* value measures the red/green spectrum, and since all values are statistically similar, consistent observations among the samples indicate no significant changes. The highest b value (12.66) was observed in WPI, indicating a more pronounced yellow tone compared to other treatments. The b* value of the control was determined to be lower (9.61). This is consistent with findings indicating that the color of food products can significantly influence sensory evaluations and consumer acceptance (Nawi et al., 2015). It is noted that the selection of wall materials in the microencapsulation process plays an important role in color preservation and enhancement. For example, Santiago et al. (2016) concluded that colored sweet potato powders at different concentrations significantly affect the final color outcomes of baked products and highlighted the strong influence of formulation on color properties. The relationship between anthocyanin stabilization during processing and the resulting colorimetric values is supported by findings that different drying methods affect the color integrity of the produced powders (Truong et al., 2012).

Table 2. Color values of microencapsulated purple potato using different wall materials

	L	a*	b*
Control	63.72±1.31^{d}	8.27±0.10^{a}	9.61±0.14^{b}
CMC	56.82±0.14^{a}	8.15±0.05^{a}	9.98±0.07^{c}
MD	60.21±0.46^{b}	8.38±0.23^{a}	9.06±0.27^{a}
WPI	61.39±0.18^{c}	6.21±0.04^{a}	12.66±0.04^{d}
GA	62.96±0.07^{d}	8.09±0.14a	10.13±0.23^{c}

Results are the mean value of three replication and standart deviation (mean±std dev.) of microencapsulated purple potato

Different lowercase letters (a-d) in the same column are statistically significant (p<0.05)

However, significant differences were observed in b* values, with the WPI-treated sample exhibiting the highest b* value (12.66), indicating a more pronounced yellow hue. This shift may be associated with protein-related light scattering effects and possible Maillard-type reactions occurring during processing, which can alter color perception toward yellow tones. Similar increases in b* values in protein-enriched powders have been attributed to changes in surface chemistry and particle morphology (Ahmed et al., 2010).

3.3 Bulk density, compacted density and flowability

The bulk density (ρb), tapped density (ρt), Carr index (CI), and Hausner ratio (HR) values of freeze-dried purple sweet potato powders are key indicators of particle packing behavior, interparticle interactions, and flowability, all of which are strongly influenced by the carrier material incorporated into the drying matrix. As shown in Table 3, statistically significant differences were observed among the samples (p<0.05), highlighting the dominant role of formulation on powder physical properties. Maltodextrin-containing powders exhibited the highest bulk (0.55 g/cm^3) and tapped densities (0.65 g/cm^3), along with the lowest CI (0.16) and HR (1.20), indicating superior flowability. This behavior can be attributed to the glass-forming ability and low cohesiveness of maltodextrin, which promotes the formation of more spherical, compact, and less porous particles during freeze-drying. Such particle morphology facilitates efficient packing and reduces interparticle friction, resulting in improved flow properties. Similar density enhancement and flow improvement effects of maltodextrin have been reported in encapsulated food powders (Amin et al., 2021; Song et al., 2021).

Table 3. Bulk and compacted density of microencapsulated purple potato using different wall materials

	ρb	ρt	CI	HR
Control	0.35±0.04^{b}	0.46±0.05^{b}	0.23±0.01^{a}	1.30±0.01^{a}
CMC	0.23±0.01^{a}	0.35±0.02^{a}	0.34±0.01^{b}	1.52±0.03^{b}
MD	0.55±0.03^{d}	0.65±0.02^{c}	0.16±0.07^{a}	1.20±0.01^{a}
WPI	0.49±0.02^{c}	0.65±0.01^{c}	0.24±0.02^{a}	1.32±0.04^{a}
GA	0.50±0.01^{c}	0.65±0.01^{c}	0.22±0.03^{a}	1.28±0.04^{a}

Results are the mean value of three replication and standart deviation (mean±std dev.) of microencapsulated purple potato
Different lowercase letters (a-d) in the same column are statistically significant (p<0.05)

In contrast, powders produced with carboxymethyl cellulose (CMC) exhibited the lowest bulk (0.23 g/cm³) and tapped densities (0.35 g/cm³), together with the highest CI (0.34) and HR (1.52), indicating poor flowability. This unfavorable behavior is primarily related to the high molecular weight, fibrous structure, and strong hydrophilicity of CMC, which increase interparticle cohesion and hinder particle rearrangement during tapping. Additionally, the tendency of CMC to form irregular, highly porous structures contributes to low packing efficiency and reduced flow performance. Comparable effects of CMC on powder cohesiveness and flow resistance have been observed in other dried polysaccharide-rich systems (Pichaiyongvongdee et al., 2025).

Whey protein isolate (WPI) and gum arabic (GA) resulted in intermediate density and flowability values. The moderate flow behavior of WPI-containing powders may be explained by protein–protein interactions and partial surface hydrophobicity, which increase particle adhesion while still allowing relatively efficient packing. Gum arabic, due to its branched polysaccharide structure and surface-active properties, produced powders with balanced density and flow characteristics. These findings are consistent with previous reports indicating that protein- and gum-based carriers yield powders with intermediate flowability compared to carbohydrate-based matrices such as maltodextrin (Amin et al., 2021; Pichaiyongvongdee et al., 2025).

3.4 Water absorption capacity (WAC), water solubility index (WSI) and wettability

The WAC, WSI and wettability values of freeze-dried purple sweet potato powders produced with different carrier materials are presented in Table 4 and showed statistically significant differences among formulations (p<0.05). Powders formulated with gum arabic (GA) and maltodextrin (MD) exhibited the shortest wettability times (1.26 s and 1.44 s, respectively), indicating rapid water penetration and efficient surface hydration. This behavior is mainly attributed to the high water solubility and low interfacial viscosity of these carbohydrate-based carriers. Gum arabic, a highly branched polysaccharide with surface-active properties, reduces surface tension at the solid–liquid interface, thereby enhancing capillary-driven water uptake and rapid dispersion. Similar wettability-enhancing effects of gum arabic have been widely reported in encapsulated food powders (Nawi et al., 2015; Damndja et al., 2024). Likewise, the fast wettability of maltodextrin-containing powders can be explained by the amorphous, glassy structure and low molecular weight of maltodextrin, which promote surface hydrophilicity and facilitate rapid water penetration into the particle matrix (Nawi et al., 2015; Kapoor et al., 2021).

In contrast, whey protein isolate (WPI)–containing powders exhibited the longest wettability time (32.97 s), indicating delayed initial hydration. This behavior is associated with the formation of dense protein matrices during freeze-drying and partial protein denaturation, which increase hydrophobic interactions and reduce surface permeability to water. Consequently, water penetration is delayed until sufficient surface hydration and structural relaxation occur, a phenomenon commonly reported for protein-based powders with slower hydration kinetics (Kapoor et al., 2021). The control sample showed intermediate wettability (19.58 s), reflecting limited capillary water uptake due to the absence of hydrophilic carrier materials.

Wettability could not be determined for carboxymethyl cellulose (CMC)–containing powders because of immediate swelling and gel formation upon contact with water. This behavior is characteristic of high-viscosity cellulose derivatives, where rapid polymer chain expansion and gel network formation dominate over discrete particle wetting (Damndja et al., 2024).

Table 4. WAC, WSI and wettability values of microencapsulated purple sweet potato using different carrier materials

	WAC (g / g)	WSI (%)	Wettability (second)
Control	2.06 ± 0.02^{d}	34.85 ± 0.96^{b}	19.58 ± 1.32^{b}
MD	1.07 ± 0.03^{b}	68.15 ± 0.66^{e}	1.44 ± 0.06^{a}
WPI	1.24 ± 0.01^{c}	49.05 ± 0.59^{c}	32.97 ± 0.86^{c}
CMC	nd	14.72 ± 0.22^{a}	nd
GA	0.63 ± 0.01^{a}	54.13 ± 0.20^{d}	1.26 ± 0.08^{a}

Results are the mean value of three replication and standart deviation (SD) of microencapsulated purple sweet potato. Different lowercase letters (a-e) in the same column are statistically significant (p<0.05)
nd: Could not be determined

Water absorption capacity (WAC) and water solubility index (WSI) further elucidated the hydration mechanisms of the powders. The control sample exhibited the highest WAC value (2.06 g / g), which can be attributed to native starch granules and dietary fiber rich in hydroxyl groups capable of forming hydrogen bonds with water. Similar WAC and WSI ranges have been reported for non-encapsulated purple sweet potato powders (Vergara et al., 2020; Liu et al., 2021). Maltodextrin significantly reduced WAC (1.07 g / g) while yielding the highest WSI (68.15 %), reflecting a solubility-driven hydration mechanism in which rapid dissolution dominates over physical water retention (Pandey and Singh, 2025).

WPI-containing powders showed intermediate WAC (1.24 g / g) and WSI (49.05 %) values, indicating a balance between water binding and solubility. Although proteins contain hydrophilic residues, aggregation during freeze-drying can limit water-holding capacity, while partial unfolding during rehydration enhances solubility (Dehsheikh et al., 2019). Gum arabic exhibited low WAC (0.63 g / g) but relatively high WSI (54.13 %), consistent with its highly soluble, non-gel-forming nature (Pandey and Singh, 2025). For CMC, WAC could not be determined due to gelation-driven water immobilization, highlighting the limitations of conventional gravimetric methods and the need for alternative swelling- or rheology-based approaches for such systems (Dehsheikh et al., 2019).

3. CONCLUSION

This study demonstrates that carrier material selection is a critical determinant of the hydration behavior and functional performance of freeze-dried purple sweet potato powders. By comparatively evaluating maltodextrin (MD), gum arabic (GA), whey protein isolate (WPI), and carboxymethyl cellulose (CMC), the study reveals that wettability, water absorption capacity (WAC), and water solubility index (WSI) represent distinct, material-dependent hydration mechanisms rather than interchangeable quality indicators. From a mechanistic perspective, MD and GA exhibited dissolution-driven hydration, characterized by rapid wettability and high solubility but limited water retention. WPI showed controlled, protein-mediated hydration with delayed wetting and intermediate WAC and WSI values, reflecting structural rearrangement during rehydration. In contrast, CMC displayed gelation-dominated behavior, where immediate network formation suppressed dissolution and rendered conventional WAC measurements unsuitable. These findings advance the understanding of structure–function relationships in carrier-assisted, freeze-dried food powders. From an application standpoint, the results provide a systematic framework for carrier selection. MD- and GA-based formulations are well suited for instant powders and beverage applications requiring rapid dispersion and high solubility. WPI-containing powders may be advantageous for protein-enriched products where moderated hydration is desirable, while CMC is more appropriate for thickened or gel-based food systems rather than instant formulations. Future research should integrate rheological, microstructural, and moisture sorption analyses, as well as storage and digestion studies, to further elucidate carrier–matrix interactions and optimize formulation performance.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FUNDING

None.

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