Formulation and Optimization of Coconut Water Powder Using Spray Drying Technique

by

Aswini VR

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Declaration

I hereby declare that the report on the project entitled **"Formulation and Optimization of Coconut Water Powder Using Spray Drying Technique"** submitted by me to **St. Teresa's College, Ernakulam**, affiliated to **Mahatma Gandhi University, Kottayam, Kerala**, for the partial fulfillment of the requirement for the award of the degree of **Master of Vocational Studies in Food Processing Technology**, is the record of the original work carried out by me under the guidance of **Dr. Sachin R. Chaudhari**, **Senior Scientist**, **Department of Plantation Products, Spices and Flavor Technology (PPSFT)**, **CSIR-CFTRI, Mysuru, Karnataka**. I further declare that the results of the present study have not formed the basis for the award of any other degree to any candidate of any university during the period of my study.

Place: Mysuru **Aswini VR**
Date:

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Aswini VR

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List of Abbreviations and Acronym's

IAA - Indole-3-acetic acid
TCW -Tender coconut water
MDA - Malondialdehyde
SOD - Superoxide dismutase
CAT - Catalase
PPO - Polyphenol oxidase
POD - Peroxidase
HDL - High-density lipoprotein
pH - Potential of Hydrogen
NIST - National Institute of Standards and Technology
MHz - Megahertz
nm - Nanometer
UV - Ultraviolet
DNA - Deoxyribonucleic acid
MF - Microfiltration
UF - Ultrafiltration
µm - Micrometer
kV - Kilovolts
Hz - Hertz
Min - Minute
DE - Dextrose equivalent
mL - Milliliter
µl - Microliter
m - Meter
µs – Microseconds
G - Gram
aW - Water activity
CWP - Coconut water powder
CPMG - Coconut powder with maltodextrin and guar gum
TSS - Total Soluble Solids
AOAC - Association of Official Analytical Collaboration
DNSA - 3,5-Dinitrosalicylic acid

Abstract

Coconut water is a naturally refreshing and nutrient-dense beverage, rich in vital electrolytes, vitamins, and bioactive components. However, its high perishability poses significant challenges for storage, distribution, and commercialization. In today's fast-paced lifestyle, there is an increasing demand for convenient, shelf-stable, and easy-to-use functional beverages. Spray drying offers an effective solution to extend the shelf life of coconut water by converting it into a stable powder form while retaining its nutritional and functional integrity.

This study investigates the spray drying process by evaluating the effects of feed flow rate and inlet temperature on the physicochemical properties of coconut water powder. Two carrier agent formulations were employed: maltodextrin and dextrose, tested at 120 °C, 130 °C, 140 °C, and 150 °C, and maltodextrin and guar gum, tested at 140 °C, 150 °C, 160 °C, 165 °C, and 180 °C. Additionally, the influence of varying feed flow rates (1.5, 2.0, and 2.5 mL/min) was analyzed in relation to powder yield, solubility, moisture content, and stability.

The primary objective of the study is to identify optimal spray drying parameters that preserve the nutritional value, functional properties, and sensory appeal of coconut water powder. The results demonstrate that the optimized product exhibits high reconstitution ability, low moisture content, making it highly suitable for commercial use.

The findings contribute valuable insights for the food and beverage industry, enabling the development of a convenient, and shelf-stable powdered coconut water product. With its potential use in rehydration formulas, functional beverages, and instant drink mixes, this product represents a market-ready solution aligned with modern consumer expectations for health, portability, and ease of use.

Chapter 1: Introduction

1.1 Background of the Study

The coconut palm (*Cocos nucifera* L.) is a highly important plant for tropical regions and the communities living there. Once cultivated on large plantations primarily for oil production, it is now mostly farmed by small-scale farmers. This tree thrives best in coastal areas within 20° north and south of the equator, from sea level up to an altitude of 1,200 meters (DebMandal, M., *et al.*, 2011). It requires warm temperatures between 27–30 °C, high humidity, and well-aerated soils for optimal growth.

The coconut palm is the most widely cultivated and utilized palm tree in the world. It serves as a vital source of food and income for approximately 10 million families across more than 80 countries. A significant portion of the coconuts produced are used locally, underscoring the crop's importance to small communities and rural economies. Its versatility in providing food, oil, and various other products makes it an essential resource for millions of people.

The coconut industry offers a wide range of products, including desiccated coconut, coconut cream, coconut milk powder, defatted coconut, coconut fiber and fiber-based products, shell charcoal, activated carbon, coconut vinegar, and coconut arrack, many of which are used for local purposes (DebMandal, M., *et al.*, 2011).

1.2 Importance of Coconut Water

Coconut water is a pure, non-fermented, and naturally refreshing beverage extracted from the interior of young, green coconuts (*Cocos nucifera* L.). It has gained widespread popularity due to its health benefits and is now extensively used in the food, beverage, nutraceutical, and wellness industries. This clear, slightly sweet liquid is highly consumed in tropical regions owing to its thirst-quenching properties and rich nutrient profile.

Coconut water is particularly valued for its high potassium content, making it an effective natural rehydration drink, especially after physical exertion or during hot weather. It contains more water in young green coconuts than in mature ones, which have a higher proportion of thick white kernel (endosperm) and more lipids. As the coconut matures, the composition of coconut water changes significantly, affecting its sweetness, viscosity, and nutritional profile.

In addition to water, coconut water contains bioactive enzymes that aid digestion, as well as a variety of essential nutrients, including sugars, vitamin C, folic acid, amino acids**,** and B-complex vitamins such as B1 (thiamine), B2 (riboflavin), B6 (pyridoxine), and pantothenic acid. It is also rich in minerals like potassium, sodium, calcium, magnesium, phosphorus, and trace elements such as iron, copper, sulfur, and chlorides (Prades *et al.*, 2012).

Sugars:

Sugars are a major component of tender coconut water, primarily present in the form of glucose and fructose. During the early stages of nut development, sugar levels increase from approximately 1.5% to 5–5.5%. As the coconut matures, the sugar content gradually decreases to about 2%. Initially, reducing sugars (glucose and fructose) dominate. As the nut matures, sucrose, a non-reducing sugar, increases significantly, ultimately constituting about 90% of the total sugar in fully mature coconut water.

Minerals:

Tender coconut water is well-known for its electrolyte balance, especially the high potassium content, which makes up more than half of its total mineral content. Other minerals include sodium, calcium, magnesium, phosphorus, iron, and chlorides. The mineral profile contributes to osmoregulation**,** hydration, and diuretic effects, supporting kidney function and promoting urinary output. The mineral content, particularly potassium, can vary based on agricultural practices such as potash manuring**.**

Proteins and Amino Acids:

Although present in small quantities, proteins in coconut water contain essential amino acids such as arginine, alanine, cystine, and serine, with levels sometimes higher than those found in cow's milk. Due to the absence of complex proteins, coconut water poses minimal risk of allergenic reactions or protein-induced shock in clinical settings, making it suitable for rehydrating ill or postoperative patients.

Other Benefits and Applications:

- Coconut water has antioxidant and antimicrobial properties, contributing to its role in promoting overall health.
- It is used in sports drinks**,** functional beverages**,** and infant and elderly nutrition**.**
- Its composition is similar to human plasma, which has led to its use as an emergency intravenous hydration fluid in some situations.
- Coconut water also supports gut health due to the presence of enzymes and certain oligosaccharides.

Forms of coconut:

Coconut water is available in various processed forms to enhance its usability, shelf life, and convenience without compromising its nutritional value. The major forms include:

1. Coconut Water Concentrate

Coconut water concentrate is produced by reducing the water content of fresh coconut water through methods such as vacuum evaporation. This process removes a significant portion of the moisture while retaining the essential nutrients, natural sugars, and bioactive compounds. The concentrate is often used in the manufacture of beverages and reconstituted drinks and serves as a more storage-efficient alternative to fresh coconut water for industrial applications.

2. Packed Coconut Water

Packed coconut water refers to commercially processed and packaged coconut water extracted from fresh coconuts. The processing typically involves steps such as filtration, pasteurization, and aseptic packaging in airtight containers like bottles, cans, or tetra packs. These measures ensure the product's safety, shelf stability, and nutrient retention during transportation and storage. While some variants may contain preservatives or flavoring agents, premium brands usually offer 100% pure coconut water with no added ingredients. This form of coconut water provides consumers with a ready-to-drink, hygienic, and portable beverage option.

3. Coconut Water Powder

Coconut water powder is a dehydrated form of coconut water, obtained through processes such as spray drying or freeze drying. The resulting fine, water-soluble powder preserves the natural composition of electrolytes, vitamins, and minerals found in fresh coconut water. It offers several advantages, including extended shelf life, reduced bulk for transportation, and ease of storage. When reconstituted with water, coconut water powder delivers a hydrating and nutritious beverage, making it an ideal option for use in instant drinks, sports nutrition products, and functional food formulations.

1.3 Need for Coconut Water Powder

Fresh coconut water is highly perishable due to its high moisture content and rich nutrient profile, making it prone to microbial spoilage and limiting its shelf life. Converting it into a powdered form offers a practical solution to this challenge by significantly extending its shelf life while preserving its nutritional and functional qualities.

Coconut water powder provides several advantages:

- **Convenience and Portability**: It is lightweight, compact, and easy to transport, making it ideal for use by athletes, travellers, and health-conscious consumers who require a quick and convenient hydration solution.
- **Year-Round Availability**: Coconut harvesting is seasonal in many regions, which can limit the availability of fresh coconut water. Powdered coconut water ensures continuous supply and market stability throughout the year, independent of harvesting cycles.
- **Storage and Cost Efficiency**: Unlike fresh coconut water, the powdered form does not require refrigeration, thereby reducing storage and transportation costs. Its low volume and weight make it more economical to ship, benefiting both manufacturers and consumers.
- **Ease of Use**: The powder can be easily reconstituted with water to deliver the same hydrating benefits as fresh coconut water, making it suitable for a wide range of applications—from ready-to-drink beverages to functional food ingredients.

A list of available coconut water powder products in the market is presented in **Table 1**.

Table 1: Commercially Available Coconut Water Powder Products and Their Key Attributes Including Brand Name, Formulation Type, Carrier Agents, and Target Applications.

Brand name	Ingredients	Process	Shelf life
Plix	sucrose, spray dries tender coconut water powder, coconut milk powder, salt	-	Up to 1 year
Poptopia	Coconut water concentrate powder, minerals, sucrose	-	12 months
Altern8	Coconut water, sucrose, minerals	-	6 months
Nutrijet	Coconut water concentrate powder, minerals, sucrose	-	Before 12 months
Urban platter	Coconut water powder (61%), sucrose	Freeze drying	-
NaturUp	Coconut water powder, minerals	Freeze drying	1year
Coco Nirvanaa	Spray dried coconut water powder, glucose, dextrose and sucrose	Spray drying	Before 15 months
Sweetmate	Coconut water concentrate powder, minerals, sucrose, stevia	Freeze drying	24 months
Food essential	Dried coconut water powder, sucrose	-	12 months
Coco Aqua	Sucrose, minerals, coconut concentrate powder	-	1 year
Yeshvi natural	Coconut water concentrate powder, minerals, sucrose	-	-

D ‘aromas	Sucrose (26%), spray dried coconut water (15%), minerals, salt, acidifying agent, anti cacking agent	Spray drying	Before 12 months

1.4 Spray Drying as a Processing Technique

Spray drying is a single-step technique that converts liquid ingredients directly into powder (Chiou & Langrish, 2007). It is extensively used in the food industry for producing food powders and agglomerates due to its cost-effectiveness and operational efficiency. According to Hammami and Rene (1997), spray drying is approximately 4 to 5 times more economical than freeze drying, primarily because it consumes less electricity and has a significantly shorter drying duration.

One of the major advantages of spray drying is its rapid processing time—typically ranging from 5 to 100 seconds—which helps preserve heat-sensitive attributes such as nutrients, flavor, and color. The process involves atomizing the liquid feed into fine droplets and exposing them to a stream of hot air, allowing moisture to evaporate quickly and leaving behind dry particles. The resulting product can be obtained in various forms such as powder, granules, or clusters.

Spray drying offers several benefits, including high throughput, continuous operation, and the ability to produce free-flowing, uniform, and spherical particles with consistent size distribution. However, the use of high temperatures may lead to degradation of certain sensitive components like vitamin C, beta-carotene, volatile flavors, and aroma compounds (Dziezak, 1988).

One of the technical challenges in spray drying is handling sugar-rich materials, such as mango juice, which tend to adhere to the inner walls of the dryer due to their low glass transition temperature. To overcome this, drying aids such as maltodextrin are commonly added to the feed. These carriers increase the glass transition temperature, reduce stickiness, and improve the overall drying performance and powder quality.

1.5 Objective of the Thesis:

- Development of instant coconut water powder.
- Optimization of formulation parameters to improve the quality and flavor.
- Characterization of the final products, physicochemical properties, sensory attributes.

1.6. Scope and Significance of the Studies

The present research focuses on the development of coconut water powder using spray drying technology, aiming to enhance its shelf life, portability, and commercial viability. With increasing global demand for natural and health-oriented beverages, coconut water stands out due to its excellent nutritional profile—rich in electrolytes, vitamins, and bioactive compounds. However, its high perishability and limited harvesting season restrict its availability and widespread distribution.

This study addresses these limitations by converting fresh coconut water into a stable, easy-to-store, and reconstitutable powder form using spray drying. It evaluates the effect of key process parameters such as inlet temperature and feed flow rate on the physicochemical properties of the resulting coconut water powder. The performance of different carrier agents (e.g., maltodextrin–dextrose and maltodextrin–guar gum) is also assessed to optimize powder quality and yield.

Coconut water powder is a dehydrated form of coconut water that retains its essential nutrients and electrolytes, making it a highly versatile product with broad applications across multiple industries. In the food and beverage industry, it is commonly used in sports drinks, flavored beverages, smoothies, and instant drink mixes due to its natural electrolyte composition. It also enhances the nutritional profile of bakery products, confectionery, and dairy alternatives, making it a valuable ingredient in functional foods. In the pharmaceutical and nutraceutical sectors, it is used in oral rehydration solutions (ORS), dietary supplements, and gut health formulations for its hydration benefits and bioactive compounds. Furthermore, in the cosmetic industry, coconut water powder is incorporated into skincare and haircare products for its hydrating, antioxidant, and anti-aging properties.

Beyond its functional applications, coconut water powder supports environmental sustainability by reducing food waste from coconut processing, offering a long shelf-life alternative to fresh coconut water, and minimizing transportation costs due to its lightweight form. Its development promotes sustainable resource utilization and adds economic value to coconut-producing regions, particularly benefiting small-scale farmers.

The significance of this studies lies in the intersection of economic impact, and environmental sustainability. Rich in natural electrolytes such as potassium, sodium, and magnesium, coconut water powder supports hydration, muscle recovery, cardiovascular health, and metabolic functions. Additionally, it contains antioxidants and cytokinins that may slow aging and reduce inflammation. Economically, it creates value-added products from surplus coconut water, reduces waste, and opens up new trade opportunities, particularly in sports nutrition, wellness, and organic product markets.

1.7 Structure of the Thesis:

This thesis is structured into five main chapters, each addressing key aspects of the study on the development and processing of instant coconut water powder. The content of each chapter is outlined as follows:

Chapter 1: Introduction

This chapter provides an overview of the study, emphasizing the significance of coconut water and its various applications. It discusses the need for converting coconut water into powder form, highlights spray drying as the selected processing technique, and outlines the research objectives. The scope and significance of the study are also presented.

Chapter 2: Literature Review

This chapter presents a comprehensive review of existing literature related to coconut water, including its composition and various processing techniques. A detailed discussion on different drying methods, with a particular focus on spray drying, is included. Additionally, previous studies on the optimization of formulation parameters and the challenges in producing high-quality coconut water powder are explored.

Chapter 3: Materials and Methods

This chapter describes the materials used in the study and the experimental procedures adopted. It outlines the processing techniques for producing coconut water powder, particularly spray drying, and explains the optimization of formulation parameters. The analytical methods employed to evaluate the physicochemical, nutritional, and sensory properties of the final product are also detailed.

Chapter 4: Results and Discussion

This chapter presents and interprets the findings of the study. The effects of various processing parameters on the quality and functionality of coconut water powder are analyzed. The results are compared with existing literature, and significant observations are highlighted to support the conclusions drawn.

Chapter 5: Conclusions and Recommendations

This chapter summarizes the key findings of the research and discusses their implications. The importance of the study in the food and beverage industry and its potential commercial applications are emphasized. Recommendations for future research and improvements in processing techniques are also provided.

This structured approach ensures a logical flow of information, guiding the reader from the background and objectives of the study to its conclusions and future perspectives.

Chapter 2 - Literature Review

2.1. Overview of Coconut Water

The well-known coconut fruit, which is strictly a drupe, is considered a significant and widely produced crop worldwide. The drupe envelope, also known as the mesocarp or husk, is widely sold as carpets, rope, geotextiles, and growing media. We can make activated charcoal from the shell (endocarp). The white kernel that makes up the inner portion (endosperm) contains a liquid known as "coconut water." Copra is the dried kernel meat that is used to make desiccated coconut or to extract oil. Clear and colorless, coconut water is a liquid that is extracted straight from the inside of the coconut fruit without releasing the meat. The taxonomical classification of coconut is given in the **Table 2**.

Table 2: Taxonomical Classification of Coconut

Sub kingdom	Tracheobionta -Vascular plants
Super division	Spermatophyta – Seed plants
Division	Mangnoliophyta – Flowering plant
Class	Liliopsida - Monocotyledons
Sub class	Arecida
Order	Arecales
Family	Arecaceae – Palm family
Genus	Cocos L – Coconut palm
Species	Cocos nucifera – Coconut palm
Kingdom	Plantae-Plants

Taxonomical Classification of Coconut:

Varieties of coconut:

There are different varieties of coconut and it is mainly grouped as two, they are;

a. Dwarf coconut
b. Tall coconut

Dwarf Coconut: This variety starts producing nuts 4-6 years after planting. Examples include Ivory Coconut (*Eburnia* variety), Coconut King (*Regia*), King Malabar (*Pretiosa*), and Quail (*Pumila*).

Tall Coconut: This variety produces fruit after about 15 years of planting, and the tree can grow as tall as 30 m. Examples include Green Coconut (*Viridis*) and Red Coconut (*Rubescens*). Hybrids are the result of crossbreeding between dwarf and tall coconut varieties (Rethinam et.al., 2005).

2.2 Nutritional Composition:

Tender coconut water is rich in essential nutrients, including phytohormones like auxins and cytokinins, minerals, vitamins, and sugars that support overall health and recovery. Key components include:

- **Auxins**: These plant hormones, especially indole-3-acetic acid (IAA), regulate growth, response to light and gravity, and development of plant organs. IAA helps maintain hormonal balance and promote root and shoot growth.
- **Cytokinins**: Plant hormones found in coconut water, cytokinins promote cell division, rapid growth, and delay aging in plants. They are beneficial for plant farming and have health benefits, such as reducing cancer risk and preventing blood clots.
- **Vitamins**: Coconut water is a source of important vitamins like B1, B2, B3, B5, B6, B7, B9, and vitamin C. These support metabolism, immune function, and cellular health, with vitamin C acting as a powerful antioxidant and aiding in iron absorption and wound healing.
- **Sodium**: Essential for hydration, sodium helps retain fluid balance in the body, particularly through sweat and urine loss.
- **Potassium**: Coconut water contains a high amount of potassium, which helps regulate heart function and fluid balance. Both high (hyperkalemia) and low (hypokalemia) potassium levels can affect heart rhythms.
- **Magnesium**: Supports muscle function, energy production, and helps prevent cramps and spasms during intense physical activity.

- **Phosphorus**: Crucial for bone health, energy transfer, muscle contraction, and nerve function.
- **Calcium**: Important for muscle contraction, electrical signal transmission between cells, and maintaining strong bones and teeth.

Together, these components make coconut water a nutrient-dense beverage, contributing to hydration, electrolyte balance, and overall well-being.

Health benefits of coconut water:

1. **Natural Isotonic Drink**: Coconut water, rich in potassium, helps maintain cellular pressure balance. The semi-permeable cell membrane ensures water moves in or out based on external pressure. An isotonic solution maintains balance, preventing cells from swelling or shrinking.
2. **Prevents Oxidative Stress**: Coconut water can lower blood pressure, reduce triglycerides, and enhance antioxidant activity. Studies show that it decreases MDA (a marker of cell damage) and increases the body's ability to fight oxidative stress, reducing free radical damage. Some studies also suggest it helps prevent blood clots (Zulaikhah, S. T. et al., 2019).
3. **Antioxidant Activity**: Coconut water boosts antioxidant enzymes like SOD and CAT. Research shows it reduces liver damage, inflammation, and cell damage, thanks to its L-arginine and vitamin C content, both known for their antioxidative properties.
4. **Improves Blood Pressure**: Fresh coconut water helps lower systolic blood pressure without affecting diastolic pressure. It also provides hydration, enhances blood circulation, and reduces the risk of heart disease, diabetes, and atherosclerosis.
5. **Cardiac Protective Activity**: High HDL levels, which can be supported by coconut water, are linked to a reduced risk of ischemic stroke and myocardial infarction, promoting heart health.
6. **Treats Diarrhea**: Coconut water contains enzymes like reductase and polyphenol oxidase that help treat diarrhea, gastroenteritis, and gastrointestinal infections. It

also aids in dissolving urinary stones and provides hydration during illness (Zulaikhah, S. T. et al., 2019).

In summary, coconut water offers a wide range of health benefits, from promoting hydration to reducing oxidative stress, improving blood pressure, and supporting heart health.

2.3. Methods of Coconut Water Processing:

Coconut water processing involves various techniques to ensure product safety, extend shelf life, and retain nutritional and sensory qualities. These methods include both thermal and non-thermal treatments such as pasteurization, sterilization, spray drying, microwave processing, ohmic heating, UV radiation, pulsed light, and irradiation. Each method has its advantages and limitations depending on the desired final product quality and application.

The key processing methods are discussed below:

Thermal processing:

Conventional processing

Conventional heating is a common method used to preserve coconut water and inactivate spoilage enzymes such as peroxidase and polyphenol oxidase. However, a major challenge lies in maintaining the quality and nutritional value of the coconut water during the heating process. Pasteurization and sterilization are frequently employed to eliminate enzymes and microorganisms, but these processes can degrade heat-sensitive vitamins and alter the natural aroma of coconut water. Heating also impacts various properties, including acidity, pH, color, flavor, sugar content, and vitamin levels. To enhance product quality, heating is often combined with other preservation techniques such as filtration, cooling, freezing, or the addition of food-grade preservatives.

Microwave processing

Microwave processing is used to eliminate harmful microorganisms and deactivate enzymes in food through heating, pasteurization, and sterilization. Its effectiveness depends on the dielectric properties of the material, which determine how efficiently it absorbs microwave energy and converts it into heat. Franco et al. investigated the effects of microwave frequency and temperature on the dielectric properties of coconut water and a simulated solution containing sugar and salt. They evaluated the samples across temperatures ranging from 0 °C to 90 °C and frequencies between 500 and 3000 MHz. At 915 MHz, electrical conductivity had a greater influence on the loss factor and penetration depth (12%) than at 2450 MHz (8%). The loss factor and penetration depth were strongly affected by conductivity. At 2450 MHz, a balance between ionic and dipolar mechanisms was observed, resulting in a lower penetration depth. Sugars exhibited weaker polarization compared to salts, as salts behave like conductors at lower frequencies, increasing the loss factor and reducing permittivity.

Ohmic heating

Ohmic heating is a thermal processing technique widely used in food processing for applications such as blanching, sterilization, pasteurization, drying, and enzyme inactivation. It can alter the structural properties of food, deactivate enzymes, inhibit microbial growth, and enhance the release of cellular materials during treatment. Prades et al. investigated the effects of ohmic heating (at temperatures ranging from 100–140 °C for durations of 0–600 seconds) on the volatile compounds in coconut water. Their study revealed that the composition of these compounds changed with increasing temperature. Using gas chromatography, they identified over 60 volatile compounds in coconut water. Among these, 3-pentane-2-one and ethyl octanoate were recognized as reliable indicators of ohmic heating (Naik, M., et al., 2022).

Non- thermal processing:

Pulsed light treatment

Pulsed light treatment is an advanced technology used to inactivate microorganisms on food surfaces, packaging, and processing equipment. It delivers short, intense bursts of broad-spectrum light (200–1100 nm) using a xenon flash lamp housed in a treatment chamber. Liquids are placed on an adjustable stainless-steel shelf below the lamp and exposed to pulses—typically up to 12 pulses at 3 pulses per second, each lasting 360 μs. Turbulence can be introduced by adjusting the speed to enhance exposure.

The effectiveness of pulsed light depends on the nature of the food. In liquid foods, high solid content and low transparency reduce light penetration and thus its antimicrobial efficacy. Treating liquids in thin layers improves effectiveness by minimizing radiation absorption. In solid foods, microbial inactivation is most effective on smooth surfaces. However, components like proteins and lipids can absorb radiation, diminishing the treatment's efficiency.

UV radiation

UV radiation is an FDA-approved, cost-effective method for pasteurizing fruit and vegetable juices. A typical UV reactor includes a UV-C light source (200–280 nm), an absorption tank, heat exchangers for temperature control, and a mechanical system to ensure uniform exposure of the liquid. UV-C effectively inactivates microorganisms by damaging their DNA, preventing replication.

The effectiveness of UV treatment depends on factors such as wavelength, UV dose, reactor design, liquid flow, and the optical properties of the liquid. For liquids with high UV absorbance, treatment in thin layers improves efficacy. UV is most effective at wavelengths near the DNA absorption peak and works best in clear liquids with low fat and minimal suspended solids, making it well-suited for tender coconut water (TCW).

In addition to microbial reduction, UV treatment can reduce enzymatic activity. For instance, a 15-minute UV exposure decreased peroxidase (POD) and polyphenol oxidase (PPO) activity by 4% and 6%, respectively, in a model coconut water solution.

Gamma Irradiation

Irradiation is a non-thermal food processing technique that uses gamma rays, electron beams, or X-rays to expose food to ionizing radiation. This method is considered safe and preserves the nutritional quality of food. It inactivates microorganisms by damaging their cellular structures and metabolic functions, thereby enhancing microbial stability. High-energy photons, such as gamma rays, generate free radicals that interact with organic molecules, contributing to the process's effectiveness.

When tender coconut water (TCW) was irradiated at 5 kGy/h at 10 °C and stored at 4 °C, it developed a yellow coloration. This discoloration is likely due to the formation of hydroxyl phenyl compounds, resulting from reactions between tyrosine-derived phenol groups and gallic acid, which can lead to O-quinone formation. Irradiation also caused a decrease in pH and an increase in turbidity. Since higher turbidity may promote bacterial growth, irradiation is not recommended for TCW (Kulal et al., 2020).

2.4. Spray Drying:

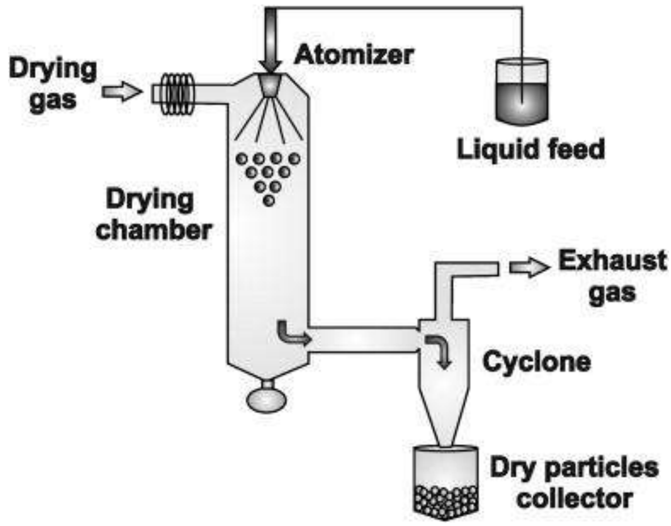

Figure 1 Schematic Diagram of Spray Drying

Spray drying is a widely recognized technique for producing particles, which involves converting a liquid material into dried particles using a hot gaseous drying medium. Since its initial discovery, the spray-drying technique has undergone significant advancements in both operational design and applications.

The spray-drying process is based on removing moisture by exposing the feed product to a heated atmosphere (santos). This spray drying involves mainly 4 steps;

a) Atomization of liquid into spray droplets
b) Droplet-hot air contact
c) Evaporation of droplet water
d) Recovery of the powder

The schematic representation of these steps is shown in **Figure 1**, which illustrates the core stages involved in spray drying and highlights how each component contributes to the final powder formation.

a) Atomization of liquid in to spray:

The initial step of spray drying is the atomization. The atomizer, which creates the spray, is regarded as the heart of the spray drying process. By breaking the liquid into fine droplets, atomization increases the surface area, facilitating better heat and mass transfer between the hot drying gas and the liquid particles. The greater the energy used for atomization, the smaller the droplet size will be. This step is crucial for achieving optimal operational efficiency and high product quality. The type of atomizer used primarily determines the size of the liquid droplets and the resulting dried powder.

There are mainly two types of atomizers are there;

- Rotary atomizer
- Nozzle atomizer

b) Droplet-hot air contact

The atomized droplets interact with the drying medium in various ways to evaporate the solvent in the product, such as co-current, counter-current, and mixed current flow.

- Co-current flow:

In a co-current design, both the feed and the drying medium move in the same direction within the chamber. This setup is typically used for heat-sensitive materials, as the wet product first encounters the hottest air, while the progressively dried product interacts with cooler air. This method allows for a high rate of moisture evaporation, resulting in the dried product having a significantly lower temperature than the air leaving the chamber. In this arrangement, the liquid droplets are exposed to an inlet temperature of 150 °C to 220 °C, leading to rapid evaporation of water and causing the air temperature to decrease to a more moderate level.

c) Evaporation of droplet water

When the liquid droplets come into contact with hot air, water evaporates because of the temperature and pressure differences between the droplets and the air. This causes heat and mass to transfer from the droplets to the air. As they interact, the temperature of the droplets rises until it reaches a steady point near the wet bulb temperature, where most of the water evaporates. At this stage, the rate of water moving from inside the droplet to the surface stays constant and matches the rate at which it evaporates. As the solid content in the droplet increases and reaches a certain level (critical moisture content), moisture diffusion slows down. The drying rate then drops quickly as the drying front moves further inside the droplet.

d) Recovery of the powder

The last step in the spray drying process is collecting the dried product. The coarse powder is removed through the outlet, and the exhaust air is separated by a cyclone separator, which also captures the very fine particles. How easily the particles are separated from the air depends on their density, size, and how fast they settle in the cyclone.

Cyclone separator:

Cyclone separators are used to collect powders produced in spray drying. The powder and air mixture are pushed into the top of a cylindrical vessel at high speed, creating a swirling motion inside. This motion causes the heavier powder particles to move to the wall of the cyclone. When they hit the wall, they lose their speed and fall to the bottom where they are collected. The air is then taken out through a separate exit. Cyclones are simple and don't have moving parts, making them easy to maintain. A large spray dryer uses many cyclones to recover as much powder as possible.

Wet scrubbing is another method used to remove very fine powders. It typically uses water to dissolve the powder particles, as the powder is more easily dissolved in water than the air is (Santos et.al.,2018).

2.5. Techniques for Formulation of Coconut Water Powder:

The development of instant coconut water powder depends significantly on drying technologies to maintain its nutritional and sensory attributes. Among the various methods, **spray drying** and **freeze drying** are the most extensively applied and utilized. While this study centers on spray drying, freeze drying serves as an alternative method with its own set of benefits and challenges.

Spray drying:

Spray drying is extensively utilized in the commercial production of milk powders, fruit powders, and vegetable powders (Kim et al., 2009; Kha et al., 2010). This method provides several benefits, such as rapid drying, high production capacity, and the ability to operate continuously (Duffie & Marshall, 1953). During the process, the feed solution is atomized into droplets and exposed to a stream of hot air (Saravacos & Kostaropoulos, 2002). The final product can be obtained in various forms, including powder, granules, or agglomerates (Nindo & Tang, 2007). Spray drying processes can be helps to produce free-flowing, uniform, and spherical particles with a specific particle size distribution (Barbosa-Cánovas et al., 2005; Duffie & Marshall, 1953). However, due to high temperatures used in spray drying can lead to the loss of certain quality and sensory attributes, particularly vitamin C, β-carotene, flavors, and aromas. Drying aids like maltodextrin are frequently added to the feed mixture to raise the glass transition temperature of the final dried product, which helps to prevent stickiness during the spray drying process.

Freeze drying:

The low-temperature drying method known as freeze drying (lyophilization) better retains the nutritional value and flavor of coconut water. Water is extracted from the liquid by sublimation in a vacuum after the liquid has been frozen. A product with more flavor and nutritional value is produced by freeze-drying coconut water powder, which retains a higher concentration of volatile chemicals and heat-sensitive nutrients (Caparino et al., 2012). But comparing spray drying, freeze drying is more expensive and time-consuming process, which makes it difficult for large-scale industrial applications (Ratti, 2001).

Drum drying:

Drum drying is a continuous drying technique where a liquid or semi-solid product is spread as a thin film onto a heated rotating drum, allowing moisture to evaporate rapidly due to direct heat transfer. As the drum rotates, the dried product forms a thin layer, which is then scraped off using a stationary blade and further ground into a powder or flakes. This method is widely used for baby food, instant soups, mashed potatoes, and cereal-based powders, as it ensures fast drying, high energy efficiency, and good product rehydration properties. Drum drying offers advantages such as cost-effectiveness, high production capacity, and minimal loss of nutrients, making it suitable for processing heat-stable food products. However, due to direct contact heating, it may not be ideal for heat-sensitive compounds.

Fluidized bed drying:

Fluidized bed drying is a drying technique in which hot air is passed through a bed of solid particles, causing them to behave like a fluid due to air movement. This enhances heat and mass transfer, resulting in efficient and uniform drying. The process is widely used for granules, powders, and heat-sensitive materials, such as pharmaceuticals, instant drink powders, and encapsulated flavors. The key advantages of fluidized bed drying include fast drying rates, improved product quality, and better control over moisture content. However, it may lead to particle agglomeration or fluidization difficulties with irregularly shaped materials.

By comparing these methods which highlights the trade-offs between cost and quality. Spray drying is more economical and scalable, making it suitable for commercial production, while freeze drying is preferred for applications where nutrient retention and product quality are prioritized over cost (Shishir & Chen, 2017).

2.6. Challenges in Powdering Coconut Water

- The price of coconuts can fluctuate significantly depending on the season, weather conditions, and global demand. Natural disasters such as droughts and typhoons can further reduce coconut harvests, leading to sudden price increases. Major coconut-producing countries like India, Indonesia, and the Philippines often face these fluctuations, making it challenging for industries that rely on a steady supply.
- Coconut powder is used across various industries from food and cosmetics to pharmaceuticals—but its popularity varies by region. In some areas, limited awareness of its benefits and applications keeps demand lower than its potential. To address this, companies need to invest in marketing, consumer education, and strong branding to position coconut powder as a healthy, convenient, and versatile ingredient. The growing interest in plant-based and vegan diets is helping increase its visibility, but there is still untapped potential, especially in baking, beverages, and nutritional supplements.
- Coconut farming is highly sensitive to climatic conditions. Changes in temperature, excessive rainfall, drought, or poor soil quality can hinder healthy crop growth. Since coconut trees take years to mature, any disruption in their development can reduce yields for multiple seasons. To safeguard coconut production, farmers must adopt sustainable practices such as crop rotation, organic farming, and improved irrigation

systems. However, many face challenges in implementing these methods due to limited resources or lack of government support.

2.7. Previous Studies on Coconut Water Powder Formulation

The studies by Nambiar K, effects of 1.5% Moringa oleifera gum, 30% maltodextrin, and 120°C inlet temperature on spray-dried TCW powder were assessed in this study. Rich phenolic content (21.82 mg GAE/g), robust antioxidant activity, and high encapsulation efficiency (94.86%) were the outcomes of the ideal conditions. Higher MG levels were associated with greater crystallinity in XRD examination, indicating MG's potential as a useful natural wall material for TCW microencapsulation in food applications.

This study investigated how spray-dried tender coconut water (TCW) powder was affected by Moringa oleifera gum (MG), maltodextrin (MD), and inlet temperature. The highest encapsulation efficiency (94.86%), robust antioxidant activity (DPPH: 53.66%, ABTS: 54.92%), and phenolic content (21.82 mg GAE/g) were obtained with 1.5% MG, 30% MD, and 120°C. Higher MG levels were associated with greater crystallinity, according to XRD studies. According to the study, MG is a natural wall material that works well for TCW microencapsulation in food applications (Nambiar, R. B., et.al., 2017).

In previous studies of Boonnumma, s shows that, rich in vitamins and minerals, coconut water quickly loses its flavor and nutritional value when exposed to heat and air. Processing at high temperatures further degrades its quality, which affects its marketability. King Mongkut's University of Technology Thonburi devised a freeze-drying technique that yields 63.8±2.7 kg of powder per ton of coconut water while preserving the original flavor and minerals. The nutritional composition of the powder is quite similar to that of fresh coconut water. For added value and commercial potential, it was recommended that more research be done on the incorporation of tender coconut meat (Boonnumma, S., et.al., 2014).

This study of Tanongkankit, Y, investigated how the volatile aroma and physicochemical characteristics of freeze-dried coconut water were affected by three different encapsulating agents: xanthan gum (0.1–0.3%), polydextrose (4–8%), and maltodextrin (4–8%). Water activity and moisture content were unaffected by pre-freezing in plate and air blast freezers. The best encapsulant was found to be polydextrose at 8%, which greatly improved scent retention. Alkanes, aldehydes, ketones, esters, and phenols were among the flavoring components; SPME-GC-TOFMS was used to examine the volatile profiles. During the freeze-drying process, encapsulating agents were essential to maintaining the rich aroma of coconut water (Tanongkankit, Y., et.al., 2023).

In this study assessed the shelf life, sensory qualities, and nutritional value of a freeze-dried coconut beverage prepared from the water and meat of young coconuts. Lysine, leucine, valine, arginine, and fatty acids including lauric, myristic, and oleic acids were among the amino acids found in the powder, which was low in sodium and high in magnesium and iron. Despite a slight loss of sweetness and a diminished fermented scent, freeze-drying maintained the sensory quality. The shelf life was increased to 30 days at 45°C, 44 days at 35°C, and 59 days at 25°C. With improved stability, the product generally maintained the nutrition and flavor of fresh coconut drink (Setiawan, A., et.al.,2022).

In this study of Bridgemohan, P shows that, coconut water at various stages of maturity both plain and flavored with passion fruit and mango was used to create a freeze-dried oral rehydration solution (ORS). The procedure included vacuum freeze-drying and 48 hours of freezing at -30°C. The finished product had a longer shelf life, improved taste, and good electrolyte and analyte balance. As the fruit matured, the electrolyte concentration rose, and flavored coconut water occasionally had higher electrolyte levels than unflavored coconut water. The product presents a viable, more palatable, and shelf-stable substitute for traditional ORS in rural and disaster-affected areas (Bridgemohan, P., et.al., 2016).

Nandhakumar, S. studies show that, rich in proteins, vitamins, and minerals like potassium, calcium, salt, and iron, coconut water is a low-calorie, nutrient-dense beverage. It provides phenolic chemicals including tocopherols and antioxidants when combined with coconut pulp. It is advised for sportsmen and patients due to its well-known rehydrating qualities. The goal of this project is to create coconut water powder by freeze-drying and spray-drying it, then adding vitamin D to it for added health advantages (Nandhakumar, S. et.al., 2021).

Coconut water is a nutrient-dense, low-calorie beverage that naturally contains antioxidants and electrolytes. Drying techniques like freeze-drying and spray-drying assist maintain nutrients while extending shelf life. Maltodextrin, polydextrose, and Moringa oleifera gum are examples of encapsulating agents that enhance flavor stability and retention. Commercial and functional value are added by vitamin D fortification and fruit flavoring. Coconut water powder is a promising choice for rehydration solutions and health drinks because of these methods.

2.8. Research Gaps and Future Directions

Even with advancements in making coconut water powder, some challenges still need solutions. One of the biggest issues is stability and shelf life. Coconut water powder easily absorbs moisture, which can cause clumping and make it difficult to use. Additionally, important nutrients like vitamins and antioxidants can break down over time, especially in warm storage conditions. To solve this, researchers need to develop better anti-caking agents, improved packaging, and advanced protective techniques to maintain the powder's quality and nutrition for longer periods.

Another key challenge is improving the drying process. Most coconut water powders are made using spray drying or freeze drying, but other methods like vacuum drying, drum drying, and infrared drying are not widely studied. The drying method affects the taste, color, and nutrient content of the powder, so further research is needed to find the best techniques or even combine different drying methods for better results.

There is also great potential for functional and fortified coconut water powders. Coconut water is naturally rich in electrolytes, but research on enhancing its benefits with probiotics, plant-based proteins, vitamins, and minerals is still limited. Such enhanced powders could be useful for athletes, people with dietary restrictions, and health-conscious consumers. However, more studies are needed to ensure that these added nutrients remain stable and effective in powdered form.

Another challenge is maintaining flavor and aroma. Coconut water powder often loses its fresh taste during processing, which can make it less appealing to consumers. Finding ways to preserve its natural flavor using mild drying conditions, natural flavor enhancers, or special processing techniques could help maintain its original freshness.

Looking ahead, the future of coconut water powder lies in more advanced drying methods like ultrasound-assisted drying, pulsed electric field drying, and supercritical drying. These methods could help retain more nutrients and extend shelf life. Further improvements in encapsulation techniques, such as nano-coatings or biopolymer-based protection, could also help keep nutrients stable. Smart packaging, like biodegradable moisture-resistant materials, could further extend the product's usability.

Another exciting area of development is the creation of specialized coconut water powders for health and wellness. This could include versions enriched with herbal extracts, plant-based proteins, or adaptogens to cater to growing consumer demand for natural health drinks. Lastly, more clinical research is needed to better understand how coconut water powder supports hydration, electrolyte balance, and overall health in different populations.

Additives Used in Coconut Water Formulation

Additives are commonly incorporated into coconut water formulations to enhance stability, texture, mouthfeel, sweetness, and shelf life without compromising nutritional quality. These additives help improve the sensory attributes and processability of coconut water, especially when it is subjected to thermal or non-thermal preservation methods. Key additives used include:

- **Maltodextrin:**

  Maltodextrin is added primarily for its ability to improve mouthfeel and texture without adding sweetness. In coconut water formulations, it acts as a bulking agent and helps stabilize the product by forming smooth gels that contribute to a clean, coating sensation in the mouth. With a low dextrose equivalent (DE), it behaves similarly to natural starch and can be added in concentrations ranging from 1–15%. It also aids in reducing crystallization and moisture migration during drying or concentration processes and can partially replace fat in coconut-based formulations.

- **Guar Gum:**

  Guar gum serves as an effective thickening and stabilizing agent in coconut water blends. It increases the viscosity of the beverage, improving suspension of particles and preventing phase separation. Its high water-binding capacity ensures a uniform texture and helps in maintaining product stability during storage.

- **Dextrose:**

  Dextrose is added as a sweetener and mild preservative in coconut water products. Besides enhancing the sweetness, it supports fermentation control and improves flavor balance. Its fine solubility and clean taste profile make it suitable for liquid formulations. Additionally, dextrose contributes to the overall energy content and acts as a fermentable sugar source when coconut water is used in probiotic or fermented drinks.

The combination of these additives enhances the overall quality, consistency, and sensory appeal of coconut water, especially in processed or value-added forms.

Chapter 3 - Materials and Methods

3.1. Materials

3.1.1. Source of Coconut Water

Fresh coconut water was obtained from a local store. The coconuts were selected based on their freshness, quality, and ripeness. Coconut water is the primary source for producing coconut water powder. The water was extracted by manually cracking the coconuts and collecting the liquid in a bottle. It was then filtered using a sieve to remove any solid impurities. Before further processing, the Brix value of the tender coconut water was measured to assess its sweetness. Brix is a measure of the sugar content in a liquid. The filtered coconut water was then stored at 4 °C until further processing.

3.1.2. Ingredients Used for Formulation

Maltodextrin:

Food-grade maltodextrin, sourced from Amazon, was used as an encapsulating agent. It played a key role in enhancing the stability and flow properties of the coconut water powder, facilitating the production of a free-flowing and easy-to-handle product.

Guar Gum:

Commercially available food-grade guar gum powder was procured from Amazon. The product was used as received and stored in a cool, dry environment to maintain its quality. Prior to use, it was characterized for its physicochemical properties to ensure suitability for formulation.

Dextrose:

Dextrose (D-glucose), a naturally occurring sugar used to impart sweetness, was also obtained from Amazon as a food-grade product. It was utilized in the formulation to improve the palatability and sensory profile of the coconut water powder.

3.2. Methodology

3.2.1. Spray Drying Process:

Figure 2 Snap Shot of Spray Dryer

For this experiment, a lab-scale spray dryer was employed to convert coconut water into a fine, shelf-stable powder. Spray drying is an efficient method for transforming liquids into dry powders and involves three primary components: an atomizer, a heating chamber, and a cyclone separator (**Figure 2**). Each component plays a vital role in the drying process.

The atomizer functions as a high-precision nozzle that breaks the liquid coconut water into a fine mist of tiny droplets. These droplets are then introduced into the heating chamber, where they come into contact with hot air. The heat causes rapid evaporation of moisture, leaving behind solid powder particles. The resulting powder is then carried into the cyclone separator, which uses centrifugal force to separate the dried powder from the air stream, allowing it to be collected efficiently for further use.

To evaluate how different operating conditions affect the quality of the coconut water powder, we systematically varied three key parameters: inlet temperature, outlet temperature, and feed flow rate. These variables were carefully adjusted to study their influence on critical powder properties such as moisture content, solubility, and nutrient retention. Meanwhile, other factors such as the concentrations of maltodextrin and guar gum, as well as the initial composition of the coconut water were kept constant. This controlled approach ensured that any observed changes in powder characteristics could be directly attributed to the operational parameters under investigation, enhancing the reliability and relevance of the results.

Prior to each trial, the spray dryer was preheated to the desired inlet temperature. This preheating step was essential for maintaining consistent thermal conditions throughout the drying process. Although it required some time, it ensured that the system was fully prepared to process the feed efficiently.

Once the target temperature was reached, the coconut water pre-mixed with maltodextrin and guar gum was introduced into the spray dryer through a feeding pipe. The atomizer dispersed the liquid into a fine mist, which was rapidly dried upon contact with the hot air in the chamber.

After drying, the powder-laden air entered the cyclone separator. As the air swirled within the cyclone, the heavier powder particles were flung outward by centrifugal force, collecting along the walls and falling to the bottom for easy recovery. The clean air, now free of powder, exited the system.

This methodical, step-by-step approach ensured uniformity in each trial, resulting in data that was both reliable and reproducible.

3.2.2. Process Parameters and Optimization

1. Coconut Powder with Maltodextrin and Dextrose

To prepare this formulation, a mixture containing 7–12% maltodextrin**,** 3–8% dextrose**,** and 85–95 mL of coconut water was used. The volume of coconut water was adjusted based on its °Brix value**,** which reflects the sugar content.

The mixture was subjected to spray drying, with an inlet temperature maintained between 120–150 °C and an outlet temperature **of** 60–85 °C. The feed rate was maintained at 1 mL/min**.**

Upon completion of the drying process, the powder was collected from two sections of the spray dryer:

- **Cyclone separator**
- **Cylindrical chamber wall**

To ensure maximum recovery, the chamber walls were gently scraped to collect any residual powder.

2. Coconut Powder with Maltodextrin and Guar Gum

For this formulation, a blend of 5–10% maltodextrin**,** 0.1–1 g of guar gum, and 90–95 mL of coconut water was prepared. This mixture was also processed via spray drying.

During spray drying:

- The inlet temperature was set between 150–180 °C
- The outlet temperature was maintained at 55–65 °C
- The feed rate was kept at 1 mL/min

After drying, the powder was collected from the cyclone separator.

To enhance sweetness and tailor the sensory properties of the final product, dextrose was added post-drying. This step ensured the powder achieved the desired level of sweetness for its intended application.

3.3. Characterization of Coconut Water Powder

3.3.1. Moisture Content

Principle

The oven drying method determines the moisture content of a sample by measuring the weight loss after drying at a specific temperature. The difference in weight before and after drying corresponds to the amount of water present in the sample.

Apparatus

- Hot air oven (capable of maintaining 105 °C ± 2 °C)
- Analytical weighing balance
- Desiccator
- Moisture dishes
- Tongs
- Coconut powder sample

Procedure

1. The moisture dish was dried in the hot air oven at 105 °C for 30 minutes and then cooled in a desiccator.
2. The dry dish was weighed and the weight was recorded as W_1.
3. Approximately 1 g of the coconut powder sample was weighed and placed in the dish. The total weight of the dish and sample was recorded as W_2.
4. The sample was then placed in the preheated oven at 105 °C ± 2 °C for 3 hours.
5. After drying, the dish containing the sample was transferred to a desiccator and allowed to cool for 30 minutes.
6. The final weight of the dish and dried sample was recorded as W_3.

Calculation

$$\text{Moisture content (\%)} = \frac{(W_2 - W_3)}{(W_2 - W_1)} \times 100$$

Where:

- W_1 = Weight of the empty dish
- W_2 = Weight of the dish + sample (before drying)
- W_3 = Weight of the dish + sample (after drying)

3.3.2. Determination of Water Activity

Figure 3 Snapshot of Water Activity Meter

Principle

Water activity (aw) refers to the amount of free (unbound) water available in a food product, which plays a critical role in determining its shelf life, safety, and stability. It is defined as the ratio of the vapor pressure of water in the food to the vapor pressure of pure water at the same temperature. For instance, a water activity value of 0.80 means that the vapor pressure of the food is 80% that of pure water under identical conditions. Water activity generally increases with temperature. It can be expressed either in decimal form (e.g., 0.80) or as equilibrium relative humidity (ERH**)** in percentage (e.g., 80%). Understanding aw helps assess the food's susceptibility to microbial growth, chemical reactions, and physical changes during storage.

Materials Required

- Sample plate
- Water activity meter

- Coconut water powder

Procedure

Approximately 1–2 grams of coconut powder were evenly spread on the sample plate and placed inside the water activity meter, as shown in **Figure 3**. The system was then allowed to stabilize, giving the sample time to reach equilibrium with the surrounding environment inside the chamber. This equilibration process typically took about 2–3 minutes, although the exact time varied depending on the nature of the sample. Once equilibrium was achieved, the water activity value was recorded directly from the instrument.

3.3.3. Estimation of Reducing Sugar Using DNS Method

Principle

Reducing sugars have the ability to reduce various chemical reagents, including 3,5-dinitrosalicylic acid (DNS). In an alkaline medium, DNS is reduced to form 3-amino-5-nitrosalicylic acid, resulting in a color change that can be quantified spectrophotometrically. This colorimetric change corresponds to the concentration of reducing sugars present in the sample.

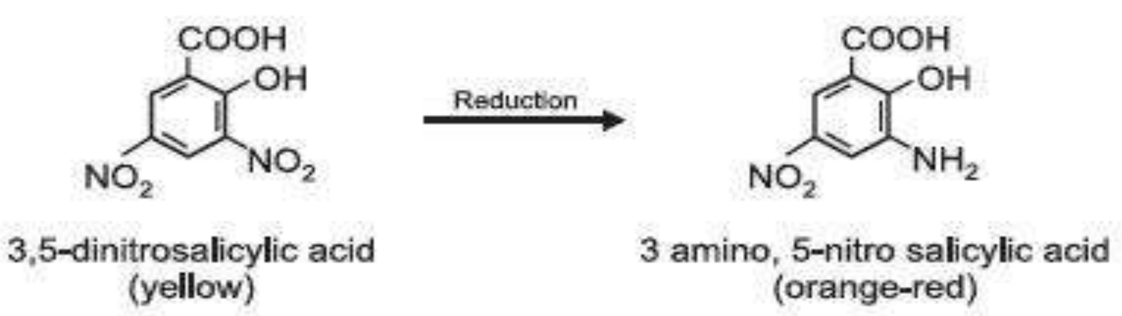

Figure 4: Reduction of 3,5 – dinitro salicylic acid to 3 amino, 5- nitro salicylic acid.

Reagents Required

1. 3,5-DNS Solution: 0.5 g of DNSA dissolved in 25 mL of distilled water.

2. 2 M NaOH: 4 g of sodium hydroxide dissolved in 50 mL of distilled water.
3. Sodium Potassium Tartrate: 9 g dissolved in 15 mL of distilled water.
4. DNS Reagent: A mixture containing 100 mg NaOH, 100 mg DNSA, 5 mg sodium sulfite, and 200 µL phenol, dissolved in 10 mL of distilled water.

Standard Solution Preparation

- **Standard Glucose Solution**: 10 mg of glucose dissolved in distilled water and made up to 10 mL in a volumetric flask.

Sample Preparation

- **Sample Solution**: 10 mg of the coconut powder sample (with maltodextrin and guar gum) dissolved in distilled water and made up to 10 mL in a volumetric flask.

Procedure

1. Seven test tubes were labelled: 0, 20, 40, 60, 80, 100 µL, along with one for the sample solution.
2. Standard glucose dilutions were prepared by transferring the respective volumes (µL) from the standard glucose solution to each tube and adjusting the total volume with distilled water, as detailed in **Table 3.**
3. To each tube, 100 µL of the sample or standard solution was added, followed by 300 µL of DNS solution.
4. All tubes were placed in a water bath at 80–90 °C for 15 minutes to facilitate the reaction.
5. After incubation, the reaction mixtures were cooled and diluted with 1 mL of distilled water.
6. Then, 200 µL of sodium potassium tartrate was added to each tube to stabilize the color.
7. The absorbance was measured at 540 nm using a UV-Visible spectrophotometer.

Table 3 Procedure for DNSA method

Concentration (μg/mL)	Glucose (μL)	Distilled water (μL)	DNSA solution (μL)			Potassium sodium tartrate (μL)
0	0	300	300	Allow the test tube to keep in water bath for 15 mins	Shake and add 1.4 mL of distilled water	200
20	20	280	300			200
40	40	260	300			200
60	60	240	300			200
80	80	220	300			200
CPMG 100	CPMG 100	200	300			200

3.3.4. Determination of Total Sugar Content

Table 4 Procedure for Total Sugar Content (Phenol-Sulphuric acid method)

Concentration (μg/mL)	Distilled water (μL)	Distilled water (μL)	5% Phenol (mL)	Conc.H_2SO_4 (mL)
0	0	2	1	5
40	40	1.96		
80	80	1.92		
120	120	1.88		
160	160	1.84		
200	200	1.8		
CPMG 100	CPMG 100	1.9		
CPMG 100	CPMG 100	1.9		

Principle

The phenol-sulfuric acid method is a widely used colorimetric technique for the estimation of total carbohydrates in a sample. In this method, concentrated sulfuric acid hydrolyzes and dehydrates polysaccharides into furfural derivatives (such as uronic acid and hydroxyfurfural). These compounds then react with phenol to form a stable orange-red colored complex, which can be quantified spectrophotometrically. The intensity of the color, measured at 540 nm**,** is directly proportional to the carbohydrate content in the sample, as represented in **Table 4**.

Reagents

- 5% Phenol solution: Prepared by dissolving 2.5 g of phenol in a 50 mL volumetric flask with distilled water.
- Concentrated Sulfuric Acid (H_2SO_4)
- Standard Solution**:** 10 mg of glucose dissolved in 10 mL distilled water (used as a calibration standard).
- **Sample Solution**: 10 mg of the sample dissolved in 10 mL distilled water**.**

Procedure

1. Standard and sample solutions were prepared as described above.
2. To each test tube containing 1 mL of either standard or sample solution, 1 mL of 5% phenol was added.
3. 5 mL of concentrated sulfuric acid was then rapidly added to each tube.
4. The mixtures were gently shaken and incubated at room temperature for 30 minutes to allow complete color development.
5. The absorbance was measured at 540 nm using a UV-Visible spectrophotometer**.**

3.3.5. pH Determination (pH meter)

Principle

The pH of a solution indicates its acidity or alkalinity by measuring the hydrogen ion activity**.** It was determined using a commercial pH meter, which measures the electrical potential between a glass electrode and a reference electrode. The pH meter was calibrated using NIST primary standard buffer solutions.

Materials Required

- pH meter
- Electrode
- Buffer tablets (pH 4.0, 7.0, 9.2)
- Distilled water
- Coconut powder

Procedure

1. The pH meter was switched on and calibrated using standard buffer solutions of pH 4.0, 7.0, and 9.2**.**
2. Each buffer tablet was dissolved in distilled water using a digital vortex mixer to prepare the calibration solutions.
3. The electrode was rinsed with distilled water and gently blotted dry using tissue paper.
4. A sample was prepared by dissolving 1 g of coconut powder in 10 mL of distilled water**.**
5. After calibration, the electrode was rinsed again with distilled water and dipped into the prepared coconut sample solution**.**
6. The system was allowed to stabilize, and once the reading became steady, the pH value was recorded.

3.3.6. Titrable Acidity:

Principle

Titrable acidity (TA) was measured to determine the total acid content in the sample by neutralizing it with a standardized base solution (0.1N sodium hydroxide, NaOH) in the presence of an indicator such as phenolphthalein. The volume of base required to reach the endpoint (approximately pH 8.2**)** represented the total acidity, typically expressed as an equivalent of citric acid**,** lactic acid, or acetic acid, depending on the food product.

Materials Required

- Coconut powder sample
- Distilled water
- 0.1N Sodium Hydroxide (NaOH) solution
- 1% Phenolphthalein indicator
- Pipette (10 mL)
- Burette (50 mL)
- Conical flask (250 mL)

Reagent Preparation

0.1N NaOH was prepared by dissolving 0.4 g of NaOH pellets in distilled water and making up the volume to 100 mL in a 100 mL volumetric flask.

Sample Preparation

1 g of coconut powder was weighed and dissolved in 10 mL of distilled water in a volumetric flask.

Procedure

1. The burette was filled with 0.1N NaOH and the reading was set to zero.
2. 10 mL of the prepared sample was pipetted into a 250 mL conical flask.
3. 2–3 drops of 1% phenolphthalein indicator were added to the sample.

4. The sample was titrated with 0.1N NaOH until a persistent light pink color appeared, indicating the endpoint.
5. The volume of NaOH used was recorded.

Calculation

$$\text{Titratable Acidity (\% Citric Acid)} = \frac{V \times N \times 0.064 \times 100}{W}$$

Where:

- V = Volume of NaOH used (mL)
- N = Normality of NaOH (0.1 N)
- 0.064 = Milliequivalent weight of citric acid
- W = Weight of the coconut powder sample (g)

3.3.7. Determination of Total Soluble Solids

Figure 5 Snapshot of Refractometer

Principle

The refractive index of the test solution is measured at 20 °C using a refractometer. This value is then used to determine the soluble solids content, typically expressed as sucrose percentage (°Brix), either through standard correlation tables or directly if the refractometer provides a °Brix reading.

Materials Required

- Distilled water
- Refractometer
- Dropper

Procedure

First, the refractometer (**Figure 5**) was calibrated using distilled water. After calibration, 2 drops of the sample were added to the refractometer using a dropper. The 'read' button was then pressed, and the °Brix value of the sample was recorded from the display.

3.3.8. Sensory Evaluation

The 9-point hedonic scale is a widely used sensory evaluation method that helps measure a person's level of liking or disliking toward a product. It consists of nine distinct points, with a neutral option positioned at the centre. The scale includes four positive levels indicating increasing degrees of liking and four negative levels indicating increasing degrees of disliking. Each point on the scale is accompanied by descriptive terms that reflect varying intensities of preference or aversion, making it user-friendly and effective for capturing consumer responses in a consistent and interpretable manner (Lim, J. et al., 2011).

Score value interpretation:

- 9 – Like extremely
- 8 – Like very much
- 7 – Like moderately
- 6 – Like slightly
- 5 – Neither like nor dislike (neutral)
- 4 – Dislike slightly
- 3 – Dislike moderately
- 2 – Dislike very much

- 1 – Dislike extremely

Chapter 4 – Results and Discussion

4.1. Effect of Spray Drying Parameters on Coconut Water Powder Characteristics

4.1.1. Influence of Inlet Temperature

Table 5 Influence of Inlet Temperature

Formulation	Inlet temperature (°C)	Powder after drying	Flowability	Other observations
CWP with maltodextrin and dextrose	120	0.12g	Poor (sticky)	The powder was hygroscopic and the sensory was not good.
	130	0.5g	Moderate	Powder felt slight thick. Sensory was also not very good.
	140	1.01g	Fair	Powder flowability improved, but sensory was not good.
	160	1.2g	Good	Powder came good, but slightly hygroscopic.
CWP with maltodextrin and guar gum	120		Very poor (very sticky)	Powder was very hygroscopic.
	140	0.5g	Fair (slightly sticky)	Powder is slightly hygroscopic. Powder is clumping together quickly.
	150	0.84g	Fair	Slightly sticky. Difficult to solubilize.
	160	1.25g	Moderate	Hygroscopic after exposed to air.
	165	1.67g	Good	Slightly hygroscopic and sensory was good.
	180	2.03g	Best	Free flowing powder got with maximum recovery of powder. Sensory was also good

The influence of inlet temperature on the formulation of spray-dried coconut water powder (CWP) is shown in **Table 5**. This study highlights how inlet temperature significantly affects powder yield, flowability, hygroscopicity**,** and sensory quality for different formulations of CWP.

1. CWP with Maltodextrin and Dextrose

Spray drying at lower inlet temperatures (120–140 °C) led to poor powder recovery and sticky, hygroscopic powders. At 120 °C, the powder yield was only 0.12 g and exhibited poor flowability and unacceptable sensory quality. Increasing the inlet temperature to 130 °C and 140 °C improved yield and flowability slightly (0.5 g and 1.01 g, respectively), but the powder remained sticky with suboptimal sensory attributes**.**

At 160 °C, yield improved to 1.2 g with good flowability, but slight hygroscopicity was still observed. These findings align with the observation that lower temperatures result in incomplete drying, leading to powder stickiness and clumping due to residual moisture.

2. CWP with Maltodextrin and Guar Gum

In the case of the maltodextrin-guar gum formulation, lower temperatures (120–150 °C) also resulted in sticky, hygroscopic powders with poor solubility and flowability. At 120 °C, no significant powder could be recovered due to stickiness, while at 150 °C**,** yield improved to 0.84 g**,** though the powder was still difficult to solubilize.

As inlet temperature increased to 160 °C and 165 °C, powder quality improved significantly yield increased, and the powder became less sticky and easier to handle, though some hygroscopicity remained. At 180 °C**,** the formulation produced the best result**,** yielding 2.03 g of free-flowing powder with good sensory attributes. In an optimized process condition (noted in **Table 5**), a maximum recovery of 4.83 g was recorded for this formulation at 180 °C, indicating excellent drying efficiency and product quality.

Comparative Insights

Comparative analysis shows that the guar gum–maltodextrin formulation outperformed the dextrose–maltodextrin blend in terms of yield, flowability, and sensory attributes**,** especially at higher inlet temperatures. This can be attributed to dextrose's hygroscopic nature, which promotes stickiness during drying. Guar gum, being a hydrocolloid, likely contributed to better structural integrity and drying efficiency.

Furthermore, the study clearly demonstrates that inlet temperature is a critical parameter influencing the drying process. While lower temperatures (120–140 °C) resulted in inadequate drying**,** higher temperatures (160–180 °C) significantly enhanced powder recovery, flowability, and overall sensory quality**.**

Overall, 180 °C was found to be the optimal inlet temperature for spray drying coconut water powder to achieve maximum powder recovery, free-flowing behaviour**,** and acceptable sensory properties**.** However, to ensure an optimal balance between quality, yield, and nutritional value, future studies should also examine the impact of high drying temperatures on the retention of nutrients and solubility of the final powder product.

4.1.2. Effect of Feed Flow Rate

Table 6 Effect of Feed Flow Rate on Yield, Flowability, and Sensory Properties of Coconut Water Powder

Feed flow rate (mL/min)	Yield	Flowability	Sensory properties
1.5	High	Good	Free flowing powder obtained.
2.0	Medium	Moderate	Slightly hygroscopic.
2.5	low	Poor (sticky)	Very much hygroscopic.

The study (**Table 6**) showed that spray-dried coconut water powder's (CWP) yield, flowability, and sensory qualities are greatly influenced by the feed flow rate during spray drying.

At a feed rate of 1.5 mL/min**,** the maximum yield and best powder flowability were obtained. The powder was free-flowing**,** non-hygroscopic, and had favorable sensory attributes, making this condition optimal among those studied. The slower input rate allowed for more efficient drying, resulting in better powder structure and minimal moisture retention.

When the feed flow rate increased to 2.0 mL/min, the yield decreased moderately, and the powder became slightly hygroscopic with reduced flowability. This suggests incomplete drying due to insufficient residence time in the drying chamber. Although the powder remained usable, the quality was clearly compromised compared to that at the lower flow rate.

At 2.5 mL/min, the powder exhibited poor flowability**,** high hygroscopicity, and low yield. The increased liquid load likely exceeded the drying capacity, leading to excess moisture retention**,** stickiness, and reduced powder recovery. The sensory quality was also poor due to the resulting clumpy texture.

Overall, it was concluded that the ideal feed flow rate for producing high-yield, free-flowing coconut water powder with desirable sensory quality is 1.5 mL/min. However, further research is recommended to assess the effects of flow rate on powder moisture content, solubility, and particle morphology, with the goal of refining spray-drying parameters for enhanced stability and reconstitution behaviour**.**

4.2. Physicochemical Properties of the Powder

4.2.1. Moisture Content

The moisture content of the coconut water powder formulated with 10% maltodextrin and 0.1% guar gum was found to be 4.11%. This low moisture level indicates that the powder is stable, with reduced risk of caking or microbial spoilage during storage, and reflects efficient drying performance. The presence of maltodextrin aids in the drying process and minimizes stickiness, while the small amount of guar gum enhances the mixture's viscosity, promoting better film formation and moisture retention control during spray drying.

4.2.2. Determination of Water activity

The water activity (aw) of the coconut water powder formulated with maltodextrin and guar gum was measured to be 0.173. This low value indicates excellent microbiological stability, as most spoilage microorganisms cannot grow below an aw of 0.6.

The inclusion of maltodextrin helps reduce water availability by effectively binding moisture, while guar gum contributes to the structural stability of the powder matrix. An aw of 0.173 suggests that the powder is shelf-stable and less susceptible to microbial growth, oxidation, and enzymatic degradation during storage.

4.2.3. Reducing Sugar

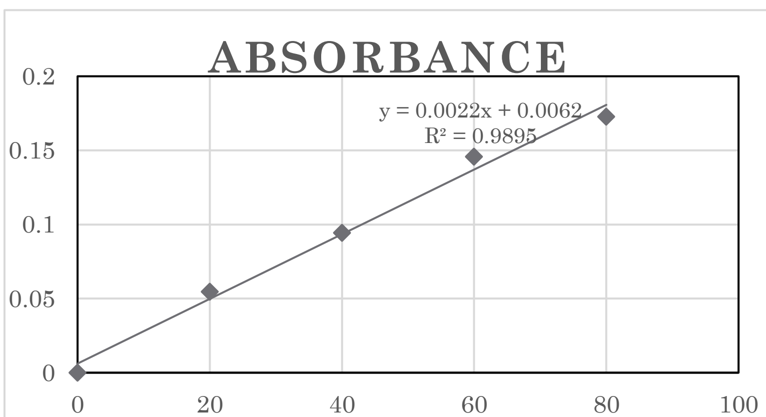

Figure 6 Graph for Absorbance of Reducing Sugar

As illustrated in **Figure 6**, the reducing sugar content in the coconut powder formulated with maltodextrin and guar gum was approximately 38.42 µg/mL.

Calculation:

y= Absorbance
x= Concentration in µg/mL

y= 0.0022x + 0.0062

y= 0.0907

$$x = \frac{0.0907-0.0062}{0.0018} = 38.42 \ \mu g/mL$$

4.2.4. Total Sugar Content

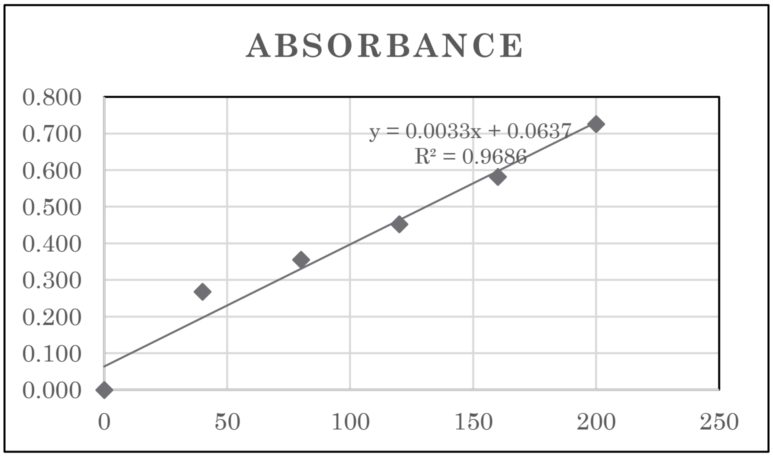

Figure 7 Graph for Absorbance of Total Sugar

As shown in **Figure 7**, the total sugar content in the coconut powder formulated with maltodextrin and guar gum was approximately 97.70 µg/mL.

Calculation:
y= Absorbance
x= Concentration in µg/mL
y=0.0033x + 0.0637

y= 0.3861

$$x = \frac{y-0.0637}{0.0033} = 97.70 \ \mu g/mL$$

4.2.5. pH Determination

The pH of the instant coconut water powder formulated with maltodextrin and guar gum was measured to be 5.15. This value indicates that the powder retains the natural acidity of fresh coconut water, which typically ranges from 5.0 to 5.6**.**

The pH of normal coconut water is 4.8.

The presence of maltodextrin and guar gum in the formulation may slightly influence the final pH by modifying the acidity or buffering capacity of the coconut water. However, since the pH remains within the expected range, it suggests that the formulation does not significantly alter the natural characteristics of coconut water.

4.2.6. Titrable Acidity

The titratable acidity of the coconut water powder formulated with maltodextrin and guar gum was found to be 0.098**%**, expressed as citric acid equivalent. This mild level of acidity is typical for coconut water products and helps preserve their characteristic flavor profile.

The inclusion of maltodextrin and guar gum as carrier agents did not significantly alter the acidity, indicating that the formulation successfully retained the natural acidity of coconut water throughout the spray drying process.

4.2.7. Determination of Total Soluble Solids

Using a refractometer, the total soluble solids (TSS) of the coconut water powder formulated with maltodextrin and guar gum were measured at 9.5°Brix. This value reflects the concentration of dissolved substances primarily sugars and other soluble components in the reconstituted beverage.

The total soluble solids of the tender coconut water was 5.1°Brix.

The TSS falls within the acceptable range for coconut water-based beverages, indicating that the formulation effectively retained the natural soluble content and sweetness of coconut water. The slight increase in Brix can be attributed to the carbohydrate content of maltodextrin, while guar gum, being a hydrocolloid, contributes minimally to TSS.

4.3. Sensory Evaluation of Coconut Water Powder

4.3.1. Color, Taste, and Aroma

Table 7 Sensory Evaluation

Sample code	Appearance	Aroma	Flavour	Color	Mouthfeel	Sweetness	sourness	Overall acceptability
CWPMG	8	7	7	8	7	7	7	7
TCW	8	8	8	8	8	8	7	8

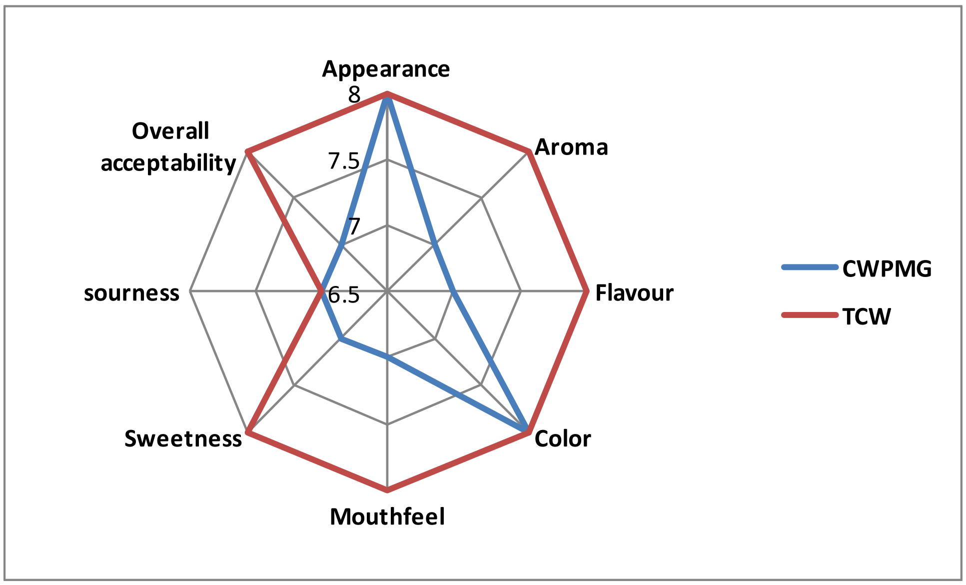

Figure 8 Sensory Evaluation of CWP

According to the sensory analysis presented in **Table 7**, Tender Coconut Water (TCW) received higher ratings for most sensory attributes, including flavor, mouthfeel, sweetness, aroma, and overall acceptability**,** indicating a stronger consumer preference compared to Coconut Powder with Maltodextrin and Guar Gum (CPMG) showed in the **Figure 8.**

However, when fresh coconut water is not available, CPMG serves as a suitable alternative, performing well particularly in terms of appearance and color. While the natural taste and texture of fresh tender coconut water are superior, powdered coconut water offers the advantages of convenience and extended shelf life. With minor adjustments to its formulation and processing, it may come even closer to replicating the sensory attributes of its fresh counterpart.

4.4. Challenges and Limitations of Spray Drying Coconut Water

One major concern is that heat can degrade both flavor and essential nutrients. Coconut water contains delicate components such as vitamin C and natural aroma compounds, which are sensitive to high temperatures. Exposure to excessive heat can reduce the nutritional quality and freshness of the final powder.

Another challenge lies in the natural sweetness and stickiness of coconut water, which can cause operational issues during spray drying. The stickiness can lead to clogging of equipment, reducing yield and efficiency. Furthermore, the resulting powder tends to be hygroscopic, meaning it easily absorbs moisture from the air, leading to clumping and shortened shelf life.

To address these issues, carrier agents such as maltodextrin are often added to improve drying performance and reduce stickiness. However, using these agents in excess can negatively affect the flavor and nutritional profile of the powder. Additionally, precise control of inlet temperature and feed rate is crucial. Too high a temperature can cause browning and nutrient degradation, while inadequate drying at low temperatures can result in incomplete moisture removal. Similarly, an excessively high feed rate may compromise the drying efficiency and quality of the final product.

Another drawback is that some coconut water powders do not reconstitute well, often forming lumps or foam when mixed with water. Moreover, spray drying is an energy-intensive and costly process, requiring specialized equipment.

Despite these challenges, spray drying remains an effective method for producing portable and shelf-stable coconut water powder. With optimized formulations**,** improvements in process parameters, and the exploration of novel drying technologies, manufacturers can develop high-quality coconut water powder that more closely mimics the taste and nutritional value of fresh coconut water**.**

Chapter 5 - Conclusions and Recommendations

5.1. Summary of Findings

This study identified an effective method for converting coconut water into a convenient powder using spray drying. The optimal results were achieved when coconut water was combined with maltodextrin and guar gum, and dried at 180°C with a slow feed flow rate of 1.5 mL/min. This condition produced 2.03 g of free-flowing, flavorful powder.

In contrast, drying at lower temperatures (120–140°C) resulted in a sticky powder with high moisture absorption, while higher feed flow rates (2.0–2.5 mL/min) led to incomplete drying and lower powder yield.

The final powder exhibited good stability with a pH of 5.15, low moisture content (4.11%), and a natural sweetness of 9.5 °Brix, closely resembling fresh coconut water. Additionally, the low water activity (0.173) suggests excellent microbial stability and extended shelf life.

Despite these positive outcomes, there is still room for improvement. Although the powdered form resembled fresh coconut water in appearance and aroma, the fresh version retained superior flavor and smoother texture. Challenges such as stickiness, clumping, and nutrient loss remain key limitations.

While the addition of maltodextrin and guar gum helped mitigate some of these issues, future research could focus on gentler drying methods or nutrient enhancement strategies to further improve the quality and sensory appeal of the coconut water powder.

5.2. Key Conclusions

The properties of coconut water powder were significantly influenced by feed flow rate and inlet temperature**.** While higher inlet temperatures may have impacted certain quality attributes, they generally contributed to improved powder yield and enhanced flowability**.**

The choice of carrier agents also played a crucial role in determining the final product's characteristics. Between maltodextrin-dextrose and maltodextrin-guar gum combinations, the inclusion of guar gum appeared to enhance powder stability, likely due to its viscosity-modifying and moisture-retention properties.

To achieve the desired powder quality while preserving the nutritional and functional properties of coconut water, it is essential to optimize spray drying parameters**,** particularly inlet temperature, feed flow rate, and carrier agent composition.

5.3. Recommendations for Future Research

To enhance both the quality and sensory properties of coconut water powder, alternative drying techniques can be explored. These methods may improve the overall sensory experience of the powder. Additionally, instead of using maltodextrin, other carrier agents could be considered to improve the stability, solubility, and overall quality of the powder. Given that maltodextrin has a high glycemic index, which can lead to rapid spikes in blood sugar levels, it may not be the best choice for a healthier formulation.

5.4. Implications for Industry

For food and beverage manufacturers, the development of spray-dried coconut water powder presents significant opportunities. This shelf-stable product addresses the perishability challenges of liquid coconut water, providing a convenient way to incorporate its natural electrolytes and nutrients into various applications.

As consumer demand for health and wellness products grows, the food industry can further enhance coconut water powder by adding beneficial ingredients such as probiotics, vitamins, and plant-based proteins, thereby boosting its nutritional value. To better preserve nutrients and natural flavors, advanced drying techniques, such as freeze-drying or a combination of spray drying with other methods, can be employed. Additionally, improving encapsulation techniques will help protect vital nutrients and maintain the fresh coconut aroma, ensuring a more flavorful and nutritious final product.

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