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Impact of carrier agents on physicochemical characteristics and bioactive compound retention in spray-dried mixed berry juice powder



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ABSTRACT

Berries, rich in phytochemicals, have always been acknowledged for their powerful antioxidant and anti-inflammatory benefits. "Blueberries, hailed as "superfruits," and raspberries, linked to blood sugar control and cancer prevention, stand out for their nutrient-packed profiles. Spray drying preserves these fruits' nutrients, producing powders that extend shelf life, ease transport, and retain their health-boosting properties. The challenges of this study were optimizing the spray drying parameters to balance nutrient retention with powder physical stability, as the natural sugars and acids in berry juice can cause stickiness and low glass transition temperatures leading to powder agglomeration and poor flowability. By selecting appropriate carrier agents and their combinations to overcome these processing difficulties and maintain the bioactive compounds posed another critical challenge. Investigation aims to standardize the spray drying procedure for mixed berry juice by examining how various carrier agents influence the physical, functional, and reconstitution features of the resultant powder. Specifically, the current study seeks to obtain the effect of varying carrier types, maltodextrin, gum arabic, whey protein concentrates, and a combination of maltodextrin and gum arabic on the physical properties, reconstitution capabilities, functional attributes, and color of spray-dried mixed berry juice powder. Physical characteristics in the formed powders included moisture content (ranging from 2.26% to 4.61% w.b.), bulk density (0.28 to 0.31 g/ml), and tapped density (0.40 to 0.53 g/ml). Powder yield varied from 59.64% to 74.49%. Reconstitution characteristics such as wettability, hygroscopicity, solubility, and dispersibility were recorded in the range of 93.5 to 215.53 seconds, 15.88 to 25.61 g/100g, 70.30% to 95.10% and 73.71% to 95.32%, respectively. Functional characteristics, such as total anthocyanin and total phenolic content, were measured between 175.69 and 239.66 mg/100g and 206.55 to 270.85 g GAE/100g, respectively. Color values indicated by L^* , a^* , and b^* values, noted from 69.164 to 75.94, 5.509 to 17.138, and -0.87 to -2.981, respectively. In addition to maltodextrin and gum arabic has, it shown effectiveness in creating mixed berry juice powder and obtained desirable physical, functional, reconstitution and color characteristics.

Keywords: Mixed berry juice powder, Blueberry, Raspberry, Spray drying, Carrier agent, Reconstitution properties Antioxidant activity, Physical and functional characteristics and Color.

Introduction

The rising awareness of phytochemicals' health benefits has resulted in increased customer demand for items rich in these compounds [14]. Diets abundant in fruit and vegetables relate to a reduced risk of non-communicable diseases related to aging and lifestyle factors [43]. Berries, which are small, juicy, and typically sweet or tangy, have long been integral to human diets, even predating agriculture through ancient foraging. Blueberries, belonging to the *Vaccinium* genus in the Ericaceae family, are particularly celebrated as a "superfruit" because of the large amounts of polyphenolic antioxidants. The Food and Agriculture Organization has identified blueberries as one of the five healthiest foods [38]. Native to North America, blueberries are now widely cultivated globally and consumed in fresh, frozen, dried, or processed forms such as jams, beverages, cosmetics, and pharmaceuticals ([18]; [14]). Similarly, raspberries, from the *Rubus idaeus* species in the Rosaceae

family, are rich in antioxidants, aiding in blood sugar control, improving insulin sensitivity, and minimizing the chances of chronic conditions like cancer and arthritis [17]. High in vitamin C, raspberries also offer immune support and antioxidant protection, with their antimicrobial and anti-inflammatory properties making them valuable for cosmetic and pharmaceutical uses ([30]; [42]).

Despite the nutritional advantages of berries, their perishable nature leads to rapid degradation of valuable compounds during storage. To solve the problem, various drying technologies have been employed to preserve berries and their juices. Notably, interest in powdered juice has grown considerably owing to its convenience and long shelf life [9]. Spray drying, in particular, has become a preferred method due to its minimal processing time and potential to retain heat-sensitive nutrients like carotenoids at relatively low temperatures [10]. Spray drying is employed in the food industry to manufacture powdered products. This method offers benefits such as cost-effectiveness, scalability, versatility, and suitability for continuous processing [9]. Other available drying technologies, such as spray drying are frequently applied for producing instant [40], and also offer an economical solution for preserving fruit and vegetable juices [5].

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Spray-dried powders are convenient for transport due to their reduced volume and weight, more compact packaging, and extended shelf life. However, the operating condition plays a major role in spray-dried powder quality, which influences aspects like flavor retention, nutrient preservation, and process efficiency [19].

One major challenge in spray fruit juice is the sticky structure and poor flowability characteristics of the resulting powder, resulting from the presence of low molecular weight and organic acids that lead to a decrease in glass transition temperature (T_g) [20]. To mitigate these, carrier agents are put into the fruit juice during spray drying to increase the T_g , carrier aids, also prevent sensitive components such as carotenoids, preserve flavor, and reduce the evaporation tendency and reactivity of the finished item [10]. Wall material supports the spray drying process by forming a protective barrier around the core material, shielding it from external factors [2].

Several studies have reviewed the usage of various carrier aids in spray-dried fruit juice powder. Common carrier agents included maltodextrin, gum arabic, whey protein concentrate, soya protein concentrate, and egg albumin [6]. Ideal carrier materials have specific characteristics, such as high molecular weight, solubility, low viscosity, and chemical inertness with the substance being encapsulated [5]. Maltodextrin is widely utilized as a carrier aid, given its soluble content and minimal viscosity and efficiency in protecting flavor, color, and bioactive compounds in harsh environments ([20]; [5]).

Gum arabic, a plant-derived polysaccharide from acacia, is another commonly used carrier because of its notable solubility as well as low viscosity even at increased concentrations [32]. Proteins, such as whey protein, are also effective carriers and are frequently used for microencapsulating flavors and oils. Whey proteins, are widely recognized as an effective plant-based carrier for bioactive compound [15], providing strong emulsifying properties and a quick surface coating, which minimizes stickiness and powder restoration at low concentration ([34]; [5]; and [32]).

Future research may focus on optimizing the drying parameters and carrier combinations to further enhance the stability, solubility, and sensory quality of the powders. Moreover, exploring the use of natural or plant-based carriers such as maltodextrin alternatives could contribute to developing clean-label products. Long-term storage studies under different environmental conditions may also provide valuable insights into the shelf-life behavior and degradation kinetics of bioactive compounds. Additionally, scaling up the optimized process to pilot or industrial level would help in evaluating the commercial feasibility and cost-effectiveness of the production system.

Extensive research has explored spray drying with various carrier aids for different fruit juices, including [34]; [31]; [5]; [27]; [41]; and [13], for jamun, goldenberry, chokeberry, pineapple, and black mulberry, respectively. However, no research has been conducted on mixed berry juice powders. Furthermore, there is limited knowledge on how various drying carriers impact the qualitative characteristics of mixed berry powders. With the rising public interest in soluble fruit powders for their health benefits and ease of use, the objective of this investigation is to fill that difference by investigating the results of various carrier agents on the production of mixed berry juice powder through spray drying. It will also evaluate key quality parameters, including physical characteristics, functional properties, and reconstitution abilities.

Material and Methods

Raw material

Well-matured, healthy, uniform in size and colour, blueberries and raspberries were procured from the market and utilized for the experimentation. The fruits had been kept at $-18\text{ }^{\circ}\text{C}$ in the deep freezer until utilized (24 h). MD, GA, and WPC performed the role of carrier agents.

Sample preparation of mixed berry juice

A mixed berry juice (blueberry and raspberry) with a soluble solids content of 12.13°Brix was prepared at the Post-Harvest Technology center of Mahatma Phule Krishi Vidyapeeth, Rahuri, India. Mixed berry juice was placed in dark glass bottles for further treatment. The mixed berry juice with TSS $12.13\text{ }^{\circ}\text{Brix}$, combined using various carrier agents, was used to formulate feeding solutions for spray drying. Four formulations were prepared: treatment T1 with maltodextrin (MD), treatment T2 with gum arabic (GA), treatment T3 with 50:50 blends of MD and GA, and treatment T4 with Whey protein concentrate (WPC). Based on earlier studies ([34]; [10]; [13]; and [32]) and preliminary trials, the concentration of each carrier agent (MD, GA, WPC, and the MD-GA mixture) was standardized at 20% (w/v). The mixtures were completely combined at 1,000 rpm for 20 minutes using a magnetic stirrer (2MLH, Remi Sales and Engineering Ltd., Mumbai, India), resulting in a homogenous and well-blended solution.

Spray drying of mixed berry juice powder

Mixed berry juice was spray-dried by utilizing a spray drier (LU-222 Labultima Pvt Mumbai, India) at a laboratory scale. The feeding solution was placed in the drying chamber. Operating element remained steady during the process, with a feeding rate of 10 mL/min, an inlet air flow rate of $63\text{ m}^3/\text{h}$, an outlet air temperature of 80°C , and an inlet air temperature of 160°C , methodology given by ([34]; [35]). A sample was taken from the cyclone collector and kept in a sealed container with desiccant at 20°C to maintain low humidity until further analysis. The powders produced from the different treatment conditions are illustrated in Figure 1.

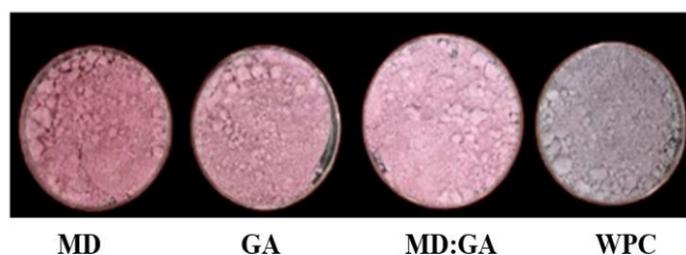


Fig. 1 Spray-dried mixed berry juice powder at various formulations

Determination of chemical characteristics of fresh mixed berry juice

Moisture content

Moisture content of the mixed berry juice was evaluated according to the procedure described by [1].

Total soluble solids (TSS)

Total soluble solids of the mixed berry juice were analyzed with a refractometer and noted as $^{\circ}\text{Brix}$.

Titretable Acidity

Acidity of the reconstituted mixed berry juice was obtained by titration, where 5 g of the juice was dissolved in water, and titration of a 50mL mixture was carried out using 0.1N NaOH in

the presence of phenolphthalein as an indicator, with the endpoint being a light pink color. Acidity was given in percent of citric acid in the juice, according to [1].

pH

pH of the mixed berry juice was calculated with the help of a pH meter.

Ascorbic acid

Ascorbic acid of the mixed berry juice was evaluated through titrimetrically using 2,6 dichlorophenol indophenol dye, following [27] method, with the powder dissolved in 4% oxalic acid and 10 mL of aliquot titrated against the dye. The findings were represented as mg of ascorbic acid for each gram of juice.

Determination of functional characteristics of fresh mixed berry juice

Total phenolic content and Total Anthocyanin content

Total phenolic and total anthocyanin content were calculated by applying procedures outlined by [34].

Antioxidant activity

Antioxidant was evaluated by 2,2-diphenyl-1-picrylhydrazyl assay to assess the anti-free radical capability of the juice, as detailed by [34].

Determination of Color characteristics properties of fresh mixed berry juice

Color

Color was measured using Hunter colorimeter, recorded with a color measurement device.

Evaluation of mixed berry juice powder

Yield

Yield was estimated by relating the ratio of mass dry solids produced by initial mass of the mixed feed ([6]; [23]; [32]).

$$\text{Powder recovery (\%)} = \frac{\text{Amount of powder obtained after drying}}{\text{Amount of feed to dryer}} \times 100$$

Physical characteristics of mixed berry juice powder

Moisture content

Moisture content was obtained by following procedure given by [1] A 5 g mixed berry powder was measured and dehydrated in a vacuum dryer at 70°C for 24 h, or till the constant weight was achieved, maintaining a vacuum between 85 and 100 mm of Hg. following drying process, the samples were collected from the oven, let to cool in a sealed container with desiccant. Repeated the procedure until consistent weight was reached. Moisture content was computed in triplicate, and the averages of three values were evaluated according to the specified formula.

$$\text{MC \% d, b} = \frac{W1 - W2}{W2} \times 100$$

Where, W1 =

where, W1 = Initial powder quantity of mixed berry powder (by weight), g, W2 = Final powder quantity of mixed berry powder (by weight), g.

Bulk density

Bulk density was computed with the procedure given by [6]. Exactly, 2g of mixed berry powder was gently placed in to a 10ml graduated measuring cylinder. Bulk density was computed as powder mass to cylinder volume.

$$\text{Bulk density (g/cm}^3\text{)} = \frac{\text{Weight of sample at recorded volume (g)}}{\text{volume of sample in the cylinder(cm-3)}}$$

Tapped density

Tapped density of powder was determined using outline given by [22]. For measuring the tapped volume, 2g of every sample were kept in 10ml measuring cylinder was gradually dropped onto rubber surface from a height of 20cm for a total 100 taps. The tapped density was then computed using the appropriate formula.

$$\text{Tapped density (g/cm}^3\text{)} = \frac{\text{Weight of sample at recorded volume (g)}}{\text{Tapped volume (cm-3)}}$$

Reconstitution characteristics of spray-dried mixed berry juice powder

Solubility

Solubility of the powder was assessed following the method outlined by [32], after minor revision. One gram of powder was carefully placed in 100 ml of DW while agitated using a magnetic stirrer at 200rpm for 4 minutes. Prepare the mixture and then it was centrifuged at 3000 g for a duration of four minutes. A 25 ml of clear liquid sample was shifted to a previously weighed petri dish and heated in an oven at 105 °C until completely dry up to 5h. Solubility was shown as the percentage of dry solid content based on initial mass weight.

Wettability

Wettability of the powder was investigated with the technique noted by [34]. The experiment entailed gently distributing 1 g of mixed berry powder, which was gently added to 150 mL of DW at ambient temperature. The duration necessary to completely moisten the powder was measured, with no agitation used during the procedure.

Hygroscopicity

Following [37] method, the powder's hygroscopicity was measured. A 1-gram sample, placed in an open weighing bottle, was stored for a week in a desiccator at 20°C and 75% RH. The weight gain, representing moisture absorption, was then calculated as the amount of water content in grams for every gram of dried powder.

Dispersibility

Dispersibility measurements were expressed by [7]. Initially, 10 ml of 25°C DW was placed in a 50 ml beaker. Next, 1 g of powder was transferred into the beaker. The timer was initiated, and the liquid was vigorously agitated for 15 seconds, resulting in completing a full 25 reciprocating motions around the beakers. The reconstituted mixed berry powder was screened using a sieve with a specified mesh size of 212 µm. The remaining powder on the sieve was collected and put in a pre-weighed, dry aluminum pan, which was then exposed to a hot air oven at 105°C for 4h. Dispersibility was determined by the formula.

$$\text{Dispersibility (\%)} = \left(\frac{10+a}{a} \right) \times \frac{\% \text{ TS}}{100-b} \times 100$$

Where, 'a' denotes the weight of powder utilized (in grams), 'b' denotes the amount of water in the powder, and % TS refers to the proportion of dry matter contained in the reconstituted powder, followed by the sieve process.

Flow characteristics of spray-dried mixed berry juice powder

Carr's Index

Carr's index (CI) was expressed by using the procedure of [22] to evaluate the flowability of mixed berry juice powders.

CI was determined depending on the relationship between TD and BD, using the appropriate formula.

$$\text{Carr's index (\%)} = \frac{\text{Tapped density} - \text{Bulk density}}{\text{Bulk density}}$$

Hausner ratio

The Hausner ratio was calculated using the approach published by [22]. The cohesiveness of mixed berry juice powders was assessed with the help of the Hausner ratio (HR), which was calculated, based on TD and BD, following the specified formula.

$$\text{Hausner ratio} = \frac{\text{Tapped density} - \text{Bulk density}}{\text{Bulk density}}$$

Functional characteristics of mixed berry juice powder

Total phenolic content

Total phenolic content (TPC) was computed with the Folin-Ciocalteu method outlined by [34]. A 5 mg powder sample, extracted with methanol, was reacted with Folin-Ciocalteu and sodium carbonate reagents. After dilution and 2 h incubation, optical density was measured at 760 nm using a Spectrophotometer. Total phenolic content was quantified using tannic acid calibration curve and expressed as gallic acid equivalents (GAE) per 100g of water.

Total anthocyanin content

Total anthocyanin content (TAC) was assessed using the pH differential technique outlined by [34], which involves two buffer systems: potassium chloride buffer at pH 1.0 (0.025M) and a sodium acetate buffer at pH 5.0 (0.4M). Specifically, 1g of juice was mixed with 24 ml of each buffer solution, and absorbance was measured at 510 and 700 nm with water as blank. The optical density was measured using formula,

$$A = (A_{510} - A_{700})_{\text{pH}1.0} - (A_{510} - A_{700})_{\text{pH}5.0}$$

TAC was denoted in milligrams of cyaniding of 3-glucoside per 100 ml, calculated by,

$$\text{TAC} = \frac{A \times \text{MW} \times \text{DF} \times 100}{\text{MA}}$$

Where 'A' denoted optical density, 'MW' represented molecular weight of cyaniding 3-glucoside (449.2), 'DF' denoted as the dilution factor (25) and 'MA' denoted molar extinction coefficient of cyaniding 3-glucoside (26,900).

Antioxidant activity

DPPH (1,1-diphenyl 2-picrylhydrazyl) analyzed was conducted to evaluate antioxidant activity, described by [34] method. The DPPH stock solution (24 mg/100 ml methanol) was stored at -20°C. A working solution was created by combining 10 ml stock with 30 ml methanol, with optical density adjusted to 1.1 ± 0.02 at 517 nm. The analysis involved mixing 500 µL juices with 3 mL DPPH solution, followed by 30 minutes of dark incubation at ambient temperature. The final optical density was evaluated at 517 nm, using radical scavenging activity (RSA%) measured against a control sample.

$$\text{Antioxidant activity (\%)} = \frac{\text{Absorbance of control} - \text{Absorbance of sample}}{\text{Absorbance of control}} \times 100$$

Statistical analysis

Each formulation was measured in triplicate to ensure statistical validity. Analysis was done using SAS software, version 9. A one-way ANOVA utilized to determine significant difference along treatment group. Statistical significance was established as $p < 0.05$, indicating 95% confidence level.

RESULTS AND DISCUSSIONS

Chemical characteristics of fresh mixed berry juice

Moisture content

Table 1. presents the physicochemical and color characteristics of fresh mixed berry juice. The high-water content in fresh berry juice reflects the characteristic of berries as water-rich fruits. This excessive moisture content provides to the juice's refreshing quality and can aid in hydration, making it appealing for consumption. The moisture level also has implications for shelf life and microbial stability, as high moisture can increase susceptibility to microbial growth, suggesting a need for appropriate storage or preservation methods. Moisture content in fresh berries juice was found 85.87 ± 0.54 (wet basis).

Table 1. Physico-chemical properties of mixed berry juice per 100g

Fresh berries juice	Values
Moisture content, %	85.87±0.54
TSS, °B	12.13±0.62
Ascorbic acid, mg/100g	25.23±0.47
Titrate acidity, %	1.2 ± 0.28
pH	3.29±0.20
Antioxidant Activity, %	81.4±1.44
Anthocyanin Content, mg/100g	275.22±0.99
Total phenols, mg GAE/100g	317.97±2.78
L*	28.64±0.27
a*	9.65±0.63
b*	1.40±0.22

Mean ± standard deviation of triplicate analysis

Total Soluble Solids (TSS)

TSS content, measured in degrees Brix (°B), was 12.13°B, indicating the total concentration of dissolved sugars, organic acids, and other soluble substances in the juice.

Ascorbic Acid Content

Ascorbic acid (vitamin C) concentration in the juice was found 25.23 mg/100g, showcasing berries as a good source of this essential nutrient. Ascorbic acid plays a crucial role as an antioxidant, neutralizing free radicals, which are unstable molecules that can damage cells, thereby shielding the body from oxidative stress, it also helps to keep the body cells healthy by preventing damage from harmful substances. Additionally, vitamin C supports collagen synthesis, immune function, and iron absorption. The ascorbic acid content in berry juice is beneficial from both a nutritional and functional perspective, contributing to its antioxidant properties as well as its potential health benefits.

Titrate Acidity

The titrate acidity of 2.84% in fresh berry juice, reflects the presence of organic acids, primarily citric acid, malic acid, and other phenolic acids, which contribute to the juice's characteristic tart flavor.

pH

A pH of 3.29 ± 0.20 classifies the juice as moderately acidic, in line with typical berry juices. The pH level not only influences flavor but also contributes to microbial stability and shelf life. A lower pH helps in preserving the juice and inhibiting spoilage by bacteria and molds. From a sensory perspective, this pH range provides a balanced tartness that is desirable in berry products, enhancing the overall flavor profile.

Antioxidant Activity

The high antioxidant activity (81.4%) indicates a significant capacity of scavenging free radicals, likely because of the synergistic effects of vitamin C, phenolic compounds, and anthocyanins.

Anthocyanin Content

Anthocyanins, measured of mixed berry juice, was found as 275.22 mg/100g, are a class of flavonoids responsible for the rich color in berries.

Total Phenols

The total phenolic content of mix berry juice was found as 317.97 mg GAE/100g reflects the juice's richness in bioactive compounds. Phenolic substance is recognized for their antioxidant, anti-inflammatory, and cardiovascular benefits.

Color Parameters

The color values were found as L values 28.64 ± 0.27 , a value 9.65 ± 0.63 and b values 1.40 ± 0.22 . The low L value indicates a darker, rich coloration typical of berry juices, which often appeal to consumers as they associate deeper colors with higher antioxidant content. The positive a value signifies a red hue, characteristic of anthocyanin-rich berries. And the low b value shows minimal yellowness, which aligns with the visual expectation for a vibrant, red-colored berry juice. The color parameters, particularly the high a^* value, reinforce the juice's visual appeal, which is an essential quality attribute for consumers. Anthocyanins primarily drive the color properties, providing both sensory appeal and health benefits.

Yield characteristic of spray-dried mixed berry juice

Powder yield

Powder yield is an important measure of spray dryer efficiency reported by [32]. A yield greater than 50% accepted as a benchmark for effective spray drying [3]. Figure 2a illustrates the impact of various carriers on yield. The yield of mixed berry juice powder varied between 59.64% and 74.49%. The type of carrier agent significantly affecting powder recovery ($p < 0.05$). From all the treatments, T4 (whey protein concentrate, WPC) exhibited the highest recovery rate, while T1 (maltodextrin, MD) showed the lowest. The order of powder yield across the different carrier agents followed the sequence: WPC > gum arabic (GA) > maltodextrin-gum arabic (MD) > maltodextrin (MD). The superior recovery in protein-containing treatments might be because of the creation of a protein-rich coating at the air-water interface during the drying process, as proteins can migrate to this interface, forming a protective skin around the droplets. This protein layer reduces droplet coalescence and minimizes adhesion to the dryer walls, mitigating stickiness [6]. The results are in line with earlier literature such as that by ([34]; [6];[32]), which demonstrate that protein-based carries outperformed maltodextrin and gum arabic in enhancing powder yield during spray drying.

Physical characteristic of spray-dried mixed berry juice powder

Moisture content

The stability of a powder is largely depended on its moisture content, as it influences critical properties such as flowability, stickiness, drying efficiency, oxidative stability, and microbial safe. A moisture content between 3% to 5% is considered optimal for powder formulations, it helps to maintain product stability while minimizing the risk of chemical reaction and microbial growth [15]. The moisture content of spray-dried mixed berry juice powders ranging from 2.26% to 4.61%, The influence of the carrier agent on moisture content was statistically significant ($p < 0.05$) among different carrier materials (Table 2).

The whey protein concentrate (T4) has the highest moisture content, possibly because of its enhanced capability for retaining water and binding capability, which increases the powder's hygroscopicity. Maltodextrin (T1), with a lower moisture level, creates powders that are more stable and less prone to clumping, benefiting shelf life. Gum arabic and its combination with Maltodextrin (T2 and T3) show moderate moisture, balancing between water retention and powder stability. The moisture level in the powdered apple juice concentrate was consistent with previous findings [32].

Bulk density

The spray-dried mixed berry juice powder exhibited a BD between 0.28 and 0.40 g/cc a key characteristic influenced by molecular weight, carrier type, and process parameters [6]. The effect of carrier composition on bulk density was significant ($p < 0.005$). Carriers with larger molecule such as MD and GA were particularly efficient in increasing bulk density by minimizing interstitial spaces between particles, as demonstrated in treatment T3 [34]. Conversely, treatment T4, which utilized whey protein concentrate (WPC), resulted in the minimum bulk density due to its film-forming properties that retain air within the particles, creating a porous structure and reducing stickiness during drying which affects the final density of the powder [15]. The combined use of maltodextrin and gum arabic further enhanced bulk density compared to their individual application, as these carriers-' exhibit complementary effects that improve particle packing efficiency. This phenomenon aligns with observations from [31] for spray-dried fig powder and [27] for pineapple powder. These studies highlight that the relationship between these carriers reduces void spaces, resulting in denser powders. The different types of carriers employed had a statistically significant impact ($p < 0.05$) on the powder's bulk density. Additionally, higher bulk density reduces trapped air, which helps to minimize oxidation and improve storage stability, thereby prolonging the shelf life of the powder [21]. These results emphasize the critical role of carrier selection and spray drying optimization in developing powders with favorable physical and functional characteristics.

Tapped density

Tapped density of spray-dried mixed berry juice powder, measured between 0.40 and 0.53 g/mL, represents an essential physical attribute influenced by molecular weight, carrier agents, and spray drying conditions [6]. The effect of carrier composition tapped density was significantly ($p < 0.005$). These variations are mainly due to difference in the molecular weight of the carrier as well as in the particle size and flow properties of powder [15]. Similar to bulk density, higher molecular weight carriers like maltodextrin and gum arabic significantly improved tapped density by enhancing particle packing efficiency, as demonstrated in treatment T3. In contrast, treatment T4, which utilized whey protein concentrate, demonstrated the minimum tapped density. The film-forming properties of WPC reduced particle adhesion and retained more air within the powder, resulting in a porous, less compact structure when tapped. Using maltodextrin and gum arabic together resulted in higher tapped density than using either ingredient alone, suggesting their combined effect improved particle adhesion and decreased empty spaces between particles [31]. These observations underline the critical role of carrier selection and spray drying optimization in achieving ideal powder density, which directly impacts key

functional properties such as flowability, compressibility, and packaging performance

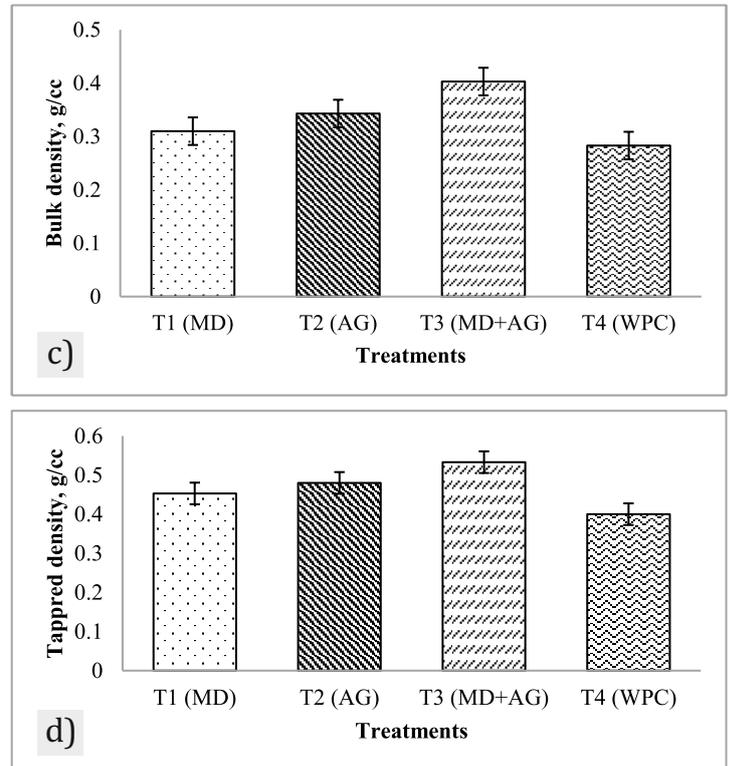
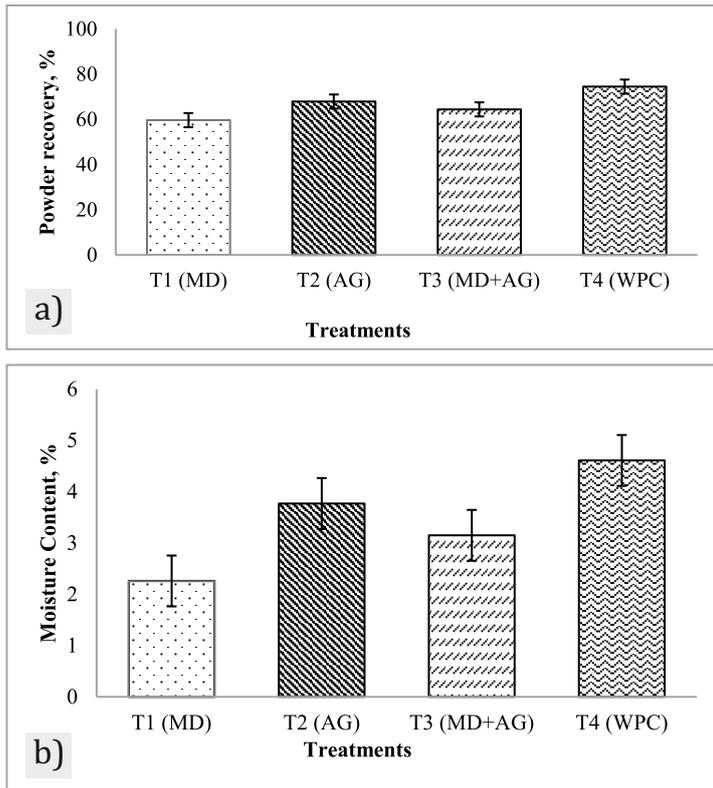


Fig. 2 a) Powder yield, b) moisture content c) Bulk density d) Tapped density of mixed berry juice powder

Table 2. Characteristics of spray-dried mixed berry juice powder.

Characteristics	Treatments			
	T ₁ (Maltodextrin)	T ₂ (Gum Arabic)	T ₃ (MD+AG)	T ₄ (Whey Protein)
Powder Recovery. (%)	59.64±0.032 ^d	67.88±0.076 ^b	64.40±0.050 ^c	74.49±0.040 ^a
Moisture Content, (%)	2.26±0.036 ^d	3.77±0.021 ^b	3.15±0.059 ^c	4.61±0.078 ^a
Bulk Density, g/cc	0.31±0.010 ^c	0.34±0.015 ^b	0.40±0.015 ^a	0.28±0.006 ^d
Tapped Density, g/cc	0.45±0.015 ^c	0.48±0.020 ^b	0.53±0.025 ^a	0.40±0.010 ^d
Solubility, (%)	95.10±0.046 ^a	84.79±0.032	90.83±0.104 ^b	70.30±0.095 ^d
Wettability, s	93.51±0.017 ^d	116.49±0.025 ^b	101.83±0.020 ^c	215.53±0.025 ^a
Hygroscopicity, g/100g	23.18±0.042 ^b	25.61±0.040 ^a	21.84±0.045 ^c	15.88±0.144 ^d
Dispersibility, %	95.32±0.015 ^a	87.26±0.026 ^c	93.52±0.015 ^b	73.71±0.020 ^d
Hausner Ratio	1.45±0.015 ^b	1.41±0.030 ^c	1.32±0.059 ^d	1.53±0.121 ^a
Carr's Index	31.58±0.006 ^b	28.36±0.01 ^c	24.36±0.015 ^d	35.09±0.010 ^a
Partical Size(µm)	11.35±0.124 ^a	10.81±0.365 ^c	11.10±0.117 ^b	10.69±0.125 ^d
TPC, g GAE/100g	246.39±0.290 ^c	256.69±0.090 ^b	270.85±0.210 ^a	206.55±0.342 ^d
TAC (mg/100g)	208.92±0.029 ^c	222.78±0.205 ^b	239.66±0.115 ^a	175.69±0.186 ^d
AA, (%)	64.36±0.335 ^c	74.183±0.193 ^b	76.323±0.148 ^a	62.277±0.042 ^d
L* value	69.439±0.059 ^c	70.541±0.046 ^b	69.164±0.063 ^d	75.94±0.041 ^a
a* value	17.138±0.054 ^a	14.587±0.179 ^b	11.752±0.271 ^c	5.509±0.226 ^d
b* value	-2.062±0.032 ^c	-0.87±0.108 ^b	-0.509±0.029 ^a	-2.981±0.010 ^d

Mean± standard deviation from triplicate analyses

AA- Antioxidant Activity, TPC- Total phenol content and TAC- Total Anthocyanin content

Reconstitution characteristics of spray-dried mixed berry juice powder

Wettability

The capacity of dry material to absorb water is crucial for rehydration, as it initiates the dissolution of micro particles by overcoming surface tension. Reduced Poor wettability can cause decreased solubility and a wetting time exceeded 400 seconds indicates reduced hydrophilicity. The number of carriers' agent influences the wettability of spray-dried powder ([41]; [6];[34]). Wettability of mixed berry juice ranged from 93.51 to 215.53 seconds shown in Table 2, powders containing maltodextrin (T1) showed the lowest wettability [15], while those with whey protein concentrate (T4) exhibited the highest values. Statistical analysis (Table 2) confirmed a significant effect of carrier type on wettability ($p < 0.05$).

According to [41], elements such as the size of the particle, shape, water content and internal composition of the carrier agents influence wettability time. The reduced wettability in maltodextrin-based powders is likely because of the larger particle size, which linked with slower liquid penetration. Comparable patterns were noted by [28] and [34]. This indicates that wettability shows an inverse relationship with particle size; larger particles tend to absorb liquid more quickly due to their greater void volume [27].

Solubility

Solubility in powders is largely affected because of hydrophilic groups [6]. Solubility index of the spray-dried powder covered in the range of 70.30% to 95.10%, also mentioned in Table 2. Powders with more porous structures generally exhibit greater

water solubility. Statistical analysis confirmed that the variety of carrier agents significantly impact the solubility of the powders ($p < 0.05$). The treatment T1(MD) had maximum solubility, while treatment T4 (WPC) had the lowest. Existing literature suggests that bulk density and solubility are negatively correlated with protein-protein interactions enhancing solubility [6]. In this variation, the same patterns have been detected in the crystal structure of the powder and the higher structure of the polar functional group in maltodextrin and gum arabic. The higher value of solubility obtains with low moisture and particle size decrease [15]. Analogous trends have been found in earlier investigation by ([41]; [27]; [34]). This property is crucial for assessing the wettability and dispersibility of spray-dried powders ([12]; [16]). Additionally, particle size influenced solubility, with smaller particles offering a larger surface area, resulting in increased contact with the continuous phase and resulting in higher solubility [27].

Hygroscopicity

High hygroscopicity increase the tendency of the product to become sticky, which can negatively affect its structural integrity and reduce overall stability during storage [15]. Capacity of food products to draw water content from their environment, it called as hygroscopicity, is a key characteristic that influences both their quality parameters and long-term storage durability [34]. Powder with hygroscopicity values exceeding 20% is consider as hygroscopic in nature [15]. Generally, powder containing low hygroscopicity and high solubility are preferred for quality purpose. Hygroscopicity of mixed berry juice powder obtained with different carries found between 15.88 to 25.16g/100g of dry solids (Table 2). In spray-dried powder moisture absorption properties were statistically demonstrated ($p < 0.05$) based on the carriers used in the formulated solution. Powder obtained from treatment T2 (GA) exhibited highest hygroscopicity, likely because of the increase of existence of hydrophilic group in maltodextrin and gum arabic, which enable more effective moisture absorption from the air. That conclusion accords with the results by [29]. Conversely, powder obtained from treatment T4 (WPC) demonstrated the lowest hygroscopicity. This occurrence might be in relation to the capability of the protein to form a barrier around the particles, resulting in reduced hygroscopicity [32]. Parallel result was reported by ([34]; [6]; [39]). Additionally, the combined effect of carrier aids in formulation T3(MD:GA) also significantly influenced the hygroscopicity values($p < 0.05$).

Dispersibility

Dispersibility refers to the ability of hydrated, mixed particles to disperse when they are exposed to solvents [6]. This characteristic is crucial for determining whether a powder can be classified as instant. According to [35], the acceptable dispersibility range for food powder is between 73.71% and 95.32% (Table 2). The mixed berry juice powder in this study exhibited good dispersibility, ranging from 70.97% to 95.79% [34] meeting the standards for acceptable food powders. Different carrier agent emerges as determinant of spray-dried powder dispersibility. Specifically, the powder produced using whey protein concentrate (T4) exhibited the lowest dispersibility, whereas maltodextrin (T1) resulted in the highest dispersibility. Notably, the maximum dispersibility observed in this research, was a statistically significant reduction in particle size reported. For mixed berry juice powder as noted by [34], the dispersibility occurrence is closely related to particle size [6];

Particles of greater size show better dispersibility compared to smaller particles. In this research, maltodextrin was led to the formation of larger particles. A comparable observation was documented in previous research by [6] investigating bottle gourd juice powder.

Flowability characteristics of spray-dried mixed berry juice powder

Carr's index and the Hausnar ratio

Powders with good flow characteristics typically exhibit Carrs indices (CI) below 15% and Hausner ratio below 1.25[6]. The flowability of powder can be determined based its their tapped and bulk density values [25]. CI and HR are parameters determined through experimental observation that correlate bulk and tapped density to assess powder flowability [21]. The average reading of Carrs and Hausnar ratios of mixed berry juice powder was found within the range of 24.36% to 35.09% and 1.53 to 1.32, indicating moderate flowability and cohesiveness in the case of mixed berry juice powder. Table 2 shows the significant difference between CI and HR values. The highest reading of CI and HR was observed in treatment T4, and the lowest reading of CI and HR was found in treatment T3. It noted that the high cohesion and poor flowability as observed by [31] and [21] are likely attributable to elevated moisture content, which facilitates particle aggregation and increased flow resistance. The combined effect occurred when combining carrier agents to achieve optimal powder flow properties [6]. Powders produced using MD: GA (T3) exhibited lower Carr Indices (CI) and Hausner Ratios (HR) compared to those produced using other treatments. The MD:GA (T3) combination, resulted in a more notable decrease in CI and HR readings, showing that the improved flowability and reduced cohesive strength. Similar findings were shown in ([21]; [34]; [31]).

Particle Size

Particle size significantly impacts powder properties, affecting its stability, storage, flow, bendability, and compaction. Particles that are smaller have a greater surface area, leading to increased moisture absorption and a greater tendency to agglomerate given by [6]. The average size of spray-dried particle can reach up to 50 μm and larger particle offer better protection for sensitive bioactive compound [15]. The mean value of mixed berry juice powder from 10.69 to 11.35 μm . The significantly larger particle size ($p < 0.05$) observed in values of mixed berry juice powder. The significantly larger particle size ($p < 0.05$) observed in powders produced using (T1) among all the carrier agents may be attributed to MD's higher viscosity, leading to larger droplet formation during atomization [34] and lowest values was observed in (T4) due to protein denaturation which results in quick breakdown and the formulation of irregular, small sized particle.

Functional characteristics of spray-dried mixed berry juice powder

TAC and TPC

Anthocyanins and phenolic compounds are vital bioactive components obtained in mixed berry [34]. However, these compounds are notably unsteady and very susceptible because of the process of spray drying [35]. Therefore, it is crucial to preserve these phytochemicals throughout the drying process [8]. Deterioration of photochemical reaction rate is influenced by several parameters, including air flow, temperature, feed flow, and the variety and concentration of carrier types used.

The retention of both total phenolics and anthocyanins in spray-dried mixed berry juice powder was significantly influenced by the choice of carrier agent used during processing. The treatments with maltodextrin and gum arabic in combination (MD:GA) consistently showed the highest values for both TPC (270.85 g GAE/100g) and TAC (239.66 g GAE/100g). This combination improved spray drying efficiency and protected both classes of bioactive compounds in the powder, likely due to enhanced encapsulation and stabilization effects.

By contrast, powders produced with T4 (WPC) had lower TPC and TAC (175.69 g GAE/100g) values, which is possibly attributed to greater particle shrinking, higher moisture content, increased hygroscopicity, and thus weaker phenolic and anthocyanin stability over storage. These physical changes create unfavorable conditions for the preservation of sensitive compounds. The results also showed that gum arabic alone preserved phenolics and anthocyanins comparably well to the MD:GA blend, with maltodextrin alone supporting intermediate retention and WPC the lowest. Similar trends for phenolic and anthocyanin retention depending on carrier choice have been observed in spray-dried powders similar result was found in ([27]; [6]; [5]) for pineapple powder, bottle gourd juice, and chokeberry juice powder.

Antioxidant Activity

Antioxidant active compound helps to protect cells by neutralizing damaging free radicals. Their effectiveness is often tested using DPPH, a stable free radical that loses its reactivity when it reacts with an antioxidant [11]. In this research, the antioxidant activity of mixed berry powder was obtained with DPPH procedure, with results detailed in Table 2. The DPPH scavenging potential of the spray-dried mixed berry juice powder ranged from 62.28% to 76.23%. The various carriers significantly ($p < 0.005$) influenced the radical scavenging capacity of the spray-dried powder. Specifically, highest antioxidant activity (76.23%) was noted in the powder generated during treatment T3 (MD:GA) is due to the synergistic effect of these carriers. Maltodextrin reduces viscosity and improves drying efficiency, while gum arabic forms a protective encapsulating layer that preserves heat-sensitive antioxidants and prevents oxidative degradation during drying. This combination enhances the retention and stability of antioxidant compounds in the powder. While treatment T4 (WPS) demonstrated the lowest antioxidant activity at 62.23% because of it may not bind well with polyphenols, which expose antioxidant during drying also not strong protective layer which important for sensitive compound. Gum arabic also showed high antioxidant values [34]. Comparable observation was reported by [9] for spray-dried wild Andean blueberries for powdered juice.

Color of spray-dried mixed berry juice powder

The color of the mixed berry juice powder has a considerable influence on the restored juices hue, a quality attribute that significantly affects the visual and is important for customer acceptance [24];[26];[5]. In this research, the L^* (Lightness), a^* (redness/greenness), and b^* (yellowness/blueness) readings for spray-dried mixed berry juice powder were found to range from 69.164 to 69.439, 5.509 to 11.752, and -0.87 to -2.062, respectively (Table 2). These values consistently place the sample within the fourth quadrant of Cartesian coordinate system due to the distinctive maroon red color of anthocyanins, the primary pigments responsible for the color of the berry fruit.

The obtained color of the spray-dried mixed berry juice powder was significantly changed with different carriers ($P < 0.005$). A lower L^* value indicates a darker powder, suggesting a higher anthocyanin retention. Within the treatments, the powder obtained by using T3 (MD:GA) exhibited the lowest L^* value, while the powder from T2 (GA) showed the lowest b^* value, indicating a dark purple hue. This color retention can be ascribed to the reduced deterioration of polyphenols at the powders surface, because of the protective qualities of gum arabic as a binding agent. Additionally, the intrinsic color of gum arabic itself may also affect the final product's color properties [32].

In contrast, treatment T4 (WPC) showed higher L^* and lower a^* values, indicating a lighter color, which may be attributed to the lower degree of color change in the protein-based carrier [15]. Similarly, it showed increased lightness with WPC addition. Treatments T1 (MD) and T4 (WPC) displayed elevated a^* and b^* readings, signifying significant redness. This observation may be linked to browning processes while drying, notably non-enzymatic browning such as Maillard reaction and caramelization [27].

Conclusions

Spray-dried mixed berry juice powder produced by using various carrier agents exhibited moisture content ranging from 2.26% to 4.61% (w.b.), which is low enough to maintain microbiological stability. Research findings showed that the maximum yield was obtained using whey protein concentrate (WPC) as the carrier agent. While the samples containing maltodextrin (MD) demonstrated excellent reconstitution properties, their functional qualities were comparatively lower. The optimal powder characteristics, including elevated bulk and tapped density, were observed with the maltodextrin and gum arabic combination. Samples containing gum arabic (GA) preserved more color, and functional characteristics. Overall, the combination of MD and GA emerged as an effective carrier, enhancing the powder's physical characteristics, rehydration, color, and functional qualities. Research findings highlight the crucial role of carrier selection in evaluating physicochemical characteristics of spray-dried mixed berry juice powder.

Conflict of interest: The authors declare no conflicts of interest.

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