Italian Journal of Food Science, 2025; 37 (4): 34–46

Enhancing functional and physical properties of spray dried mixed fruit juices using composite carrier agents

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Academic Editor: Prof. Fabrizio Cincotta, University of Messina, Piazza Pugliatti, Messina ME, Italy

Received: 11 April 2026; Accepted: 8 July 2025; Published: 1 October 2025

PAPER

Abstract

The aim of this study was to examine the impact of carrier agents on physiochemical properties, reconstitution ability, and functional properties of fruit juice powder that has been spray dried. Toward this end, *Emblica officinalis* (amla), *Mangifera indica* L (raw mango), and *Citrus limon* (lemon) fruit juices with maltodextrin (MD), gum Arabic (GA), and a combination of MD, GA, and whey protein concentrate (WPC) were spray dried. Results demonstrated that the physical characteristics of the resulting powder included moisture content, bulk, and tapped density, which were between 2.2% and 4.8% (w.b. [weight by bulk]), 0.29% and 0.45%, and 0.48% and 0.58% g/cc (cubic centimeter), respectively, as well as the powder recovery ranging from 53.5% to 71.4%. Wettability, solubility, hygroscopicity, and dispersibility were recombination attributes that fluctuated between 93.7/second and 205.6/second, 66.38% and 94.29%, 15.67 g/100 g and 25.88 g/100 g, and 75.51% and 93.53%. The functional characteristics comprised of antioxidant activity, total phenol content, and ascorbic acid ranging from 59.69% to 74.75%, from 202.12 gallic acid equivalents (GAE)/100 g to 382.13 g GAE/100 g, and from 160 mg to 349.66 mg. The color values varied from 87.68 to 93.49, from 0.47 to 0.67, and from 6.77 to 12.55. The outcome indicated that the combination of GA and MD was successful in creating a mixed fruit juice powder with the right color, functionality, and physical attributes. The outcome should be helpful in optimizing the powder production and streamlining the industrial manufacture.

Keywords: carrier agents; fruit juice; functional properties; spray drying; stability

Introduction

Consumed worldwide, fruits and fruit juices are essential components of a well-balanced diet; additionally, dried fruits are a considerable source of energy, antioxidants, vitamins, and minerals (Sangeetha *et al.*, 2024). The drying process is primarily aimed at prolonging shelf life by lowering the fruits' water activity, thereby decelerating deterioration and maintaining quality. Fruit drying has significant advantages, notably in terms of lowering packaging, storage, and transportation costs (Arslan and Alibaş, 2024).

The Indian gooseberry or amla (*Emblica officinalis*) is a natural source of bioactive substances that are essentially used to improve human nutrition and health (Avinash *et al.*, 2024). Amla extract consists of bioactive components and its use has a variety of biological effects, covering antimicrobial, anti-inflammatory, antidiabetic, neuroprotective, and immunomodulatory effects (Annapoorna and Kumar, 2024).Through the 21st century, mango (*Mangifera indica* L., family Anacardiaceae), a popular fruit in tropical regions, has been described to exert nutritional, antioxidant, anti-inflammatory, metabolic, and immunomodulatory functions related to human health and well-being (Rocha *et al.*, 2024). Lemon (*Citrus limon*), belonging to the Rutaceae family, has healthy nutrients, including vitamin B9, vitamin C, potassium, flavonoids, coumarins, pectin, and dietary fibers as well as a great source of essential oil (Chakraborty *et al.*, 2025).

Vegetables and fruits are perishable agricultural products, and fruits harvested too soon or too late have a lower shelf life and lose quality (Hailu and Bekele, 2024). To address these challenges, fruits are often processed to extend their shelf life and transformed into products such as jams, jellies, dried flakes, juices, and more. Along with time, preserving food is important to maintain its quality, as factors like nutritional value, color, texture, and taste are susceptible to degradation. Using a variety of methods, food preservation is aimed toward reducing the internal and external elements that cause spoiling (Du *et al.*, 2024). The primary goal is to extend the food's shelf life while retaining its key attributes, such as nutrition, color, texture, and flavor (Lohita and Srijaya, 2024). Various methods are commonly used to enhance food products' shelf life, including drying, canning, freezing, fermenting, storing in acidic solutions like vinegar, curing, smoking, dry salting, and sealing (Ogwu and Ogunsola, 2024).

Drying is a traditional preservation technique that can extend a product's shelf life and make it available all year long, especially during off seasons. One potential way to exploit underutilized fruit is to dehydrate fruit juices and turn them into dried powder (Güldane, 2024). Energy expenses and changes to the food matrix that are technological, nutritional, or sensory should be taken into account when selecting a food drying system, especially if the final product's quality could suffer if the drying procedure is improper or insufficient. This suggests unpredictable alterations could result in an unmarketable product, like the loss of food flavor, color, or noticeable moisture gradients (Nowacka *et al.*, 2024).

Spray drying is the process of converting liquid or slurry (solids suspended in liquid) into solid forms of powder. This is achieved by eliminating the water content in the liquid solution (Dantas *et al.*, 2024). Spray dried products in the production are stored and have a good shelf life in a low water activity, which is easy for the production (Weng *et al.*, 2024). Spray drying is a low-cost operation compared to other drying methods; it is eight times cost-effective compared to freeze drying and four times (Cereda, 2024) than vacuum drying.

Research shows key points to think about in altering fruit powders, safe managing, and storage and also the stickiness of powder fragments (Khatri *et al.*, 2024). Spray drying of food with high levels of sugar and acid is challenging as it is rich with low molecular weight substances (Sobulska and Zbicinski, 2021). The high hygroscopicity, thermoplasticity, and low glass transition temperature (Tg) of these low molecular weight substances triggers stickiness during spray drying (Samborska *et al.*, 2023). The purpose of using drying agents is to avoid the stickiness problem (Ghalegi Ghalenoe *et al.*, 2021).

Carrier agents form a central aspect in the optimization of the stability of fruit juice powders through the spray drying process owing to various important challenges involved in the practice. The low molecular weight sugars (like glucose, fructose, sucrose) naturally contained in fruit juices have low Tg (Kumari *et al.*, 2024), the low Tg of these sugars in subsequent powders mean that they can be sticky, cake up, and have low storage stability. Inclusion of carrier agents like maltodextrin (MD), gum Arabic (GA), and whey protein concentrate (WPC) increase Tg of the feed solution and hence decrease stickiness and the drying yield (Etzbach *et al.*, 2024; Yousefi *et al.*, 2011). Furthermore, the type and concentration of carrier agents that influence the physical properties of the powder, such as bulk density, solubility, and color, are critical for product quality and consumer acceptance.

Mixed fruit juice powders have the ability of mixing several fruits for blending flavors, nutritional profiles, and colors to answer the market requirements. Although considerable research had been done on individual fruit juice powders, there are only a relatively smaller number of studies concerning mixed fruit juice powders that have been reported (Sathyaruban *et al.*, 2024). Existing studies primarily used MD as the carrier agent in varying concentrations. The effect of different drying carriers on the qualitative characteristics of mixed fruit juice powders is still largely unexplored, despite growing consumer and scientific interest (Halliwell, 2024). Therefore, this study was aimed at developing spray dried mixed fruit juice powders and evaluate the effects of various carrier agents on their physicochemical properties.

Materials and Methods

Raw material

Well-grown amla (*E. officinalis*: variety NA-4) are harvested when fruits are firm and pale-yellow; semi-ripe fruits are preferred for juice due to its higher vitamin C retention (Gul *et al.*, 2022). Lemon (*Citrus lemon*: variety Phule Sarbhati) harvested when fully ripe (bright yellow), and mango (*M. indica* L: variety Kesar), harvested unripe (green, firm)—raw mangoes have higher phenolic content, enhancing juice stability during drying (Tarecha and Umar, 2023). Fruits stored at 10°C ± 1°C were obtained from the department of horticulture, Rahuri, India (Deepa and Mohapatra, 2020). MD, (Specification: MF (manufacturing facility): NA; MW (molecular weight): NA, and dextrose equivalent Max 20, GA (Loba Chemicals Pvt. Ltd., Mumbai, India) and WPC (Advance Nutratech, New Delhi, India), was used as carrier agents.

Formation of mixed fruit juice and feed sample for spray drying

Mixed fruit juice (15.08° Brix) was prepared at the PHT Center, MPKV, Rahuri, India, and juice bottles were stored at 4°C until use. Four treatments were taken: T1 MD, T2 GA, T3 a 50:50 combination of GA/MD, and WPC (T4). Rendering on research by (Etzbach *et al.*, 2020) and earlier trials, the carrier concentrations were set as 16% (w/v [weight per volume]). The juice and carrier agents were then mixed until homogeneously well mixed with the help of a magnetic stirrer (2MLH; Remi Sales & Engineering Ltd., Mumbai, India) with 1000 rpm stirrer speed for 15 minutes.

Spray drying

The laboratory scale spray dryer model LU-222 (A) (Labultima Private Limited, Mumbai, India) served as the equipment for conducting spray drying operations (Shelke *et al.*, 2022). The drying chamber received feed solutions through a nozzle from a peristaltic pump. The primary spray drying variables for total operation included an inflow rate of 10 mL/minute and inlet stream air at 65 m^3/hour with the outlet steam air maintained at 80°C. The obtained powder was stored at 20°C inside a desiccator containing silica gel to prevent damage or deterioration of the powder samples before analytical evaluation. Figure 1 presents the results of powders generated through various treatments.

Chemical, functional, and color properties of fresh mixed fruit juice

Total soluble solids (TSS) of the juice were measured using a digital refractometer (SKU: HI96801; Hanna Instruments Pvt. Ltd., Mumbai, India) and expressed as degrees Brix (°Bx). After that, the pH (potential of hydrogen) was obtained by the pH meter (ELICO Ltd., Hyderabad, India) and moisture content of the mixed fruit juice was measured by hot air oven (TI128, Tempo Instruments Pvt. Ltd., Mumbai, India). The methods given by Singh *et al.* (2019) were used to determine the total phenolic and antioxidant content of the mixed fruit juice. Additionally, titration was used to assess the

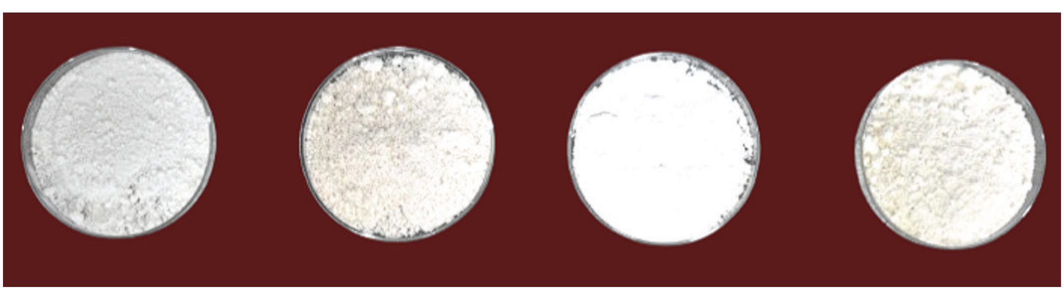

Figure 1. Spray dried mixed fruit juice powder at different treatments.

ascorbic acid and titratable acidity in accordance with the AOAC 2005 procedure (Singh *et al.*, 2019). Using a premier color scanning instrument (Premium Color Scan, Bhandup (E), Mumbai), the color was assessed using the hunter color attributes (L^*, a^*, and b^*).

Physical properties of spray dried mixed fruit juice powder

The powder recovery (percentage) of the fruit juice powder was done following Santhalakshmy *et al.* (2015) equation:

$$\text{Powder Recovery} = \frac{\text{Weight of powder produced}}{\text{Weight of feed } \textit{on dry basis}} \times 100 \tag{1}$$

The bulk density (ρB) and tapped density (ρT) of the powder were measured following the standard method proposed by Rosland Abel *et al.* (2020), with some minor adjustments made to the procedure. A graded 10 mL cylinder was filled with a known amount of spray dried mixed fruit juice powder. After recording the volume occupied, the BD (ρB) (w/v) was computed. The cylinder was tapped for five minutes (32 taps per minute) in order to get the TD (ρT). Flowability (Carrs index) and cohesiveness (Hausner's ratio [HR]) were calculated with the help of BD and TD by using the following standard formulas (Bhat *et al.*, 2021):

$$\text{Carrs index, CI} = \frac{\text{TD} - \text{BD}}{\text{TD}} \times 100 \tag{2}$$

Where TD and BD represent the tapped and bulk density, respectively. Cohesiveness (HR) was done according to the following equation:

$$\text{HR} = \frac{\text{BD}}{\text{TD}} \times 100 \tag{3}$$

Where TD and BD represents the tapped and bulk density, respectively. Low cohesiveness is indicated by HR values of 1.2, moderate cohesiveness of 1.2–1.4, and strong cohesiveness is indicated by HR values > 1.4 (Bhat *et al.*, 2021). The particle size disbursement and average size of the mixed fruit juice powder utilized a particle analyzer (Delsa NanoC from Beckman Coulter Ltd., Mumbai, India). A 1 g of the powder was dispersed in 10 mL of distilled water to create an aqueous suspension. A slight sample of this suspension was then placed in a cuvette and positioned in the measuring device. The analyzer automatically collected data, which determined the mean particle size, reporting the results in microns (µm) (Santhalakshmy *et al.*, 2015).

Reconstitution properties of spray dried mixed fruit juice powder

Solubility of spray dried powder was determined according to the rehydration by (Shelke *et al.*, 2022), with slight modifications. A 100 mL of distilled water with 1 g dry base powder sample were added to the blender running at a high speed for 5 minutes. After being put in a tube, the solution was centrifuged for 5 minutes at 3000 rpm. After transferring to a 25 mL aliquot of the supernatant into preweighed Petri dishes, it was promptly oven dried for 5 hours at 105 ± 1°C. The weight difference was then used to calculate the solubility (percentage). The powder sample's wettability was assessed using with some modifications according to (Shelke *et al.*, 2022). In a 400 mL beaker, 100 mL of distilled water was placed. The water's surface was immediately covered with a 2 g powder sample. It was noted how long it took for the powder to get fully wet, which is visually measured as the moment when every particle of powder entered the water's surface. The dispersibility was conducted using the procedure specified by Bhusari *et al.* (2014). A 50 mL beaker was filled with 10 mL of distilled water at 25°C. The beaker was filled with 1 g powder. After starting the stopwatch, the sample was forcefully agitated for 15 seconds, causing 25 full motions forward and backward across the beaker's diameter. After being reconstituted, the powder was moved through a 212 µm sieve. A weighed and dried aluminum pan was used to hold the sieved powder, which was then dried for 4 hours at 105 ± 1°C in an hot air oven. The following formula was used to determine the powder's dispersibility:

$$\text{Dispersibility (\%)} = \frac{\text{BD}(10 + \text{a}) \times \text{ \%TS}}{\text{a} \times (100 - \text{b})\text{TD}} \times 100 \tag{4}$$

The formula contains three variables which include "a" representing the weight of powder (g) with "b" indicating the percentage of the powder water content while that of TS denotes dry substance content in sieved reconstituted powder. The study by Sarabandi *et al.* (2018) reported hygroscopicity by measuring the amount of moisture absorption per 100 gdry matter during the samples' one-week weighing process.

Antioxidant and phenolic content of spray dried mixed fruit juice powder

It is used to assess the antioxidant activity (AA) of the powder using the 1, 1-diphenyl-2 picrylhydrazyl (DPPH). Using the changes in the published procedure by (Shelke *et al.*, 2022), it worked with a few minor adjustments. The DPPH solution was prepared by dissolving 24 mg of DPPH in 100 mL of methanol and stored at −20°C until it was used. To create the working solution, 10 mL stock solution and 30 mL methanol was mixed, and the absorbance was measured at 517 nm by a ultraviolet-visible (UV-Vis) spectrophotometer. Thus, a reaction between 500 mg powder and 3 mL of DPPH solution was allowed. This was shaken again thoroughly and left in the dark at room temperature for half an hour. The absorbance was measured at 517 nm. The results of the analysis of the control group which did not receive any sample was presented either as a percentage of the radical scavenging activity (RSA) or as a percentage of the AA.

$$\text{Antioxidant activity (\%)} = \frac{\text{Absorbance of control} - \text{Absorbance of sample}}{\text{Absorbance of control}} \times \quad (5)$$

As described by the procedure of (Shelke *et al.*, 2022), total phenolic content (TPC) was determined by a modified Folin-Ciocalteu procedure. In this approach, 10 mg of spray dried powder was dissolved in 30 mL methanol and then centrifuged for 10 minutes, obtaining 2.5 mL of 0.2 N Folin-Ciocalteu reagents, of which 0.5 mL of the supernatant was mixed and left for 5 minutes. Then, 2 mL sodium carbonate (7.5%) was added, and then diluted to 25 mL with distilled water. Two hours incubation at room temperature determined the absorbance at 760 nm by double beam UV-V is spectrophotometer in the presence of methanol as a reference. In the standard calibration curve, the concentrations ranged from 0 mg/L to 100 mg/L tannic acid. In GAE/100 g of the spray dried powder, the overall TPC was expressed.

Statistical analysis

The results derived from the triplicate experiments underwent analysis through three replicates of a completely randomized design (CRD) based on the software OP Stat (Ranjan *et al.*, 2024).

Results and Discussion

Composition of mixed fruit juice

Table (1) shows the physicochemical and color characteristics of the mixed fruit juice. The usual level of moisture was measured as 87.36% (w/b [substance dissolved in 100 mL of solution]). TSS was recorded as 15.08 °Brix, with a pH of 4.33 and ascorbic acid concentration at 651.11 mg. Also, the TPC was evaluated and 475.94 g GAE/100g and AA were found at 85.32%. The average color values for juice exhibited moderate lightness, with a slightly green hue and underlying yellow tones based on the reported *L**, *a**, and *b** values of 42.56, –1.04, and 6.57, respectively (Akonor, 2020). These results on the color properties were in agreement with the findings from the studies on fruit juices by (Kowalska *et al.*, 2023).

Table 1. Physicochemical properties of mixed fruit juice (per 100 g).

Properties	Value
Moisture (%)	87.36 ± 1.10
Total soluble solids (oBrix)	15.08 ± 0.37
Ascorbic acid (mg)	651.11 ± 0.89
Acidity (%)	4.16 ± 0.16
pH	4.33 ± 0.23
Total phenolic content (g GAE/100g)	475.94 ± 0.58
Antioxidant activity (%)	85.32 ± 0.73
*L**	42.56 ± 0.04
*a**	–1.04 ± 0.09
*b**	6.57 ± 0.15

Mean ± standard deviation of triplicate analysis.

Recovery and physical properties of spray dried mixed fruit juice powder

Powder recovery

Powder recovery is essential to measure the productivity of spray drying process (Sarabandi *et al.*, 2018). T1 (MD), T2 (GA), T3 (GA and MD), and T4 (WPC) were the treatments applied in the study, with a recovery rate of more than 50%. The recovery of T4 (WPC) got the highest amount of recovery rate at 71.4%, T2 (GA) at 63.7%, T3 (MD + GA) at 58.7%, and T1 (MD) at 53.5% (Figure 2a). This implies that WPC is superior to either MD or GA, singly or in combination, in aiding powder recovery. The features of WPC, for example, improved water binding and film formation that reduced stickiness and enhanced powder formation of powder. Its structure assisted in encapsulation and decrease clumping which is good for making a solid powder. Additionally, the creation of a protective layer defends droplet adhesion and stickiness on the dryer walls. This observation supports previous observations by (Bhat *et al.*, 2021) that protein forms effective drying agent more than MD and GA in spray drying of various fruit juices.

Moisture content

This, in turn, finds differences in moisture content among treatments (Table 2b), with T4 (WPC) being the highest with a moisture content of 4.8% and T1 (MD) having the lowest moisture content of 2.2%. The stickiness, stability, and storage properties of a spray dried powder are influenced by their moisture content. A good quality powdered food product needs to have a moisture content below 5% for optimal quality. Interestingly, the mixed fruit powder acquired from treatment T1 (MD) showed considerably lower moisture content than other treatments. As indicated by (Shelke *et al.*, 2022), they had obtained the same findings regarding the spray dried powders, where the powders processed with MD contained considerably lower moisture compared to powders processed with GA. The difference could be from the divaricates presentation of GA—it can absorb and retain moisture due to its high concentration of hydrophilic groups from the environment (Etzbach *et al.*, 2020). On the other side, the level of moisture in T4 (WPC) is expected to be raised since it is recognized for its moisture-retaining capacity within food matrices (Shelke *et al.*, 2022).

Bulk density and tapped density

Bulk density and tapped density are key attributes of fruit powders which are very important for the process, show, holder, and conveyance (Barretto *et al.*, 2022). The values of bulk density play a critical role in what the packaging and storage conditions of the spray dried powders need. The high bulk density powder is more volumetric and hence packaged better with smaller storage spaces. Compared to other powders, those with low bulk density are easier to handle as they are less sensitive to caking, yet they consume more space when packed, meaning that more resources are spent on storing and transporting them (Kumar *et al.*, 2023). The bulk density data show that T3 (MD + GA) was the highest in bulk density (0.457 g/cc) and in T2 (GA) (0.403 g/cc), T1 (MD) (0.333 g/cc), and T4 (WPC) (0.293 g/cc) (Figure 2c). The higher bulk density in T3 could be due to the collaborative influence of MD and GA that might have caused the denser packaging structure because of their complementary binding and structuring properties (Janiszewska-Turak *et al.*, 2019). GA, which possesses high viscosity and liquid film-forming characteristics, may improve in filling in the voids of the matrix and enhance density. However, T4 (WPC) had the lowest bulk density, which could be a result of being very light and airy due to enrichment with WPC, as it does not have as strong a binding action as the MD or GA (Janiszewska-Turak *et al.*, 2019). For both tapped density, the highest value was recorded in T3 (MD + GA) 0.58 g/cc, T2 (GA) 0.57 g/cc, whereas T1(MD) and T4 (WPC) showed lower TD values at 0.51 g/cc and 0.48 g/cc (Figure 2d). The higher tapped density in T3 and T2 treatments suggests that GA enhances the ability of particles to settle more compactly when tapped, possibly due to the cohesive nature of GA, which reduces interparticle space upon tapping. MD alone, as in T1, resulted in a moderate tapped density, but without the same compacting benefit that GA provides (Salbi *et al.*, 2021).The powders that have a greater tapping density when compared to bulk density are more cohesive than the ones with poorer flowability (Hao, 2015). T4 (WPC) had the lowest tapped density, which aligns with its lower bulk density, again indicating that WPC does not contribute significantly to particle cohesion and compaction under tapping conditions but Bhat *et al.* (2021) found comparable outcomes.

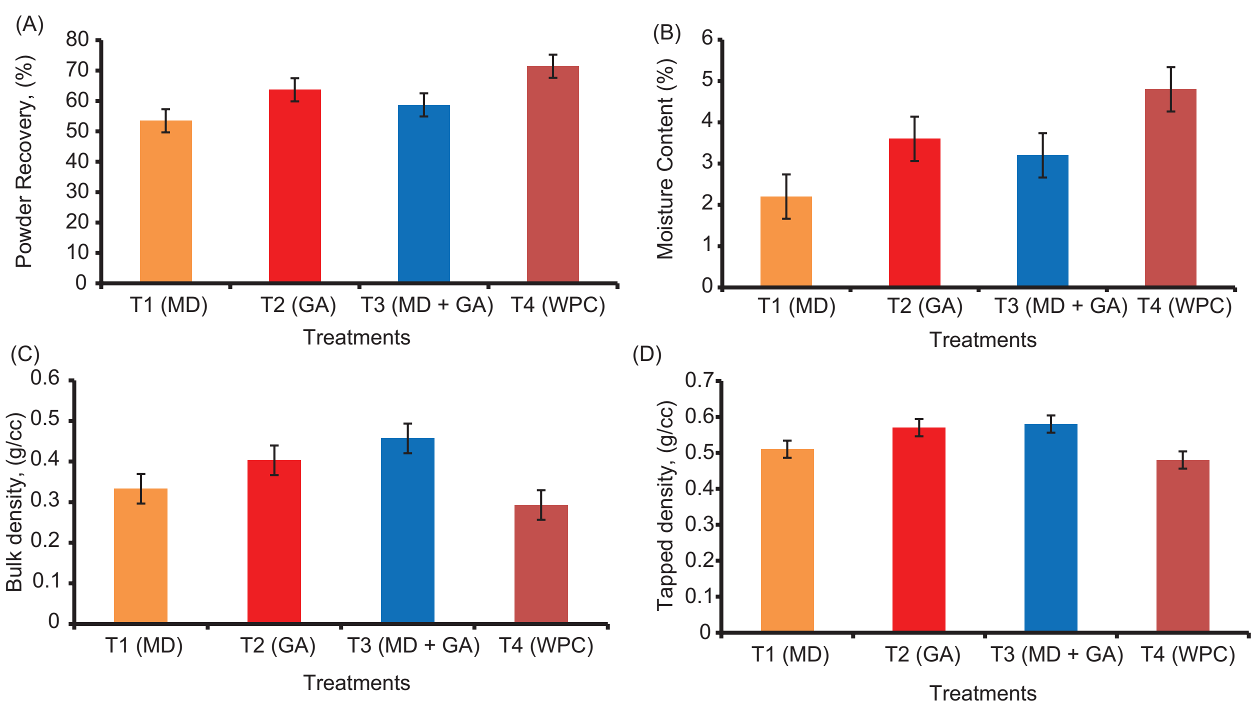

Figure 2. (A) Powder yield, (B) moisture content, (C) bulk density, and (D) tapped density of mixed fruit juice powder.

Flow properties of spray dried mixed fruit juice powder

In order to properly package, process, transport, fill bags, handle, and select variables for blending and conditioning, powders must flow properly for both the manufacturer and the consumer (Mahdi *et al.*, 2020). A particle's compressibility can also be indicated by its Compressibility Index (CI)—large values suggest high compressibility and poor flowability. Powder cohesiveness can be measured by the HR—less values indicate particles with good flowability (Bhat *et al.*, 2021). Treatment T3 (MD + GA) exhibited the lowest HR (1.270), followed by T2 (GA) with 1.423, T1 (MD) with 1.553, and T4 (WPC) with the highest ratio of 1.667 (Figure 3a). An HR close to or below 1.25 generally indicates good flowability, suggesting that the combination treatment (T3) improves flow characteristics significantly, likely due to the synergistic effect of MD and GA (Bhat *et al.*, 2021). This combination may reduce particle cohesion, making the powder less cohesive and easier to handle. In contrast, T4 (WPC) showed the poorest flowability, possibly due to the hygroscopic nature of WPC, which can cause particle agglomeration and result in higher interparticle friction (Salbi *et al.*, 2021). On the other side, Carr's index, similar to HR, was lowest in T3 (20.69%), indicating a high degree of flowability, followed by T2 (GA) at 29.82% and T1 (MD) at 35.27%. T4 (WPC) again showed the highest Carr's index (39.58%), indicative of poor flow properties (Figure 3b). A Carr's index value below 21% suggests excellent flowability, supporting that T3 (MD + GA) has an improved bulk density and reduced cohesiveness. This improvement may result from GA's anticaking properties, which enhance particle mobility (Shelke *et al.*, 2022). The higher Carr's index in T4 is consistent with its higher HR, reinforcing that WPC may promote aggregation or clumping due to its surface properties and interaction with moisture, thus impairing flow.

Reconstitution properties of spray dried mixed fruit juice powder

Wettability

One of a characteristic feature of food powders is wettability, defined as the mass' capacity to be permitted through a suspension by capillary effect (Mahdi *et al.*, 2020). A reconstitution quality of wettability above 400 seconds was considered unacceptable (Bhat *et al.*, 2021). The wettability results show that T4 (WPC) had the highest wettability time (205.60 seconds), followed by T2 (GA)

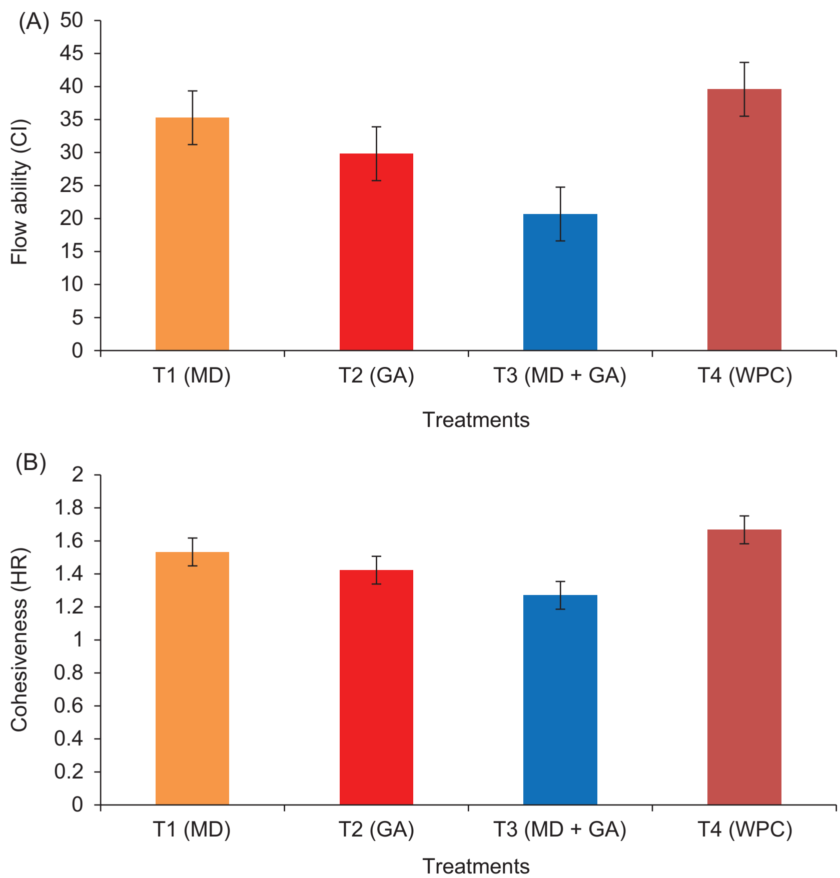

Figure 3. **(A) Flowability and (B) cohesiveness.**

(115.26 seconds), T3 (MD + GA) (99.26 seconds) and T1 (MD) (93.57 seconds) (Figure 4a). Treatment T1 (MD), with a wettability time of 93.57 seconds, demonstrates a relatively quick wetting. The presence of MD in this treatment might contribute to enhanced dispersion in water due to the hydrophilic nature of MD, which facilitates quicker wetting, and the T4 (WPC) shows the highest wettability time of 205.60 seconds. WPC may have formed a hydrophobic layer around the powder particles, leading to reduced wettability. The high wettability time of T4 indicates that whey protein is less effective in promoting fast wetting than GA or MD (Shelke *et al.*, 2022).

Solubility

A powder's capacity to become dissolved in a liquid serves as an indicator for complete rehydration of the powder substance. Laboratory studies by Mahdi *et al.* (2020) show that solubility serves as an important characteristic for spray dried powder to examine liquid wetting behavior and dispersion behavior of powders. The carrier agents play a big role in the rehydration time and solubility index of sprayed dried fruit juice powders, which are affected by the alteration of the reconstructed particle structure, surface properties, and hydrophilicity (Quadri *et al.*, 2023). The results show that T1 (MD) had the highest solubility (94.29%), followed by T3 (MD + GA) (89.83%), T2 (GA) (84.63%), and T4 (WPC) (66.38%) (Figure 4b). T1 (MD) had the highest solubility value because MD has hydrophilic properties and a high degree of polymerization, which increases the water affinity of the powder and enhances solubility. GA has slightly lower solubility than MD. GA molecules are relatively large and complex, which may hinder solubility compared to MD (Bhat *et al.*, 2021). However, WPC shows lowest solubility because WPC has a high protein content, which, in certain formulations, tends to reduce solubility because of protein aggregation or denaturation. The hydrophobic amino acid residues in WPC proteins may also contribute to lower water affinity, resulting in reduced solubility (Quoc, 2020).

Hygroscopicity

Hygroscopicity is the ability of a food product to gain moisture from its surroundings, which significantly influence the quality and storage life of the food (Moghbeli *et al.*, 2020). Hygroscopicity has a considerable effect on shelf life and storage of spray dried fruit powders, as it affects the moisture uptake, which leads to caking, stickiness, and microbial growth causing the quality of powder to degrade. Increased hygroscopicity also results in higher water activity and moisture content in storage, which causes deadening of both the physical and chemical properties and increases loss of flowability and functional properties (Pui *et al.*, 2024). Generally, food powders characterized by lower hygroscopicity and higher solubility are regarded as superior products (Kinalski and Noreña, 2019). The hygroscopicity results show that T2 (GA) had the highest hygroscopicity (25.88 g/100 g), followed by T1 (MD) (22.25 g/100 g),

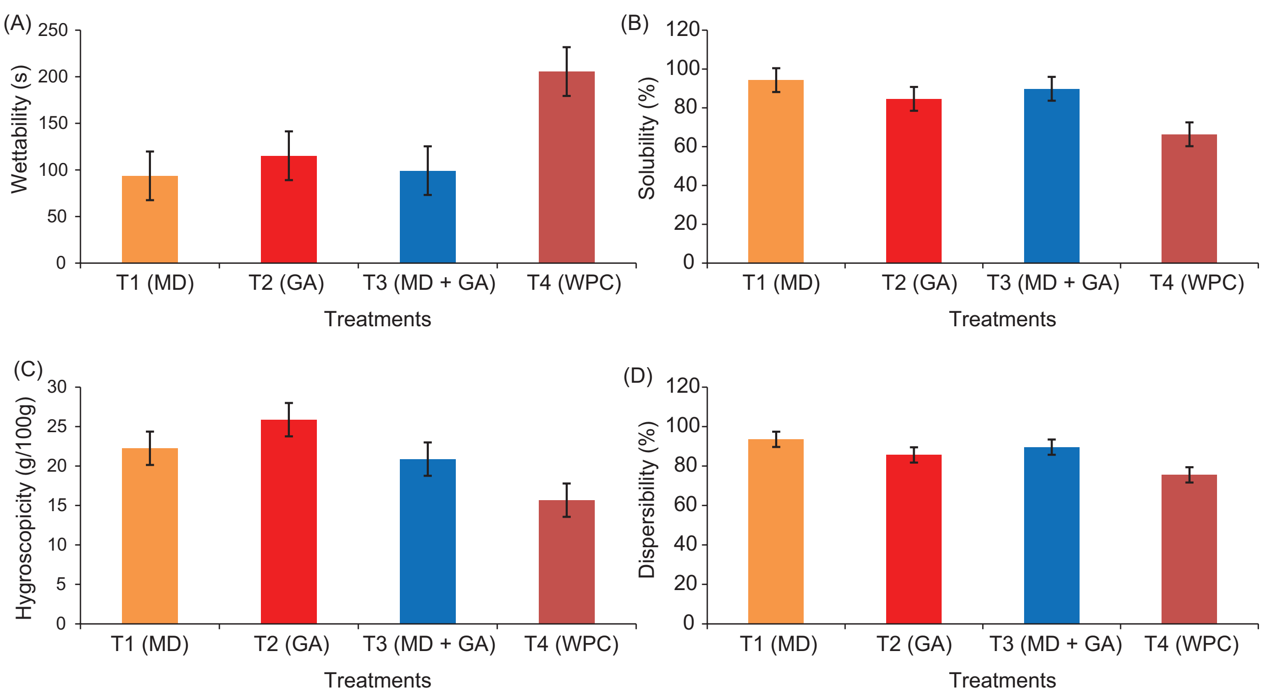

Figure 4. (A) Wettability, (B) solubility, (C) hygroscopicity, and (D) dispersibility.

Table 2. Reconstitution, functional, and color properties of spray dried mixed fruit juice powder.

Properties	Treatments			
	T1 (MD)	T2 (GA)	T3 (MD + GA)	T4 (WPC)
Powder recovery (%)	53.5 ± 0.30[d]	63.7 ± 0.26[b]	58.7 ± 0.26[c]	71.4 ± 0.37[a]
Moisture content (%)	2.2 ± 0.15[d]	3.6 ± 0.10[b]	3.2 ± 0.15[c]	4.8 ± 0.10[a]
Bulk density (g/cc)	0.333 ± 0.005[c]	0.403 ± 0.01[b]	0.457 ± 0.01[a]	0.293 ± 0.01[d]
Tapped density (g/cc)	0.51 ± 0.01[c]	0.57 ± 0.01[b]	0.58 ± 0.01[a]	0.48 ± 0.01[d]
Hausner's ratio	1.553 ± 0.005[b]	1.423 ± 0.01[c]	1.270 ± 0.017[d]	1.667 ± 0.008[a]
Carr's index (%)	35.27 ± 0.03[b]	29.82 ± 0.005[c]	20.69 ± 0.006[d]	39.58 ± 0.02[a]
Solubility (%)	94.29 ± 0.40[a]	84.63 ± 0.59[c]	89.837 ± 0.10[b]	66.383 ± 0.61[d]
Hygroscopicity (g/100 g)	22.25 ± 0.03[b]	25.88 ± 0.08[a]	20.883 ± 0.06[c]	15.67 ± 0.01[d]
Wettability (s)	93.57 ± 0.16[d]	115.26 ± 0.03[b]	99.26 ± 0.20[c]	205.60 ± 0.25[a]
Dispersibility (%)	93.533 ± 0.09[a]	85.647 ± 0.45[c]	89.58 ± 0.01[b]	75.51 ± 0.11[d]
Ascorbic acid (mg)	201 ± 1.15[c]	274.667± 0.57[b]	349.667 ± 0.57[a]	160 ± 0.57[d]
Total phenols (mg GAE/100 g)	264.05 ± 0.04[c]	382.13 ± 0.17[a]	324.38 ± 0.09[b]	202.12 ± 0.08[d]
Antioxidant activity (%)	66.67 ± 0.22[c]	74.757 ± 0.32[a]	70.663 ± 0.24[b]	59.69 ± 0.17[d]
Particle size (μm)	9.25 ± 0.03[a]	8.60 ± 0.005[d]	8.75 ± 0.002[b]	8.50 ± 0.04[c]
*L** value	92.762 ± 0.05[b]	87.686 ± 0.21[d]	93.491 ± 0.36[a]	89.028 ± 0.004[c]
*a** value	–0.568 ± 0.02[c]	0.387 ± 0.003[a]	0.47 ± 0.01[b]	0.677 ± 0.002[d]
*b** value	8.779 ± 0.06[c]	9.452 ± 0.03[b]	6.773 ± 0.02[d]	12.55 ± 0.22[a]

Mean ± standard deviation of triplicate analysis.
[a–d]No significant variations between any two means in the same "row" that have the same superscript letter ($P \geq 0.05$).
GA, gum Arabic; MD, maltodextrin; WPC, whey protein concentrate.

T3 (MD + GA) (20.88 g/100 g), and T4 (WPC) (15.67 g/100 g) (Figure 4c). Results indicate that T2 (GA) shows maximum hygroscopicity due to its galactomannan and hydrophilic components present in GA that allow the increased absorption of moisture. Research by Shelke *et al.* (2022) established equivalent findings with regard to hygroscopic properties of jamun juice powder. Among all samples, T4 (WPC) showed the lowest hygroscopic property. The water affinity of WPC falls behind polysaccharide-based ingredients because it functions as a protein-based material. Due to its low hygroscopic behavior, WPC delivers prolonged storage stability in addition to longer shelf life since it prevents moisture absorption in moisture-sensitive applications.

Dispersibility

Wet accumulated particles show dispersibility when they interact with a solvent; so, they separate and distribute homogeneously (Bhat *et al.*, 2021). The level of dispersing powder components serves as the primary indicator for identifying instant-classified materials. Food powder dispersibility must be maintained between 67.05% and 99.98% as per Singh *et al.* (2019). T1 (MD) achieved the maximum dispersibility level at 93.53% while T3 (MD + GA) displayed 89.58% and T2 (GA) reached 85.64% and T4 (WPC) recorded 75.51% (Figure 4d). T1 (MD) displayed the highest dispersibility (93.53%) due to its excellent water-stable properties that prevent powder clumping during suspension, according to Shelke *et al.* (2022) when they tested spray dried jamun juice powder. After T1 (MD), a mixture of T3 (MD + GA) showed excellent dispersibility by taking advantage of the complementary functional properties of the two ingredients. The high-water solubility and low viscosity of MD help to rapidly dissolve and shorten the dissolving time of the powder; GA is a successful emulsifier and film-former that dissipates aggregation of particles and enhances the consistency of dispersion (Akdeniz *et al.*, 2023). The dispersibility of T4 (WPC) amounted to 75.51%. The dispersibility in water becomes reduced through gel formation and aggregation of WPC particles. The protein shows natural behavior to develop structure complexes when dissolved in watery solutions. Bhat *et al.* (2021) demonstrated the same dispersibility results between bone broth powder and bottle gourd juice powder.

Functional properties of spray dried mixed fruit juice powder

Ascorbic acid

Vitamin C stands as the most vital water-soluble antioxidant because it functions as an efficient protector of reactive oxygen species. Fruits like lemon, amla, and raw mango are recognized as a substantial source of this essential nutrient. The results shows that T3 (MD + GA) had the highest ascorbic acid (349.66 mg), followed by T2 (GA) (274.66 mg), T1 (MD) (201 mg), and T4 (WPC) (160 mg). In T3 (MD + GA), the ascorbic acid content was the highest at 349.66 mg. This finding suggests that the composite mixture of MD and GA not only preserves ascorbic acid effectively but may also enhance its stability through encapsulation. GA acts as an antioxidant to protect ascorbic acid while it undergoes industrial processing through its protective mechanism. The combined functionality of both compounds seems to work in harmony for protecting nutrients, as shown by this improved retention by de Barros Fernandes *et al.* (2014). The whey protein contained the least amount of ascorbic acid (160 mg) since this protein material proved to be highly sensitive to processing conditions that may have led to substantial ascorbic acid loss during manufacturing procedures (Janiszewska-Turak *et al.*, 2019).

Antioxidant activity

Antioxidants implement several activity mechanisms that begin with free radical oxidation reaction retardation through prevention of free lipid radical formation (Salbi *et al.*, 2021). The phenolic content results show that T2 (GA) had the highest antioxidant (74.75%), followed by T3 (MD + GA) (70.66%), T1 (MD) (66.67%), and T4 (WPC) (59.69%). GA has established itself as an encapsulation solution that protects bioactive compounds against deterioration. Its hydrophilic nature might have contributed to better retention of antioxidants during processing, leading to the highest AA observed in T2 (GA) (Shelke *et al.*, 2022). The lowest antioxidant activities are found in WPC, a protein-based carrier with encapsulation potential, but its antioxidant retention capabilities are hindered by interactions with phenolic compounds, leading to lower AA (Janiszewska-Turak *et al.*, 2019).

Total phenolic content

Phenolic compounds are crucial components of fruits like amla, lemon, and raw mango; however, they are highly unstable and prone to degradation during the spray drying process. According to the phenolic content measurement, T2 (GA) had the highest level at 382.13 mg GAE/100 g while T3 (MD + GA) followed at 324.38 mg GAE/100 g, then T1 (MD) at 254.05 mg GAE/100g, followed by T4 (WPC) at 202.12 mg GAE/100g. GA stands out for its robust antioxidant efficiency while it maintains steady complexes with phenolic compounds. The phenolics retention in T2 increased due to the protective nature of GA. GA encapsulation acted as a protective barrier against phenolic compound degradation that occurred throughout processing and storage time. According to Shelke *et al.* (2022), the incorporation of GA as a carrier agent led to the improvement of TPC recognition in spray dried jamun juice powder. Tonon *et al.* (2010) obtained more TPC results in their experiments on acai powder, dried by GA spray drying in contrast to MD as the drying agent. The T3 carrier blend promotes better encapsulation efficiency and offer better protection to thermal and oxidative degradation, thus increasing phenolics retention (Delaporte *et al.*, 2024). The TPC reached its minimum value when using WPC as the carrier agent. The peptide composition of WPC provides antioxidant properties but the materials bind and protect phenolic compounds less efficiently than GA and MD. The whey proteins might have lowered both the available amount of phenolics and their extraction efficiency due to interactions with phenolic compounds (Janiszewska-Turak *et al.*, 2019).

Physical characteristics of spray dried mixed fruit juice powder

Color. The produced powder strongly impacts how the reconditioned juice looks determining whether customers will accept it. The L^* value, which ranges from 0 to 100, indicates lightness, where 0 represents black and 100 represents white. The a^* value reflects the stability among green (negative values) and red (positive values), while the b^* value pertains to blue (negative values) and yellow (positive values) (Quoc, 2020). The L^* value indicates the lightness of the powder, where 0 signifies black and 100 implies white. Among the samples tested, the lightest powder had an L^* value of 93.491, while the darker sample recorded an L^* value of 87.686. Lightness contrast in the product relates to the type of carrier employed in production. When using MD in production, the powders appear lighter due to its white color, but GA creates darker color. The drying reaction between pigments in mixed fruit juice and the selected carrier determines the final color of the powder (Quoc, 2020). The a^* value reflects the balance between red and green hues in the powder, with negative values indicating green tones and positive values representing red tones. In this analysis, the a^* values ranged from –0.677 to 0.387. The sample that had a positive a^* value of 0.387 shows a slight leaning toward red, which may be attributed to the carrier used, likely GA or a combination of carriers. Conversely, the negative a^* values in the other samples suggest a green tint. The process of drying or interaction with certain transport agents likely caused changes to the purple color pigments known as anthocyanins. b^* value evaluates the blue-yellow spectrum, with higher values indicating a stronger yellow hue. The sample with b^* value of 12.55 shows the most noticeable yellow tint, whereas the sample with a value of 6.773 is the least yellow. The yellow color intensity increases because drying conditions allow reactions like Maillard chemistry and caramelization to occur, especially with WPCs as carrier materials or due to extra fruit juice sugar. During spray drying, the pigments break down and new chemical combinations form, according to Quoc (2020).

Particle size

Particle size rules all the physical traits of powders by controlling how they store, stay stable, blend, and flow. Small powders show increased surface exposure that easily embraces moisture and clumps together (Bhat *et al.*, 2021). The study found that mixed fruit juice powders made by spray drying produced particles with average dimensions between 8.50 μm and 9.25 μm. When comparing powder samples, the MD (T1) powder produced particles that were larger than the other ones following. Shelke *et al.*'s (2022) research demonstrated identical results when powdered jamun juice was created through spraying. During atomization, the added viscous quality of MD made larger droplets during the feed production process. Samples produced with WPC T4 created smaller particles than all other result types. Protein denaturation during the drying process produces small and irregular particles because the proteins break down quickly.

Conclusion

The spray dried mixed fruit juice powder, created by employing different carrier agents, exhibited moisture content ranging from 2.20% to 4.80% (w.b.), which is sufficient to ensure microbiological stability. The powder made with MD demonstrated excellent reconstitution characteristics, including wettability (93.57 seconds), solubility (94.29%), hygroscopicity (22.25 g/100 g), and dispersibility (93.53%); however, it displayed poor physical, flow, and functional characteristics. In contrast, the powder with GA retained improved levels of AA (74.75%) and TPC (382.13 gGAE/100 g), but had subpar physical, flow, and reconstitution properties. Meanwhile, the powder prepared using WPC achieved maximum powder recovery (71.4%), but exhibited inadequate physical, flow, reconstitution, and functional qualities. After evaluating all the attributes, it was determined the blend of MD and GA served as the most effective carrier, offering enhanced physical, flow, reconstitution, color, and functional properties. These findings highlight the significant influence of the carrier on the stability and quality of the finished product. Therefore, selecting the appropriate carrier depends on production needs and different technological considerations.

Acknowledgments

The authors extend their appreciation to Taif University, Saudi Arabia, for supporting this work through project number TU-DSPP-2024-79.

Authors' Contribution

All authors contributed equally to this work.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

This research was funded by Taif University, Saudi Arabia, Project No. TU-DSPP-2024-79.

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