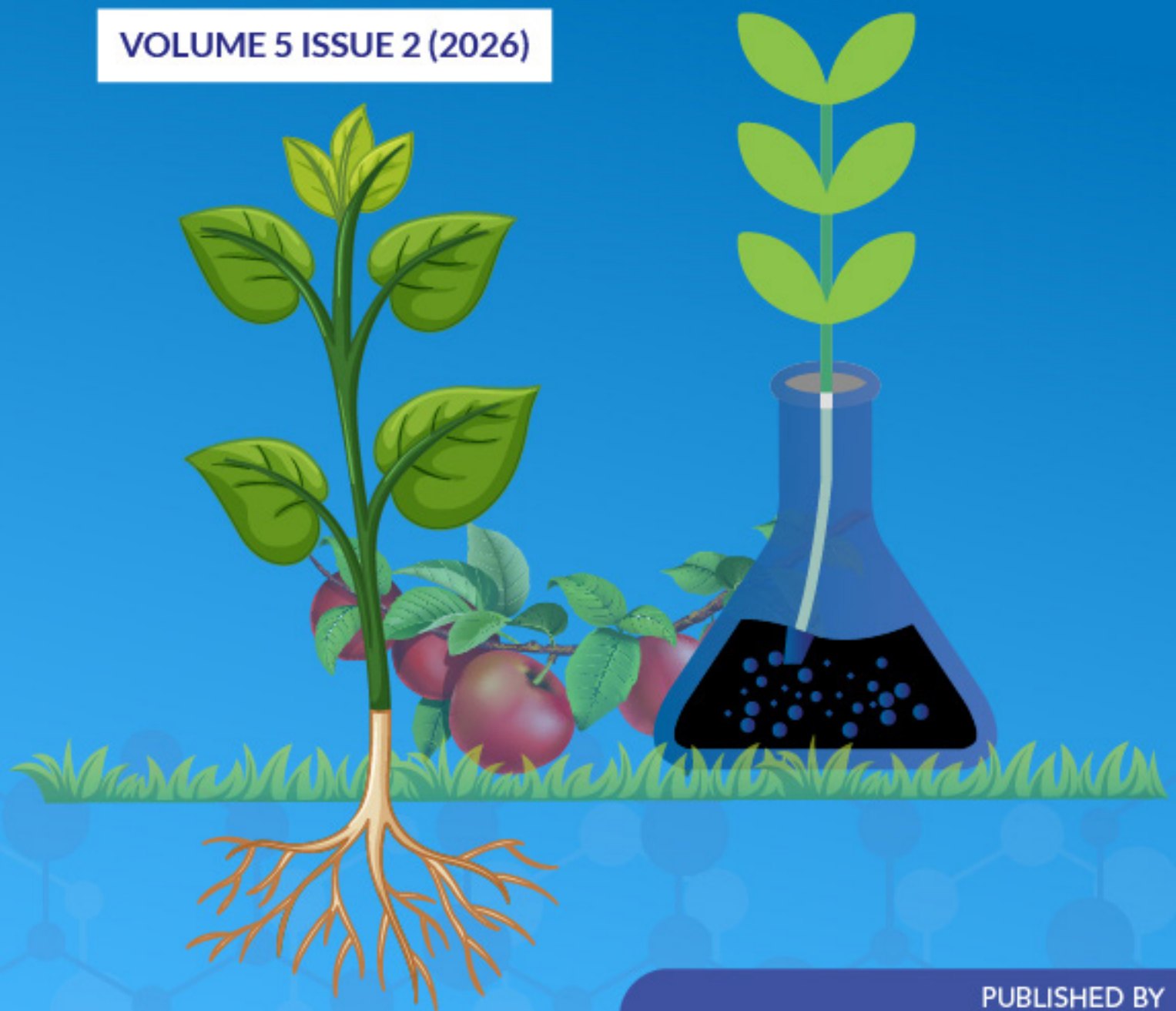




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Effect of Freeze-Drying on the Proximate Composition and Functional Properties of Watermelon-Orange-Mango Fruit Puree Composite Powder

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ABSTRACT

Watermelon, orange and mango are highly perishable tropical fruits with considerable nutritional value, but their high moisture content limits their storage stability and contributes to postharvest losses. This study investigated the effect of freeze-drying on the proximate composition and functional properties of watermelon–orange–mango composite fruit puree powder. I prepared and evaluated six composite puree formulations with different proportions of watermelon (*Citrullus lanatus*), sweet orange (*Citrus sinensis*), and mango (*Mangifera indica* L.) for sensory acceptability using a 9-point hedonic scale. The most acceptable formulation, coded 618 and consisting of 50% watermelon, 30% orange and 20% mango, was selected for freeze-drying. The proximate composition and selected functional properties of the fresh puree and resulting freeze-dried fruit powder (FDFP) were subsequently determined using standard analytical procedures. Formulation 618 recorded the highest overall acceptability score (7.72 ± 1.208), and was therefore selected for further processing. Freeze-drying markedly reduced moisture content from $83.45 \pm 3.34\%$ in the fresh puree to $3.55 \pm 3.34\%$ in the FDFP, while ash, protein, crude fibre, fat and carbohydrate contents increased from 0.74, 0.96, 0.74, 0.50 and 13.61%, respectively, in the fresh puree to 2.76, 4.39, 2.89, 0.78 and 85.63% in the FDFP. Freeze-drying also reduced bulk density, specific gravity and viscosity from 1.11 to 0.89 g/cm³, 1.13 to 0.92 and 3.84 to 1.53 cP, respectively. In contrast, water-holding capacity increased from 83.74 to 93.03%, whereas oil-holding capacity decreased from 27.01 to 18.03%. Overall, freeze-drying effectively transformed the highly perishable composite puree into a low-moisture fruit powder with substantially modified proximate composition and functional characteristics. The resulting powder has potential as a shelf-stable fruit ingredient for incorporation into beverages and other food products.

INTRODUCTION

Fruits are important components of healthy diets because they provide carbohydrates, dietary fibre, vitamins, minerals and a wide range of phytochemicals. Tropical fruits are particularly valuable as sources of nutrients and bioactive compounds, but their high moisture content, active metabolism and susceptibility to microbial deterioration make them highly perishable commodities. Consequently, rapid deterioration after harvest can result in substantial quantitative and qualitative losses, particularly where cold-chain infrastructure, processing facilities and appropriate storage systems are limited. Postharvest losses of tropical fruits are therefore not only a food-preservation problem but also an important economic and food-security concern. Evidence from the Nigerian orange value chain, for example, indicates that inadequate handling and storage facilities contribute substantially to postharvest losses (Obayelu *et al.*, 2022). Processing fruits into shelf-stable products such as powders can reduce the dependence on continuous refrigeration while facilitating transportation, storage and year-round utilization.

Watermelon (*Citrullus lanatus*), sweet orange (*Citrus sinensis*) and mango (*Mangifera indica* L.) are nutritionally complementary tropical fruits with considerable potential

for composite-product development. Watermelon is characterized by very high moisture content and provides lycopene, β -carotene, vitamin C, potassium and the non-protein amino acid L-citrulline. Recent literature continues to identify watermelon as an important dietary source of L-citrulline and other constituents of potential nutritional interest (Baião *et al.*, 2025). Sweet orange contributes vitamin C, flavonoids, phenolic compounds, carotenoids and organic acids, while mango provides carbohydrates, vitamins A and C, carotenoids, phenolic compounds, flavonoids and other phytochemicals (Yahia *et al.*, 2023). The diverse phytochemical profile of *Citrus sinensis* has been associated particularly with flavonoids, phenolic acids, carotenoids and other secondary metabolites (Zahr *et al.*, 2023). Similarly, the nutritional and phytochemical characteristics of mango include carotenoids, phenolic compounds, flavonoids, vitamins and minerals, making the fruit a valuable ingredient for nutritionally enriched food products (Yahia *et al.*, 2023).

Combining watermelon, orange and mango into a composite puree provides an opportunity to exploit the complementary nutritional, physicochemical and sensory characteristics of the three fruits. The proportions of individual fruits in a composite formulation can influence sweetness, acidity, colour, aroma, viscosity, consistency

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and overall acceptability. Thus, sensory optimization is an important preliminary step before selecting a composite formulation for dehydration. In the present study, six watermelon–orange–mango puree combinations were evaluated, with formulation 618, comprising 50% watermelon, 30% orange and 20% mango, identified as the most acceptable formulation and subsequently selected for freeze-drying. This approach is consistent with the principle that the development of fruit powders should consider not only nutritional composition but also the sensory and technological characteristics of the starting material.

Drying is one of the principal approaches used to improve the stability of fruits by reducing moisture availability and, consequently, the conditions required for microbial proliferation and many deteriorative reactions. However, the drying method can substantially influence the nutritional, physical, functional and sensory quality of the resulting product. Conventional thermal drying may cause undesirable changes in colour, texture, volatile compounds and heat-sensitive nutrients because of prolonged exposure to elevated temperatures. Reviews of fruit-drying technologies consequently emphasize the importance of selecting drying conditions according to the characteristics of the raw material and the quality attributes required in the final product (Sagar & Suresh, 2010; Yao *et al.*, 2023).

Freeze-drying, or lyophilisation, is particularly attractive for high-value and heat-sensitive food materials because water is removed predominantly by sublimation from a frozen product under reduced pressure. The process therefore substantially reduces the exposure of the product to the high temperatures normally associated with conventional dehydration. Recent reviews indicate that freeze-drying can preserve colour, microstructure, nutritional constituents and rehydration characteristics more effectively than many conventional drying processes, although its long processing time, high energy requirement and relatively high production cost limit widespread industrial application (Ma *et al.*, 2023; Salehi, 2023; Yao *et al.*, 2023). Freeze-drying can also generate a porous dried structure, which may improve water penetration and reconstitution of the resulting powder. Importantly, the effect of freeze-drying on food composition cannot be interpreted simply as either “nutrient loss” or “nutrient preservation.” Removal of a large proportion of water increases the concentration of non-water constituents when results are expressed per 100 g of product. At the same time, individual nutrients and phytochemicals may undergo degradation or changes in extractability during freezing, sublimation and subsequent storage. Ma *et al.* (2023) emphasized that freezing itself can influence phenolic compounds, while prolonged drying may affect compounds such as ascorbic acid and anthocyanins. Therefore, apparent increases in nutrient concentration following freeze-drying should be distinguished from true nutrient retention, particularly when fresh and dried samples are compared on a product-

weight rather than dry-matter basis.

The production of fruit powder also requires consideration of functional properties because these characteristics determine how the powder behaves during handling, storage, reconstitution and incorporation into other foods. Properties such as bulk density, specific gravity, water-holding capacity, oil-holding capacity, wettability, solubility and related hydration characteristics are influenced by moisture content, particle structure, porosity, fibre and carbohydrate composition. Drying can modify the physical structure of plant tissues and thereby alter the interaction between the powder and water or oil. Reviews of dried fruit products have consequently identified porosity, rehydration, water interaction and structural changes as important quality characteristics for evaluating dried fruit materials (Serna-Cock *et al.*, 2015; Fu *et al.*, 2022).

Despite the considerable literature on drying individual fruits, information remains comparatively limited on the combined effect of freeze-drying on the proximate composition and functional properties of watermelon–orange–mango composite puree powders, particularly using locally available fruit varieties in Nigeria. Previous work has examined the drying behaviour and quality of individual fruit products, while comparatively fewer studies have addressed the interaction of these three fruits in a composite powder system. The present study was therefore designed to produce a watermelon–orange–mango composite fruit powder by freeze-drying and evaluate changes in proximate composition and functional properties. Specifically, individual and composite fruit purees were characterized, sensory evaluation was used to select the most acceptable formulation, the selected composite puree was freeze-dried, and the proximate composition and functional properties of the fresh and freeze-dried materials were compared. The study consequently provides information relevant to the development of value-added, shelf-stable fruit ingredients from locally available tropical fruits.

Justification of the study

The present study was designed to formulate watermelon–orange–mango composite fruit purees, evaluate sensory acceptability of different blend ratios, select the most preferred formulation for freeze-drying, produce freeze-dried composite fruit powder, and determine the effects of freeze-drying on proximate composition and functional properties. The research provides scientific evidence regarding the suitability of freeze-drying as a preservation technology for locally available tropical fruits and contributes to efforts aimed at reducing postharvest losses through value-added processing.

The findings are expected to benefit food scientists, nutritionists, product developers, and food-processing industries by providing information on the development of shelf-stable composite fruit powders that can be incorporated into beverages, complementary foods, bakery products, confectioneries, dairy products, and

other functional food formulations. The study also supports sustainable utilization of abundant tropical fruits in Nigeria and contributes to improved dietary diversity and food security through innovative fruit-processing technologies.

Aim and Objectives of the Study

Aim

The aim of this study was to produce watermelon–orange–mango composite fruit powder by freeze-drying and evaluate the effect of the process on its proximate composition and functional properties.

Objectives

The specific objectives of the study were to:

1. Produce individual and composite watermelon, orange and mango fruit purees and determine their proximate composition and functional properties.
2. Evaluate the sensory acceptability of the formulated watermelon–orange–mango composite purees and select the most acceptable formulation for freeze-drying.
3. Produce powder from the selected watermelon–orange–mango composite puree using freeze-drying under specified processing conditions and evaluate its proximate composition and functional properties.
4. Determine and compare the proximate composition and functional properties of the fresh composite puree and freeze-dried composite fruit powder in order to evaluate the effect of freeze-drying on their proximate composition and functional properties.

Scope of the Study

This study was limited to the development of watermelon (*Citrullus lanatus*), orange (*Citrus sinensis*) and mango (*Mangifera indica* L.) individual and composite fruit purees and their conversion into fruit powder by freeze-drying. The study covered the determination of the proximate composition and functional properties of the individual fruits and formulated composite purees, sensory evaluation of the composite formulations, and selection of the most acceptable formulation for freeze-drying. The selected composite puree was subsequently freeze-dried under specified processing conditions to produce fruit powder, which was evaluated for its proximate composition and functional properties.

The study was restricted to the selected watermelon, orange and mango fruits, the formulated composite puree proportions, the sensory attributes evaluated, the specified freeze-drying conditions, proximate composition and functional parameters included in the experimental analyses. Physicochemical profiling, antioxidant activity and other quality characteristics not specified in the study objectives were outside the scope of the study.

LITERATURE REVIEW

Nutritional and Functional Importance of Watermelon, Orange and Mango Watermelon (*Citrullus lanatus*)

Watermelon is a high-moisture fruit belonging to the

Cucurbitaceae family and is widely consumed because of its characteristic sweetness, refreshing flavour and high water content. Its nutritional importance extends beyond its water content because the fruit contains carotenoids, vitamin C, minerals, phenolic compounds and L-citrulline. Lycopene is particularly important in red-fleshed watermelon and is responsible for much of the characteristic red colour of the fruit. Watermelon is also recognized as one of the principal dietary sources of L-citrulline, a non-protein amino acid involved in nitric oxide metabolism and associated with vascular and cardiometabolic research (Burton-Freeman *et al.*, 2021; Baião *et al.*, 2025).

The high moisture content that contributes to the desirable refreshing characteristics of watermelon simultaneously limits its storage stability. Consequently, dehydration is an important strategy for converting watermelon into a more stable ingredient. Reduction of moisture can decrease water availability and facilitate the production of powders that can be transported, stored and incorporated into other food products. The challenge, however, is to achieve adequate moisture removal while minimizing undesirable changes in colour, flavour, nutrients and functional properties.

Sweet Orange (*Citrus sinensis*)

Sweet orange is an important citrus fruit characterized by a substantial content of vitamin C, organic acids, soluble sugars, flavonoids, phenolic compounds and carotenoids. Its phytochemical profile is complex and includes flavonoids, phenolic acids, limonoids and other secondary metabolites. An updated review of *Citrus sinensis* identified phenolic acids, flavonoids and essential-oil constituents among the important chemical components associated with the biological characteristics of the species (Zahr *et al.*, 2023).

The combination of acidity, sweetness, aroma and colour makes orange particularly suitable for blending with other fruit purees. In a composite formulation, orange can contribute acidity that balances sweetness and can modify the sensory profile of the final product. Nevertheless, orange pulp and juice are highly perishable and can undergo quality deterioration during storage. Processing into a powder therefore provides an opportunity to extend utilization beyond the fresh-fruit period.

Mango (*Mangifera indica* L.)

Mango is a nutritionally important tropical fruit with substantial amounts of carbohydrates, vitamins, minerals, carotenoids and phenolic compounds. The composition varies with cultivar, maturity and environmental conditions. Yahia *et al.* (2023) described mango as a source of macronutrients, vitamins A and C, minerals, carotenoids, phenolic compounds, flavonoids and volatile constituents. Mangiferin and other phenolic compounds have attracted considerable research attention because of their biological activities and potential contribution to the functional value of mango products.

Mango also possesses desirable technological

characteristics for fruit-puree production because its pulp provides sweetness, colour, viscosity and characteristic aroma. These properties can complement the high-moisture and relatively mild flavour profile of watermelon and the acidity and aroma of orange. However, mango is also highly susceptible to ripening-associated changes, softening and deterioration, making value-added processing important for extending its utilization.

Composite Fruit Purees as a Food-Product Development Strategy

The formulation of composite fruit products allows different raw materials to be combined to obtain desirable nutritional, sensory and technological characteristics. In contrast to single-fruit products, composite formulations can provide a broader range of nutrients and phytochemicals and can permit the adjustment of sweetness, acidity, colour, aroma and consistency. The relative proportions of the component fruits are therefore important determinants of product quality.

For watermelon–orange–mango formulations, the three fruits provide complementary characteristics. Watermelon contributes high moisture, natural sweetness and lycopene/L-citrulline; orange contributes acidity, vitamin C and citrus flavonoids; while mango contributes carotenoids, sweetness, colour, aroma and pulp solids. The resulting composite formulation may consequently possess a more balanced sensory and nutritional profile than any single component. However, such benefits depend on the proportions used, since excessive inclusion of one fruit can alter acidity, sweetness, viscosity, colour or aroma.

Sensory evaluation is therefore essential in the optimization of composite fruit formulations. The use of a hedonic scale provides a means of determining the relative consumer or panel acceptability of alternative formulations before committing resources to subsequent processing. In the present study, six formulations were assessed and the 50:30:20 watermelon–orange–mango formulation was selected as the most acceptable. The use of sensory optimization before freeze-drying is particularly relevant because drying can modify the physical characteristics and flavour perception of fruit products.

Freeze-Drying of Fruits and Fruit Purees

Freeze-drying involves freezing the food material followed by removal of ice primarily through sublimation under reduced pressure. The process generally consists of freezing, primary drying and secondary drying. During primary drying, ice is sublimated, whereas secondary drying removes more strongly associated moisture. Because the product remains at relatively low temperatures compared with many conventional drying methods, freeze-drying is particularly suitable for heat-sensitive food materials.

Bhatta *et al.* (2020) identified freeze-drying as an important technology for plant-based foods because of

its capacity to preserve quality while producing porous products. More recent reviews have similarly emphasized the capacity of freeze-drying to retain colour, structure and nutritional quality while improving rehydration characteristics (Ma *et al.*, 2023; Salehi, 2023; Yao *et al.*, 2023). The formation of ice crystals during freezing and their subsequent sublimation produces pores within the dried matrix. These pores can facilitate rapid penetration of water during reconstitution.

Nevertheless, freeze-drying is not universally protective. The freezing stage itself can cause cellular disruption and changes in the distribution or extractability of compounds. Ma *et al.* (2023) noted that freeze-drying may cause either degradation or enhanced release of phenolic constituents depending on the characteristics of the food matrix and processing conditions. Thus, the final composition of a freeze-dried product represents the combined effects of freezing, sublimation, matrix disruption, concentration and possible degradation reactions.

Another important limitation of freeze-drying is its high energy consumption and relatively long processing time. Yao *et al.* (2023) reported that freeze-drying can require substantially more energy than hot-air drying. Salehi (2023) similarly emphasized the continuing research interest in improving freeze-drying efficiency through technological modifications and combination with other drying approaches. Consequently, the principal justification for freeze-drying is generally linked to the higher quality of the resulting product rather than low processing cost.

Effect of Freeze-Drying on Proximate Composition

Proximate composition provides an overall assessment of major food components, commonly including moisture, ash, crude protein, crude fat, crude fibre and carbohydrate. Drying can cause major changes in the measured concentration of these components because removal of water changes the mass basis on which the results are expressed. Consequently, a dried product may show apparently higher concentrations of ash, protein, fibre and carbohydrate per 100 g even where the absolute quantity of the individual constituent has not increased. The reduction in moisture is the principal compositional consequence expected from freeze-drying. A low moisture content is desirable because it reduces the amount of water available for microbial proliferation and many chemical and enzymatic reactions. Reviews of freeze-dried foods consistently identify moisture reduction as a central mechanism through which drying improves stability (Ma *et al.*, 2023; Yao *et al.*, 2023).

The apparent concentration of protein, fibre, ash and carbohydrate following dehydration should therefore be interpreted carefully. Caparino *et al.* (2012), in their investigation of mango powders produced using different drying methods, demonstrated that drying method substantially affects the physical properties and microstructure of fruit powders. Changes in the measured concentration of nutrients can arise from water

removal as well as from differential losses or changes in extractability during processing.

Fat may behave differently because lipid oxidation can occur during processing and storage, while the relative concentration of lipid may also change because of moisture removal. Therefore, changes in crude fat between fresh and freeze-dried products should not automatically be interpreted as destruction of lipids. They may reflect the combined influence of concentration, analytical basis, oxidation and matrix changes.

Effect of Freeze-Drying on Functional Properties

Functional properties determine how food powders interact with water, oil and other ingredients and are consequently important for their application in beverages, bakery products, dairy formulations and other food systems. Bulk density, specific gravity, water-holding capacity and oil-holding capacity are among the properties commonly used to characterize dried food powders.

Freeze-drying can substantially alter powder structure because sublimation of ice creates a porous matrix. Such porosity may reduce apparent density and increase the ability of water to penetrate the powder. Serna-Cock *et al.* (2015) identified porosity, water interaction and rehydration capacity as important consequences of freeze-drying fruit materials. More recent reviews have likewise reported that mild drying technologies such as freeze-drying can produce low-density products with relatively high rehydration capacity (Reis *et al.*, 2022).

Water-holding capacity describes the ability of a food material to retain water within its structure. It is affected by dietary fibre, proteins, polysaccharides, particle structure and the availability of hydrophilic groups. Freeze-drying may expose or alter such groups through cellular disruption and formation of a porous structure, thereby modifying water interaction. Conversely, changes in particle size, surface characteristics and matrix collapse can reduce water uptake in some materials. Thus, the direction and magnitude of change depend on the composition of the fruit and the specific freeze-drying conditions.

Oil-holding capacity is similarly influenced by surface characteristics, porosity, fibre and protein composition. The development of a porous matrix can create sites capable of retaining oil, although structural collapse or changes in the accessibility of hydrophobic regions may produce different responses. Functional-property measurements are therefore useful because they provide information that cannot be obtained from proximate composition alone.

Freeze-Dried Fruit Powders as Value-Added Food Ingredients

Fruit powders provide several technological advantages over fresh fruit. Their lower moisture content facilitates storage and transportation, while their concentrated solids can permit incorporation into a variety of food formulations. Fruit powders can be used in beverages,

bakery products, dairy foods, confectionery products, complementary foods and other formulations in which fruit flavour, colour and nutritional constituents are desirable.

Freeze-drying is particularly relevant where preservation of quality is more important than minimizing processing cost. The resulting porous structure can favour rapid rehydration, while the relatively low processing temperature can reduce thermal damage to sensitive constituents. However, the quality of a freeze-dried powder is not determined by drying alone; raw-material composition, freezing conditions, drying temperature, vacuum, final moisture content, packaging and storage conditions can all affect stability.

Recent research continues to investigate ways of improving freeze-drying efficiency without sacrificing product quality. Yao *et al.* (2023) reviewed several physical technologies for enhancing freeze-drying efficiency, while Salehi (2023) discussed technological developments intended to shorten drying time and reduce energy consumption. These developments demonstrate that freeze-drying remains relevant for premium-quality fruit ingredients despite its comparatively high processing cost.

Research Gap

Although freeze-drying of individual fruits such as mango and other tropical fruits has been investigated, substantially less information is available on the combined proximate and functional characteristics of watermelon–orange–mango composite powders. Existing literature has often emphasized single-fruit systems, phytochemical retention, antioxidant properties or physical characteristics, whereas fewer studies have simultaneously considered the proximate composition and functional behaviour of a composite puree before and after freeze-drying.

This gap is important because blending watermelon, orange and mango produces a matrix containing different concentrations of sugars, organic acids, fibre, pigments, proteins, minerals and other constituents. These components may interact differently during freezing and sublimation, meaning that observations from single-fruit powders cannot necessarily be extrapolated directly to the composite system. The recently reported freeze-drying work on watermelon–orange–mango composite powder demonstrates the relevance of this product system, but further characterization of its proximate and functional properties is necessary to establish how freeze-drying modifies the food matrix (Ankeli & Kundam, 2026).

Accordingly, the present study focuses specifically on the proximate composition and functional properties of watermelon–orange–mango composite puree and its freeze-dried powder. The study first characterizes the individual and composite purees, uses sensory evaluation to select the most acceptable formulation, produces a powder from the selected formulation by freeze-drying, and finally compares the fresh and freeze-dried materials. The resulting information is intended to contribute to

the scientific basis for developing stable, value-added composite fruit powders from locally available tropical fruits.

MATERIALS AND METHODS

Materials

Fresh, fully mature watermelon (*Citrullus lanatus*), sweet orange (*Citrus sinensis*), and mango (*Mangifera indica* L.) fruits were purchased from Railway Market, Makurdi, Benue State, Nigeria. Fruits were selected based on uniform maturity, freedom from visible defects, and absence of microbial spoilage or mechanical damage. All chemicals and reagents used for laboratory analyses were of analytical grade and obtained from standard laboratory suppliers.

Methods

Study Location

The experimental work was carried out in the Food Science and Technology Laboratory, University of Mkar, Mkar, Benue State, Nigeria. Botanical identification and cultivar authentication of the fruit samples were conducted at the Department of Horticulture, Joseph Sarwuan Tarka University, Makurdi, Benue State, Nigeria.

Preparation of Individual Fruit Purees

Fresh fruit purees were prepared separately following standard fruit processing procedures with slight modifications from previously published methods. The general flow chart for fruit puree production is shown in Figure 1 using the method described by Mateescu *et al.*

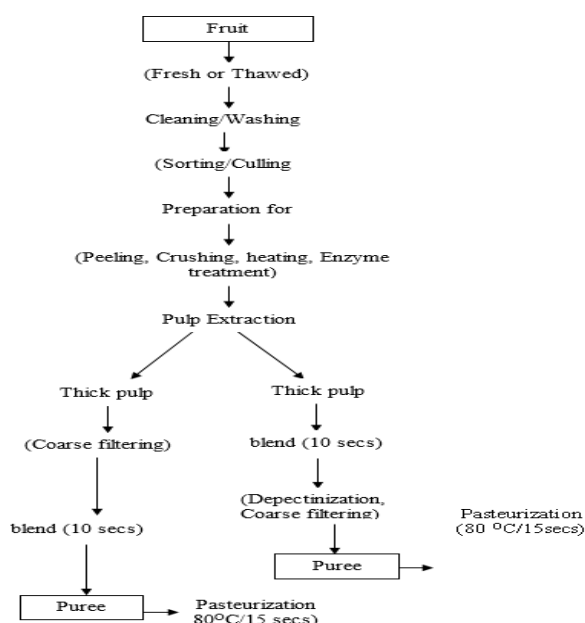


Figure 1: General flow for fruit puree production

Source: Mateescu *et al.* (2022)

(2022). The analyses of the nutrients were performed on the purees 30 min after production.

Preparation of Watermelon Puree

Using the method of Akinwande & Ojo (2023) watermelon fruits were sorted to remove bruised and damaged fruits, washed thoroughly under running potable water, and manually peeled using stainless-steel knives. The seeds were removed and the edible flesh was cut into small cubes before blending with a household electric blender (Kenwood, United Kingdom) for approximately 15 s to obtain a homogeneous puree. The puree was pasteurized at 70°C for 15 s, immediately cooled in an ice bath, and stored under refrigeration at approximately 4°C until composite formulation.

Preparation of Orange Puree

According to the method described by Sharma & Anand (2022), sweet oranges were washed thoroughly, manually peeled, and separated into segments. Seeds were

carefully removed before blending the pulp into a smooth puree using the same blender. The resulting puree was pasteurized at 70°C for 15 s, rapidly cooled in an ice bath, and refrigerated at approximately 4°C until further use.

Preparation of Mango Puree

The method of Labaky *et al.* (2020) was adopted. In the method, mango fruits were sorted, washed, and blanched in hot water at 98°C for 5 min to facilitate peeling and reduce enzymatic activity. After blanching, the fruits were cooled under running water, peeled, and sliced into smaller pieces. The pulp was blended with 0.2 M citric acid buffer (pH 5.2) to minimize enzymatic browning and preserve colour quality. The prepared mango puree was refrigerated at approximately 4°C prior to formulation of the composite purees.

Formulation of Watermelon–Orange–Mango Composite Purees

Six composite fruit puree formulations were prepared

by blending watermelon, orange, and mango purees in different proportions. Each formulation was assigned a randomly generated three-digit identification code to eliminate panelist bias during sensory evaluation. The

formulations used are presented in Table 1.

The formulated purees were homogenized thoroughly to obtain smooth and uniform mixtures before sensory evaluation. The formulation with the highest overall

Table 1: Watermelon–Orange–Mango Composite Puree Formulations Used for Sensory Evaluation

Sample code	Puree composition (%)		
	Watermelon	Orange	Mango
573	30	50	20
618	50	30	20
335	20	50	30
804	50	20	30
732	20	30	50
408	30	20	50

acceptability (Sample 618; 50% watermelon, 30% orange, and 20% mango) was selected for spray-drying and subsequent analyses.

Sensory Evaluation of Fresh Watermelon–Orange–Mango Composite Purees

Sensory evaluation of the freshly prepared watermelon–orange–mango composite purees was conducted using 50 previously trained panelists comprising staff and students of the University of Mkar, Mkar, Benue State, Nigeria. Before the evaluation, the panelists were familiarized with the sensory attributes and scoring procedure to promote consistency in assessment.

The six composite puree formulations were dispensed into transparent disposable cups and identified using randomly assigned three-digit codes to minimize bias associated with sample identity. The samples were presented to the panelists in randomized order under similar environmental and serving conditions. Drinking water was provided for mouth rinsing between samples. The panelists evaluated the samples for appearance, aroma, taste, texture, consistency, and overall acceptability using a nine-point hedonic scale, where 9 represented like extremely and 1 represented dislike extremely.

The sensory scores were subjected to analysis of variance (ANOVA), and significant differences among treatment means were separated using Duncan's Multiple Range Test (DMRT) at $p \leq .05$. The formulation with the highest overall acceptability was selected for subsequent freeze-drying and physicochemical analyses.

Freeze drying operations

Freeze drying of the composite fruits puree was as described by Varghese *et al.* (2014) using a pilot scale freeze dryer (model: LabconcoFreeZone Triad, Freeze Dry System, Freeze Dry Ltd., Warwickshire, UK). The freeze-drying machine (with a Capacity of 18 litres of ice condensing capacity) was preheated to 50°C with an initial pressure of 0.030 mbar according to the manufacturer's instructions. The mixed fruit puree was poured into 250g capacity freezer bags, sealed and placed on freezer trays prior to loading and in the freeze-drying chamber of the

freeze dryer. The initial freezing was done to -45°C while during drying the temperature was increased up to 60°C . A vacuum of 100 mmHg was maintained during freeze drying. The process was regularly monitored to ensure proper drying. The freeze-dried composite fruit puree powder containing 2–3 % moisture was allowed to cool to room temperature. The freeze dried puffy material was then blended in a household Kenwood dry mixer for 2min and the powder packaged in air tight aluminum pouches which were then stored on dry shelves in glass desiccators containing activated silica.

Proximate Composition Analysis

The proximate composition of the fresh watermelon–orange–mango composite puree and the corresponding freeze-dried fruit powder was determined using standard procedures of the Association of Official Analytical Chemists (AOAC, 2012). The parameters analyzed were moisture, crude protein, crude fat, crude fibre, ash, total carbohydrate, and estimated energy value. All determinations were performed in triplicate.

Moisture Content

Moisture content was determined by the hot-air oven drying method. Approximately 2 g of each sample was weighed into a previously dried and weighed moisture dish. The samples were dried in a hot-air oven at 105°C to constant weight. The dishes containing the dried samples were cooled in a desiccator and reweighed. Moisture content was calculated from the loss in sample mass during drying and expressed as a percentage of the original sample weight.

Crude Protein

Crude protein was determined using the Kjeldahl method involving digestion, distillation, and titration. Approximately 0.2 g of each sample was digested with concentrated sulfuric acid in the presence of an appropriate Kjeldahl catalyst. Following digestion, the digest was neutralized with sodium hydroxide and subjected to steam distillation. The liberated ammonia was collected in boric acid solution and titrated against

standardized hydrochloric acid. The nitrogen content was calculated from the titration result and converted to crude protein using the appropriate nitrogen-to-protein conversion factor.

Crude Fibre

Crude fibre was determined by the acid digestion method. Approximately 5 g of sample was subjected to acid digestion under reflux conditions. The resulting residue was filtered and washed thoroughly to remove the digestion reagents. The residue was subsequently dried to constant weight and incinerated in a muffle furnace. Crude fibre was calculated from the loss in mass of the dried residue following ashing and expressed as a percentage of the sample weight.

Ash Content

Ash content was determined by dry ashing. Approximately 2 g of each sample was weighed into a previously dried and weighed porcelain crucible. The samples were incinerated in a muffle furnace at 550°C for 3 h. After incineration, the crucibles were cooled in a desiccator and weighed. Ash content was calculated as the percentage of the original sample weight remaining as inorganic residue after incineration.

Crude Fat

Crude fat was determined by Soxhlet solvent extraction using petroleum ether as the extraction solvent. A known quantity of each sample was subjected to continuous extraction with petroleum ether. Following extraction, the solvent was recovered by evaporation, and the extracted lipid fraction was dried to constant weight. Crude fat content was calculated as a percentage of the original sample weight.

Total Carbohydrate

Total carbohydrate content was determined by difference using the following equation:

$$\text{Carbohydrate (\%)} = 100 - [\text{Moisture (\%)} + \text{Protein (\%)} + \text{Fat (\%)} + \text{Ash (\%)} + \text{Crude fibre (\%)}]$$

The calculated value represents the carbohydrate fraction by difference and includes the non-protein, non-fat, non-fibre and non-ash components of the sample.

Estimated Energy Value

The estimated energy value was calculated using the Atwater general conversion factors of 4 kcal/g for protein, 9 kcal/g for fat, and 4 kcal/g for carbohydrate: Energy value (kcal/100 g) = $[4 \times \text{Protein (\%)}] + [9 \times \text{Fat (\%)}] + [4 \times \text{Carbohydrate (\%)}]$

The calculated energy value was expressed as kcal/100 g of sample.

Functional Properties of the Freeze-Dried Watermelon–Orange–Mango Composite Fruit Powder

The functional properties of the fresh composite puree and freeze-dried watermelon–orange–mango composite fruit powder were evaluated using established analytical

procedures. The properties determined included water absorption capacity, oil absorption capacity, bulk density, specific gravity, and viscosity.

Water Absorption Capacity

Water absorption capacity (WAC) was determined according to the method described by Onwuka (2018). One gram of sample was weighed into a previously weighed centrifuge tube and mixed with 10 mL of distilled water. The mixture was thoroughly dispersed and allowed to stand at room temperature for 1 h to permit hydration. It was subsequently centrifuged at 3,500 rpm for 30 min. The supernatant was carefully decanted, and the tube was inverted to drain excess water. The tube containing the hydrated sample was weighed, and water absorption capacity was calculated as the amount of water retained per gram of sample and expressed as g/g.

Oil Absorption Capacity

Oil absorption capacity (OAC) was determined using the method of Que *et al.* (2008), with slight modifications. One gram of sample was weighed into a centrifuge tube and mixed with 10 mL of refined soybean oil. The mixture was vortexed for 1 min and allowed to stand at room temperature for 30 min. It was then centrifuged at 4,000 rpm for 25 min. The unabsorbed oil was carefully decanted, and the amount of oil retained by the sample was determined gravimetrically. Oil absorption capacity was expressed as grams of oil retained per gram of sample (g/g).

Bulk Density

Bulk density was determined according to Onwuka (2018). Approximately 50 g of the sample was gently transferred into a 100-mL graduated measuring cylinder without compacting the powder. The cylinder was gently tapped until a constant volume was obtained. Bulk density was calculated as the ratio of the mass of the sample to the final settled volume and expressed as g/mL.

Specific Gravity

Specific gravity was determined using a 50-mL density bottle. The clean, dry density bottle was weighed and subsequently filled with the sample according to the procedure adopted for the determination. The mass and volume of the sample were used to calculate sample density. Specific gravity was calculated as the ratio of the density of the sample to the density of distilled water under the same measurement conditions.

Viscosity

Viscosity was determined using a Brookfield DV-II+ Pro viscometer (Brookfield Engineering Laboratories, USA). Approximately 250 mL of the sample, prepared at the specified concentration for viscosity determination, was transferred into the sample container. Measurement was performed using Spindle No. 2 at 150 rpm at room temperature. The viscosity reading was recorded in centipoise (cP). Measurements were performed under the same conditions for the fresh composite puree and

the reconstituted freeze-dried fruit powder to permit comparison between treatments.

Statistical Analysis

All experimental determinations were carried out in triplicate, and results were expressed as mean $\pm$ standard deviation. Data were analyzed using SPSS Version 20.0

(IBM SPSS Statistics, USA). One-way analysis of variance (ANOVA) was used to determine significant differences among treatment means, while Duncan's Multiple Range Test (DMRT) was employed for post-hoc mean separation at a significance level of $p \leq 0.05$.

RESULTS AND DISCUSSION

Table 2: Sensory attributes of the fresh mango-orange-water melon composite puree samples

Sample Codes	Appearance	Aroma	Taste	Texture	Consistency	Overall acceptability
573	7.00 $\pm$ 1.080ab	6.72 $\pm$ 1.243a	6.28 $\pm$ 1.021c	6.32 $\pm$ 1.435a	6.52 $\pm$ 1.530b	7.08 $\pm$ 1.115a
618	7.72 $\pm$ 1.060b	7.20 $\pm$ 1.251ab	7.20 $\pm$ 1.040ab	7.12 $\pm$ 1.301a	7.32 $\pm$ 1.069a	7.72 $\pm$ 1.208a
335	6.84 $\pm$ 0.943b	7.00 $\pm$ 1.154ab	7.08 $\pm$ 1.222ab	6.40 $\pm$ 2.020a	7.08 $\pm$ 1.382ab	7.20 $\pm$ 1.208a
804	6.88 $\pm$ 1.201b	7.52 $\pm$ 0.770b	7.48 $\pm$ 1.084a	6.76 $\pm$ 1.984a	6.88 $\pm$ 1.268ab	7.52 $\pm$ 1.357a
732	7.24 $\pm$ 1.640ab	6.96 $\pm$ 1.206ab	6.92 $\pm$ 1.288abc	7.04 $\pm$ 1.428a	7.12 $\pm$ 0.781ab	7.64 $\pm$ 1.036a
408	7.44 $\pm$ 1.193ab	6.80 $\pm$ 1.374ab	6.64 $\pm$ 1.350ab	7.12 $\pm$ 0.971a	6.92 $\pm$ 1.037ab	7.12 $\pm$ 1.266a

Values are mean $\pm$ standard deviation (SD) of triplicate determinations. Samples with different superscripts within the same column were significantly ($p < 0.05$) different.

Key:

573 = 20% mango, 50% orange, 30% watermelon

*618 = 20% mango, 30% orange, 50% watermelon

335 = 30% mango, 50% orange, 20% watermelon

804 = 30% mango, 20% orange, 50% watermelon

732 = 50% mango, 30% orange, 20% watermelon

408 = 50% mango, 20% orange, 30% watermelon

*Most Acceptable (Overall Acceptability)

Table 3 : Effect of Freeze-drying at a temperature of -45 oC and feed rate of 400 mL/h) on the Proximate composition of the fruit (composite) puree (in mg/100g)

Parameter	Fresh	Samples
		FDFP
Moisture	83.45 $\pm$ 3.34	3.55 $\pm$ 3.34a
Ash	0.74 $\pm$ 0.03	2.76 $\pm$ 0.03a
Protein	0.96 $\pm$ 0.04	4.39 $\pm$ 0.04a
Crude Fiber	0.74 $\pm$ 0.03	2.89 $\pm$ 0.03a
Fat	0.50 $\pm$ 0.02	0.78 $\pm$ 0.02a
Carbohydrate	13.61 $\pm$ 0.56	85.63 $\pm$ 0.56a

Values are mean $\pm$ standard deviation (SD) of triplicate determinations. Samples with different superscripts within the same column were significantly different ($p < 0.05$).

FDFP = Freeze-Dried Fruit Powder

All fresh and dried samples are composed of 20% mango, 30% orange, 50% watermelon freeze-dried powder

Table 4: Effect of Freeze-drying at a temperature of -45 oC and feed rate of 400 mL/h on the functional properties of the fruit (composite) puree (mg/100g)

Puree	Bulk density g/cm ³	Specific gravity	Viscosity (cP)	Water holding capacity (%)	Oil holding capacity (%)
Fresh sample	1.11a $\pm$ 0.02	1.13a $\pm$ 0.02	3.84a $\pm$ 0.04	83.74c $\pm$ 0.03	27.01a $\pm$ 0.02
FDFP	0.89c $\pm$ 0.02	0.92c $\pm$ 0.01	1.53c $\pm$ 0.03	93.03a $\pm$ 0.03	18.03c $\pm$ 0.03

Superscript letters (e.g., a, b, c) in the table indicate whether values in a column are significantly different. Different letters mean the values are significantly different, while the same letters indicate no significant difference at $P < 0.05$.

FDFP = Freeze-Dried Fruit Powder

All fresh and dried samples are composed of 20 % mango, 30 % orange, 50 % watermelon freeze-dried powder.

Discussion

Sensory Evaluation of Fresh Watermelon–Orange–Mango Composite Purees

All six watermelon–orange–mango composite purees were generally acceptable, with mean sensory scores above 6.0 on the 9-point hedonic scale. Formulation 618 (50% watermelon, 30% orange and 20% mango) recorded the highest overall acceptability score (7.72 ± 1.208) and was also highly rated for appearance, aroma, taste, texture and consistency. Its superior acceptance may be associated with the balanced contribution of watermelon sweetness, orange acidity and characteristic citrus aroma, and mango flavour and colour. Similar studies have shown that formulation and processing conditions can influence the sensory quality of fruit products intended for freeze-drying (Salvador *et al.*, 2022; Silva-Espinoza *et al.*, 2021). Although formulation 804 recorded comparatively high aroma and taste scores, its overall acceptability was lower than that of formulation 618, indicating that overall liking was influenced by the combined sensory attributes rather than by a single characteristic. Consequently, formulation 618 was selected as the most acceptable composite puree for subsequent freeze-drying and proximate and functional property analyses.

Effect of Freeze-Drying on the Proximate Composition of the Watermelon–Orange–Mango Composite Puree

Freeze-drying produced marked changes in the proximate composition of the selected watermelon–orange–mango composite puree (Table 3). Moisture content decreased substantially from $83.45 \pm 3.34\%$ in the fresh puree to $3.55 \pm 3.34\%$ in the freeze-dried fruit powder, representing approximately a 95.7% reduction. In contrast, the measured concentrations of ash, crude protein, crude fibre, crude fat and carbohydrate increased after freeze-drying. Ash increased from $0.74 \pm 0.03\%$ to $2.76 \pm 0.03\%$, crude protein from $0.96 \pm 0.04\%$ to $4.39 \pm 0.04\%$, crude fibre from $0.74 \pm 0.03\%$ to $2.89 \pm 0.03\%$, crude fat from $0.50 \pm 0.02\%$ to $0.78 \pm 0.02\%$, and carbohydrate from $13.61 \pm 0.56\%$ to $85.63 \pm 0.56\%$. Thus, the dominant pattern was a sharp reduction in moisture accompanied by an apparent concentration of the non-water components. The greatest numerical increase occurred in carbohydrate, followed by protein, crude fibre, ash and fat. The results indicate that freeze-drying effectively converted the high-moisture composite puree into a substantially lower-moisture fruit powder.

The most pronounced effect of freeze-drying was the reduction in moisture content from 83.45% in the fresh composite puree to 3.55% in the freeze-dried powder. This approximately 95.7% reduction demonstrates the effectiveness of sublimation-based dehydration in removing water from the watermelon–orange–mango matrix. Freeze-drying removes frozen water under reduced pressure through sublimation and is particularly suitable for fruit materials in which preservation of nutritional and structural quality is important. Recent reviews have consistently identified low-temperature freeze-drying as an effective approach for producing high-quality fruit

and vegetable powders because it minimizes the thermal exposure associated with conventional drying (Nwankwo *et al.*, 2023; Salehi, 2023; Yao *et al.*, 2023). The porous structure generally generated during sublimation can also facilitate subsequent hydration and reconstitution.

The present moisture value of 3.55% is within the range commonly reported for freeze-dried fruit materials. For example, Nansereko *et al.* (2022) reported approximately 2.60% moisture in freeze-dried jackfruit powder, while Alam *et al.* (2023) reported moisture values of approximately 4–8% among dried banana flours, depending on cultivar and drying method. More recently, Rafiquzzaman *et al.* (2025) demonstrated that freeze-dried tropical fruit juice powders could be produced with physical and functional characteristics suitable for subsequent reconstitution. These studies broadly support the present observation that freeze-drying is capable of converting highly aqueous fruit materials into relatively low-moisture powders (Alam *et al.*, 2023; Nansereko *et al.*, 2022; Rafiquzzaman *et al.*, 2025).

The apparent increases in ash, protein, crude fibre, fat and carbohydrate following freeze-drying should, however, be interpreted principally as concentration effects associated with water removal, rather than as evidence that freeze-drying generated additional nutrients. The ash content increased from 0.74% to 2.76%, while protein increased from 0.96% to 4.39% and crude fibre from 0.74% to 2.89%. Similar apparent increases in nutrient concentrations are frequently observed when fresh high-moisture fruit materials are converted to dried products and the results are expressed on a product-weight basis. Removal of water reduces the denominator against which the remaining constituents are expressed.

This interpretation is particularly important when comparing fresh and dried foods. On a dry-matter basis, changes in individual nutrients may be much smaller than suggested by the as-is values. Consequently, the present results demonstrate concentration of measured solids, rather than synthesis or necessarily complete retention of the nutrients. Ma *et al.* (2023) emphasized that changes in the measured concentration of phytochemicals after freeze-drying may reflect both water removal and actual changes in compound stability or extractability. Similarly, Yao *et al.* (2023) noted that although freeze-drying generally provides superior retention of nutritional quality compared with many thermal processes, the final composition remains dependent on freezing conditions, drying duration, matrix composition and the stability of individual constituents.

The increase in crude protein from 0.96% to 4.39% is therefore most reasonably attributed to concentration of the protein-containing solids following extensive moisture removal. The same interpretation applies to crude fibre, which increased from 0.74% to 2.89%. Alam *et al.* (2023) also reported measurable differences in protein and crude fibre among banana flours produced by different drying techniques, demonstrating that the apparent composition of dried fruit products can be strongly influenced by the drying process and the resulting concentration of solids. Differences between the present values and those

reported for banana or other fruit powders are expected because of differences in species, cultivar, maturity, initial composition, tissue composition and drying conditions. Crude fat increased from 0.50% in the fresh composite puree to 0.78% in the freeze-dried powder. Although this represents a relatively modest increase compared with the changes observed for protein, fibre and carbohydrate, it is still consistent with concentration following removal of water. The relatively smaller increase may also reflect the inherently low lipid content of the selected fruit combination. In addition, the analytical recovery of lipids from a freeze-dried matrix can differ from that obtained from the corresponding fresh puree because freezing and drying can modify tissue structure and the accessibility of extractable components.

The increase in carbohydrate from 13.61% to 85.63% was the largest apparent compositional change. This result is expected because carbohydrate represents a major fraction of the soluble and structural solids of watermelon, orange and mango. Since total carbohydrate in the present study was calculated by difference, its apparent increase is also mathematically influenced by the large reduction in moisture and the corresponding changes in the other proximate components. Therefore, the increase should not be interpreted as formation of new carbohydrate during freeze-drying. Rather, it represents the concentration of carbohydrate-containing solids in the dried matrix. Similar high carbohydrate values are commonly reported for fruit flours and powders after dehydration (Alam *et al.*, 2023).

The overall pattern is consistent with the established advantages of freeze-drying for fruit preservation. Nwankwo *et al.* (2023) and Yao *et al.* (2023) reported that freeze-drying can produce products with low moisture while limiting thermal deterioration of quality attributes. Nevertheless, agreement should not be interpreted as evidence that freeze-drying invariably produces identical nutritional responses. Ma *et al.* (2023) emphasized that the response of individual phytochemicals to freeze-drying can vary substantially. Differences in fruit composition, freezing rate, drying pressure, product thickness, drying time and storage conditions may therefore explain differences between studies.

Effect of Freeze-Drying on Functional Properties of the Watermelon–Orange–Mango Composite Puree

Freeze-drying also significantly altered the functional properties of the composite fruit material (Table 4). Bulk density decreased from 1.11 ± 0.02 to 0.89 ± 0.02 g/cm³, while specific gravity declined from 1.13 ± 0.02 to 0.92 ± 0.01 . Viscosity showed the largest relative reduction among the measured functional properties, declining from 3.84 ± 0.04 to 1.53 ± 0.03 cP.

In contrast, water-holding capacity increased from 83.74 ± 0.03 to $93.03 \pm 0.03\%$, representing an approximately 11.1% increase. Oil-holding capacity showed the opposite pattern, decreasing from 27.01 ± 0.02 to $18.03 \pm 0.03\%$, equivalent to approximately a 33.2% reduction.

Overall, freeze-drying produced a less dense and less viscous material with greater water-holding capacity but lower oil-holding capacity. The changes are consistent with structural modification of the fruit matrix during freezing and sublimation, particularly the development of a porous dried structure.

Bulk Density and Specific Gravity

Freeze-drying reduced bulk density from 1.11 to 0.89 g/cm³, corresponding to an approximately 19.8% decrease. Specific gravity similarly decreased from 1.13 to 0.92. These changes are scientifically plausible because sublimation of ice can leave behind a porous solid matrix. The removal of ice crystals without the extensive liquid-phase shrinkage associated with some conventional drying processes can result in an expanded structure containing internal voids.

The present reduction in bulk density agrees particularly well with Nansereko *et al.* (2022), who reported a bulk density of 0.566 g/cm³ for freeze-dried jackfruit powder and observed that freeze-drying produced lower bulk density than the alternative drying methods examined. They attributed the lower density to the porous structure produced during freeze-drying. Similar observations have been reported for freeze-dried banana flour, where freeze-drying produced relatively low bulk-density values compared with several thermal drying treatments (Alam *et al.*, 2023).

More recent evidence from fruit powders also supports this structural interpretation. Freeze-dried guava, amla and jamun juice powders have been investigated as instant fruit ingredients, with the authors emphasizing the importance of powder physical structure and density for handling and reconstitution (Rafiquzzaman *et al.*, 2025). Thus, the reduction in bulk density observed in the present watermelon–orange–mango powder is likely to reflect increased porosity and a less compact particle arrangement created during ice sublimation.

The decrease in specific gravity from 1.13 to 0.92 follows the same general structural trend. However, specific gravity is also influenced by the composition of the solid matrix, particle arrangement and the method used for density measurement. Therefore, the reduction should be interpreted as evidence of a change in the physical structure of the dried material rather than as a direct measure of nutritional quality.

Viscosity

Freeze-drying reduced the measured viscosity from 3.84 to 1.53 cP, corresponding to approximately a 60.2% decrease. This result is expected because the fresh composite puree contains a continuous aqueous phase in which soluble sugars, pectic substances, suspended pulp particles and other hydrocolloid-like constituents contribute to resistance to flow. Removal of most of the water disrupts this continuous liquid structure. When the dried material is subsequently evaluated, its flow behaviour therefore differs markedly from that of the

original puree.

The observed reduction is consistent with the broader principle that dehydration changes the physical organization and hydration state of fruit matrices. Freeze-drying produces a porous solid structure rather than preserving the continuous liquid network present in fresh puree (Salehi, 2023; Yao *et al.*, 2023). Differences among studies can nevertheless occur because viscosity measurements depend strongly on the concentration used for reconstitution, shear rate, temperature, particle size and the concentrations of soluble pectin, fibre and sugars.

Accordingly, the lower viscosity observed after freeze-drying should not necessarily be interpreted as deterioration. Rather, it demonstrates conversion of the fresh puree into a dry ingredient with substantially different flow characteristics. The practical significance of this change is that the resulting powder can be incorporated into food systems at controlled concentrations and subsequently reconstituted according to the intended application.

Water-Holding Capacity

Water-holding capacity increased from 83.74% in the fresh puree to 93.03% in the freeze-dried powder. This approximately 11.1% increase is consistent with structural changes caused by freezing and sublimation. Freeze-drying can generate an interconnected porous structure with a large surface area, increasing the number of sites through which water can penetrate and interact with hydrophilic constituents such as dietary fibre, pectin, proteins and other polar components.

The present observation agrees with findings from freeze-dried fruit materials. Nansereko *et al.* (2022) reported a water-holding capacity of 2.011 g/g for freeze-dried jackfruit powder and found that freeze-drying provided higher water-holding capacity than the alternative drying treatments investigated. Alam *et al.* (2023) likewise reported substantial water-holding capacity in freeze-dried banana flour and associated the improved hydration behaviour with the structural characteristics of the dried material. These observations provide strong support for the present increase in water-holding capacity.

Adetoro *et al.* (2020) further demonstrated that the technofunctional properties of freeze-dried fruit powders can be strongly influenced by particle structure and carrier composition. Their study of freeze-dried pomegranate juice powder showed significant differences in water- and oil-holding characteristics among powders prepared with different carrier agents. This finding is important when interpreting the present results because functional properties are not determined by drying method alone; they also depend on the botanical matrix, particle morphology, composition and analytical procedure.

The slightly higher water-holding capacity of the freeze-dried composite powder therefore suggests that the powder has favourable hydration characteristics. This property may be useful in food applications where the

ingredient is expected to bind water, contribute body or modify the moisture distribution of the final product.

Oil-Holding Capacity

In contrast to water-holding capacity, oil-holding capacity decreased from 27.01% to 18.03%, representing approximately a 33.2% reduction. This indicates that the structural changes produced during freeze-drying did not enhance the affinity of the composite powder for oil to the same extent as they enhanced its interaction with water.

Oil-holding capacity depends on several factors, including surface characteristics, particle size, porosity, hydrophobic interactions and the chemical composition of proteins, fibre and other matrix constituents. The predominance of hydrophilic fruit components in the present composite may favour interaction with water rather than non-polar oil. Freeze-drying may also alter the exposure of surface-active components and consequently change the number and accessibility of sites capable of physically retaining oil.

The direction of change differs from some reports in which freeze-dried powders exhibited comparatively high oil-holding capacity. For example, Nansereko *et al.* (2022) reported an oil-holding capacity of 1.137 g/g for freeze-dried jackfruit powder, while Alam *et al.* (2023) reported substantial oil-absorption capacities among freeze-dried banana flours. Such differences are not unexpected because oil-holding capacity is strongly matrix-dependent. Jackfruit and banana contain substantially different proportions and types of structural polysaccharides, starches, proteins and other components compared with a watermelon–orange–mango puree. Differences in particle size, drying history and the oil-to-sample ratio used in the analytical procedure may also contribute to divergent results.

Thus, the lower oil-holding capacity observed in the present study should be regarded as a genuine functional characteristic of this particular composite powder rather than evidence that freeze-drying universally reduces oil absorption. The contrasting findings in the literature reinforce the importance of fruit species, matrix composition, drying conditions and analytical methodology when comparing functional properties across studies.

Integrated Interpretation of the Functional Properties

Taken together, the functional-property results demonstrate that freeze-drying substantially altered the physical behaviour of the watermelon–orange–mango composite puree. The powder had lower bulk density, specific gravity and viscosity, but higher water-holding capacity and lower oil-holding capacity. These changes can be explained principally by the structural consequences of freezing and sublimation.

The reduction in density is consistent with formation of a porous structure, whereas the increase in water-

holding capacity is compatible with greater accessibility of hydrophilic surfaces and internal pores. The reduction in viscosity reflects conversion of the original continuous aqueous puree matrix into a dry porous solid. The decline in oil-holding capacity, meanwhile, indicates that increased porosity does not automatically translate into greater retention of non-polar liquids. Rather, the chemical nature of the exposed surfaces and the composition of the fruit matrix determine whether the newly created structure preferentially interacts with water or oil.

This interpretation agrees with current understanding of freeze-dried fruit products. Freeze-drying is capable of preserving the physical integrity of fruit materials and generating porous structures that support rehydration and functional performance, although the magnitude and direction of individual properties vary with raw material composition and process conditions (Ma *et al.*, 2023; Nwankwo *et al.*, 2023; Salehi, 2023; Yao *et al.*, 2023). Studies on jackfruit, banana and tropical fruit juice powders further demonstrate that freeze-drying can substantially modify density, water interaction, oil interaction and other powder characteristics (Alam *et al.*, 2023; Nansereko *et al.*, 2022; Rafiquzzaman *et al.*, 2025).

Overall, the present results demonstrate that freeze-drying was effective in transforming the highly perishable watermelon–orange–mango composite puree into a low-moisture powder with altered and potentially useful functional characteristics. Importantly, the observed increases in proximate constituents should be interpreted principally as concentration effects resulting from water removal, whereas the functional-property changes are more appropriately attributed to structural modification of the fruit matrix during freezing and sublimation.

CONCLUSION

This study demonstrated that freeze-drying effectively converted watermelon–orange–mango composite puree into a low-moisture fruit powder with modified nutritional and functional properties. Among the six formulations evaluated, formulation 618 (50% watermelon, 30% orange and 20% mango) recorded the highest sensory acceptability and was selected for freeze-drying. Freeze-drying reduced moisture from 83.45% to 3.55%, while the apparent increases in ash, protein, fibre, fat and carbohydrate were mainly attributable to concentration of non-water components. The process reduced bulk density, specific gravity and viscosity but increased water-holding capacity, reflecting structural changes and increased accessibility of hydrophilic sites. Overall, freeze-drying shows potential for producing a value-added fruit powder from locally available tropical fruits.

Further studies should evaluate the storage stability, rehydration, solubility, hygroscopicity and microstructure of the powder under different conditions. Investigation of vitamin C, carotenoids, phenolics, flavonoids and antioxidant activity is also recommended. Comparative studies with spray-drying and hot-air drying should assess

product quality, nutrient retention and processing costs. Finally, pilot-scale, economic and product-development studies are recommended to establish commercial feasibility and applications in beverages, bakery products and other formulated foods.

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