Encapsulation And Stability Analysis of *Syzygium Cumini* (Jamun) Anthocyanin Using Foam Mat Drying

A thesis submitted in partial fulfilment of the requirement for the award of the

degree of

MASTERS OF TECHNOLOGY

IN

BIOTECHNOLOGY

Submitted by

Harmeet Singh

(602304003)

Under the guidance of

Dr. Ovais S. Qadri

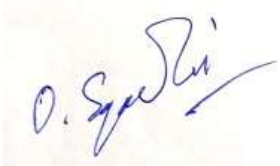
Assistant Professor

Department of Biotechnology

TIET, Patiala (2025)

CERTIFICATE

This is to certify that the thesis entitled "Encapsulation and stability analysis of anthocyanin from *Syzygium cumini* (Jamun) using foam mat drying", submitted by Mr. Harmeet Singh (602304003) in the partial fulfilment of the requirement of the award of the degree of Master of Technology in Biotechnology at Thapar Institute of Engineering and Technology (TIET), Deemed to be University, Patiala is a record of student's own work carried out under my supervision and guidance. This work has not been submitted in part or in full to any other university or institute for the award of any other degree.



Supervisor

Dr. Ovais S. Qadri

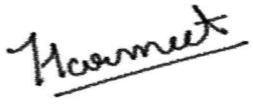
Assistant Professor

Department of Biotechnology

TIET, Patiala

DECLARATION

I hereby declare that the work presented in the thesis "Encapsulation and stability analysis of anthocyanin from *Syzygium cumini* (Jamun) using foam mat drying" in the partial fulfilment of the requirement of the award of the degree of Technology in Biotechnology at Thapar Institute of Engineering and Technology (TIET), is an original and genuine work completed by me between August 2024 and July 2025. This research was carried out under the guidance and supervision of Dr. Ovais S. Qadri, an Assistant Professor in the Department of Biotechnology, TIET. The content presented in this thesis has not been previously submitted, either in its entirety or in part, to any other educational institution or university in India or abroad for the purpose of obtaining any degree.



Place- Patiala Harmeet Singh

Date- 31st July 2025

ACKNOWLEDGEMENT

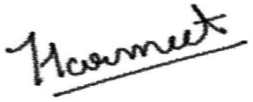
I consider myself incredibly fortunate to have received support from various sources, including the department, my family, friends, and colleagues, both locally and internationally. Without their support, it would not have been possible for me to complete my thesis successfully.

I would like to express my sincere gratitude to my thesis guide, Dr. Ovais S. Qadri, for his invaluable guidance and support throughout the duration of this thesis. His expertise, knowledge, and unwavering dedication have been instrumental in shaping and refining this research work. I am privileged to have worked under his mentorship, and I am deeply thankful for his contributions to my academic and personal growth.

I would like to extend my sincere appreciation to Dr. MS Reddy, the Head of the Department, for providing me with the opportunity to pursue this thesis.

I owe my deepest gratitude towards Ms. Darshanjot Kaur for her constant support. I am truly grateful for her willingness to dedicate time and effort to address my queries, provide feedback, and offer valuable suggestions. Her presence and responsiveness have been instrumental in ensuring the smooth progress of my thesis work.

I would like to thank, Ms. Navdeep Kaur and Ms. Renu Chaudhary, for their positive support during my experiments and for helping me adjust to the lab environment. Their positivity and camaraderie have been greatly appreciated. I would like to acknowledge and thank all those who assisted me during this memorable year. Thank you all for your constant encouragement.



Date – 31st July 2025

Harmeet Singh

Table of Contents

List of Abbreviations and Symbols

Abbreviation / Symbol	Full Form / Description
S. cumini	*Syzygium cumini* (Jamun)
MC	Methyl Cellulose
GMS	Glycerol Monostearate
UAE	Ultrasound-Assisted Extraction
EE	Encapsulation Efficiency
FDA	Food and Drug Administration
ROS	Reactive Oxygen Species
W	Watt (unit of microwave power)
rpm	Revolutions Per Minute
°C	Degrees Celsius
UV	Ultraviolet
g/cm³	Grams Per Cubic Centimeter (used for foam density)
H_2O	Water
d.m	Dry Matter
v/v	Volume/Volume
w/v	Weight/Volume
Figure.	Figureure
%	Percent
TAC	Total Anthocyanin Content
TMAC	Total Monomeric Anthocyanin Content
TPC	Total Phenolic Content

DPPH	2,2-Diphenyl-1-picrylhydrazyl
FTIR	Fourier Transform Infrared Spectroscopy
SEM	Scanning Electron Microscopy
ΔE	Total Color Difference
L*	Lightness
a*	Red-Green Axis
b*	Yellow-Blue Axis

List of Tables

List of Figures

ABSTRACT

This study explores the encapsulation and stabilization of anthocyanins extracted from *Syzygium cumini* (Jamun) using the foam mat drying technique. Anthocyanins are known for their potent antioxidant and therapeutic properties but are highly sensitive to environmental conditions such as heat, light, and oxygen. To address these limitations, the extracted anthocyanins were encapsulated using maltodextrin as the wall material, with foaming agents including glycerol monostearate (GMS) and methyl cellulose (MC) to enhance foam characteristics. The encapsulated formulations were subjected to three drying methods: microwave, vacuum, and hot air oven drying. Foam properties such as expansion, density, and drainage were evaluated to determine optimal combinations for drying performance. Structural and functional characterization was carried out using techniques such as FTIR, SEM, and antioxidant assays to assess encapsulation efficiency and compound stability. Among the drying techniques evaluated, microwave-assisted foam mat drying emerged as the most effective in preserving anthocyanin integrity and functional properties. The findings suggest that foam mat drying, particularly when combined with appropriate wall and foaming agents, is a promising approach for stabilizing thermosensitive bioactive compounds, with potential applications in the development of functional foods, nutraceuticals, and natural colorant systems.

Syzygium cumini (jamun fruit) is known by different names such as Indian blackberry, black plum or jamelan. It is a berry with a single seed and flesh around it. It is a native fruit of India and has a significant function in medicine. Jamun belongs to the Myrtaceae (family) and is preferably cropped in the Indo-Gangetic plains and tropical Asia. This fruit's trees typically withstand drought. Jamun seeds contain substances like jamboline and jambosine that help control blood sugar levels. Jamun is particularly well-known for its anti-diabetic properties. The fruit also supports dental, skin, and eye health, improves immunity, and facilitates digestion. In traditional Ayurvedic and Unani medicine, Jamun is frequently used to heal digestive issues, cleanse the blood, and enhance liver function. In addition to its health advantages, jamun is important economically since it can be grown in a range of climates and processed into a number of goods, including juices, jams, wines, and medicinal powders, which can generate revenue in rural regions. The Jamun tree is also good for the environment since it is good at preserving soil and storing carbon. All things considered, jamun is a fruit that is extremely significant for livelihood, health, and the environment. It is rich in flavonoids, antioxidants, calcium, and phosphorus. In India, *S. cumini* is a significant yet underappreciated fruit. Its fruit is generally dark colored, small, ovoid, and has colored skin due to a pigment called anthocyanin, and due to this pigment, its fruit can be used as a source of natural dye (Faria et al., 2011; Santiego et al., 2016). Anthocyanins are found mainly in the peel and possess different functional characteristics such as antiviral activities, anticarcinogenic, antiglycemic, antimicrobial, antimutagenic, and antioxidant activities (Freitas-Sá et al., 2018; Paul & Das, 2019; Sera glio et al., 2018; Emam & El-Nashar et al., 2022). Water-soluble, glycosylated polyphenolic chemicals called anthocyanins are members of the flavonoid family and are mostly found in fruits and flowers. They produce hues that range from red to blue. Anthocyanin, a purple pigment and possible biocolorant, is an antioxidant and bioactive component of *Syzygium cumini*. The most significant external factors influencing their

consumer appeal are pigments. Pigments have been employed in a variety of industries, including food, medicine, and cosmetics. The food business uses pigment to enhance the flavor and color of food. Non-nutritious and poisonous are characteristics of synthetic colors. Additionally, they are prohibited by law. So, using natural colorants is better for its health and other advantages. The presence of anthocyanins in S. cumini is what gives it its vibrant color. The amount, location, and kind of sugar inside the molecule, the amount and type of aliphatic or aromatic acids attached to the sugar, and the degree and pattern of hydroxylation and meth oxylation all affect the anthocyanins. The stability of these compounds in solution is influenced by the presence of methylations or hydroxylations. Greater stability is achieved through increased glycosylation; however, this parameter is also influenced by the type of sugar present in the medium (Schwartz et al., 2010). Physical, chemical, and environmental elements pertaining to pH, temperature, light (visible and UV), copigmentation, oxygen, ascorbic acid, relative humidity, the presence of sugars, sulfur dioxide or sulfites, enzymes, and metal ions all affect how stable these molecules are. Water-soluble anthocyanins are members of the flavonoid phenolic group. They are acknowledged for their health advantages, which include hepatoprotective, cardioprotective, and anti-inflammatory properties (Swer et al., 2019). It is susceptible to temperature and pH variations, therefore selecting the right drying methods is crucial to reducing degradation.

In region like Arunachal, Meghalya, Mizoram, etc often called seven sisters of India. The jamun fruits are typically available for a short period of time during the summer months of June to July (Mandal et al., 2023). The pigment anthocyanin provides *Syzygium cumini* their black, bluish and purple color. The flavor has a mild sweetness accompanied by a slight astringency (N. Ahmad et al., 2019). Jamun fruit has been identified by researchers and food processing businesses as a possible source of food components (Santhalakshmy et al., 2015). Strong antioxidant properties, anti-diabetic, anti-fungal, antibacterial properties, gastrointestinal issues, and gingivitis are all linked to the anthocyanin in black jamun (Chhikara et al., 2018; da Silva et al., 2023). In addition to these encouraging health advantages, the short post-harvest life at ambient temperature led to underutilization of black jamun (Madani et al., 2021).

Table 1. Physiochemical composition of small-seeded and large-seeded *Syzyium cumini*

Parameter	Large Seeded	Small Seeded
Weight (g)	9.50	3.30
Seed (%)	18.58	36.36
Edible portion (%)	81.42	63.64
Juice (%)	57.75	49.42
Acidity (%)	1.44	1.60
Total sugars (%)	13.16	8.40
Total anthocyanin (mg per 100g)	179.00	242.5
Total tannins (mg per 100g)	297.5	428.75

Depending on the size of the fruit, jamun comes in large and small varieties. The smaller type is round, has delicious flesh, and contains large seeds that are high in tannins, acids, and anthocyanins. The larger, oval-shaped type features small seeds with low levels of tannins, anthocyanins, and acids, and acidic flesh (Table 1) (Roy et al., 2013). The oblong, dark purple fruit with little seeds, known as "Ram Jamun" or "Raja Jamun," is the most frequent variety of

S. cumini grown in northern India. "Paras," a seedless variety, is grown in central India (Devi et al., 2014).

2.1 Anthocyanin

The edible pulpy jamun fruit, known as *Syzygium cumini*, has seeds that contain a good amount of phytochemical components, including anthocyanin and polyphenols (Vanzela et al., 2016). These anthocyanins have been shown to promote health benefits such as lowering blood pressure, cholesterol, diarrhea, splenic enlargement, visceral obesity, and skin-related disorders by regulating blood sugar and encouraging the pancreas to release insulin (Rizvi et al., 2022).

In 1835, Marquart coined the term "anthocyanin," which is coined from two Greek words: "anthos," meaning flower, and "kyanos," meaning blue (Markakes et al., 2012). Anthocyanins are plant pigments responsible for the different colors found in blue, purple, magenta, and violet flowers, as well as in various fruits and vegetables. In ancient times synthetic dyes were used due to their low cost and strong coloring properties; however, they pose significant environmental and health risks. Due to these risks, scientists have increased their focus on natural and safer alternatives, such as plant-based pigments like anthocyanins. Anthocyanins not only provide coloring functionality but also offer health benefits. They are primarily found in the vacuoles of plant cells, where they dissolve in water and absorb light, resulting in a range of colors.

The most commonly studied anthocyanins include malvidin, petunidin, cyanidin, peonidin, and delphinidin (Zhang et al., 2011). While these pigments are predominantly located in fruits and flowers of higher plants, they can also be found in other plant parts. Delphinidin 3-gentioside and malvidin 3-laminarbioside are the primary anthocyanins that contribute to the deep blue color of *Syzygium cumini* (Dagadbhair et al., 2017). Delphinidin, petunidin, and malvidin are the major anthocyanins present in the fruit of S. cumini (Viegas et al., 2007).

Recent reports indicate that all major types of anthocyanins are found in S. cumini, as illustrated in Figure 1, making jamun a promising natural source for studying the extraction and enhancement of anthocyanins.

2.1.1 Structure of anthocyanin

Anthocyanins are a type of natural compound known as flavonoids and are classified as water-soluble pigments. They are composed of a pigment called anthocyanidin, which is attached to a sugar molecule. The structure of anthocyanidin is primarily based on the flavylium cation (Simon et al., 2008), featuring two aromatic rings, referred to as rings A and B, along with a third ring, C, that contains oxygen and forms a six-sided structure (Zhao et al., 2017). The central structure of anthocyanin consists of a flavonoid backbone. Glycosylation is a common occurrence with anthocyanins, where one or more sugar molecules are attached to the flavonoid backbone.

The addition of different sugars at various positions on the molecule leads to the formation of different types of anthocyanins, each with unique characteristics and colors. The most common sugars bound to anthocyanidin include galactose (Gal), glucose (Glc), rhamnose (Rham), xylose (Xyl), and arabinose (Arab). In addition to their pigment properties, anthocyanins can function as antioxidants due to the positively charged oxygen atom in their structure. This feature is also responsible for the vibrant colors they display, ranging from red and orange to blue and violet, especially under acidic conditions (Buono et al., 2012).

2.2 Bio colorant

Color is an essential quality attribute in the food industry, greatly impacting consumer perception and purchasing decisions. Natural colorants, mainly sourced from plants, include key compounds such as anthocyanins, carotenoids, chlorophyll, and flavonoids.

Among these, anthocyanins stand out for their ability to produce a wide range of colors, from red and purple to blue, with the final hue depending largely on the pH of the medium. These pigments are widely utilized in food and beverage products such as juices, confections, jams, yogurts, and baked items to enhance their visual appeal. Beyond food applications, anthocyanins are also used in the cosmetic and pharmaceutical sectors for coloring makeup products, capsules, and tablets. The growing preference for natural colorants in the food industry is attributed to their multiple advantages, including increased food safety, added nutritional benefits, and improved sensory qualities (Nabi et al., 2023).

2.3 Extraction

To produce phytochemically rich products, the extraction of bioactive compounds is essential. Traditional solvent extraction methods are commonly used, but they often extract unwanted compounds such as sugars, acids, and proteins along with anthocyanins (Jampani et al., 2014). Due to the high demand for natural colorants, there is a growing interest in developing methods to extract anthocyanins more effectively. Optimizing extraction parameters is crucial since anthocyanins are sensitive to pH, heat, and temperature. Conventional methods, particularly those using polar solvents like methanol, ethanol, and acetone, are favored for their simplicity and effectiveness. Among these solvents, methanol typically yields the highest concentration of anthocyanins (Johnson et al., 2020; Sasikumar et al., 2020). Extraction is a critical step in obtaining anthocyanins from plant materials. Scientists often describe the extraction process using Fick's second law of diffusion, which explains the movement of substances from solid to liquid. Various factors such as the liquid-to-solid ratio, extraction time, temperature, and solvent concentration all play significant roles in this method. To enhance the efficiency of extraction, researchers strive to shorten extraction times and reduce solvent usage, thereby increasing anthocyanin yield. This has led to the development of several processes, including ultrasound-assisted extraction, supercritical fluid extraction, Soxhlet extraction, and enzymatic

extraction. Among these, ultrasound-assisted extraction (UAE) is particularly favored because it is efficient, straightforward, and cost-effective. The principle of UAE involves the use of ultrasound waves, which create tiny bubbles in the solvent. When these bubbles collapse, they help break down plant tissues, allowing the solvent to penetrate more effectively and extract anthocyanins rapidly from the plant material.

To achieve a more efficient extraction of anthocyanins, a conventional agitated bed extraction method was employed using an incubator shaker. This shaking process enhances the contact between the fruit and the solvent, resulting in improved anthocyanin extraction. The extraction was conducted at a controlled temperature and time for a duration of two hours. Following the extraction, the mixture was filtered using Whatman filter paper, and the resulting extract was stored in the refrigerator to maintain the integrity of the anthocyanins.

2.3.1 Total anthocyanin content

For TAC, we use the pH differential method. This method is a widely used and reliable technique for estimating total anthocyanin content in plant-based samples. This method is based on the structural change of anthocyanins at different pH levels, appearing colored at acidic pH (pH 1.0) and nearly colorless at a higher pH (pH 4.5). By measuring the absorbance difference at these pH values, the total anthocyanin concentration can be accurately quantified. It is simple, cost-effective, and ideal for analyzing anthocyanin-rich fruits, vegetables, and extracts**.**

2.3.2 Purification and isolation of anthocyanin

Anthocyanins, known for their numerous benefits, are increasingly utilized in various industries, including food, pharmaceuticals, and cosmetics. However, before their application, anthocyanins must be effectively purified to eliminate sugars, acids, and other interfering compounds. Column chromatography is a widely accepted method for this purpose, as it offers

high resolution and selectivity. Purifying anthocyanins is essential for enhancing their functionality, purity, and stability. The initial extraction typically involves methanol, which is effective for solubilizing anthocyanins. Following this, further purification is conducted using silica gel column chromatography (Johnson et al., 2020; Sasikumar et al., 2021). In column chromatography, the stationary phase is silica gel, while the mobile phase consists of methanol mixed with formic acid. The acidic conditions provided by formic acid help maintain anthocyanins in their stabilized flavylium cation form, thereby preventing further degradation during purification. Crude anthocyanins are loaded onto the silica column, and the pigments are gradually eluted using an increasing concentration of methanol with a small percentage of formic acid. This technique effectively separates non-pigmented compounds, such as sugars and organic acids, from anthocyanins, as silica gel interacts differently with each molecule based on polarity. Once separated, the purified anthocyanins can be utilized in various applications (Jampani et al., 2014; Balasundram et al., 2006).

2.4 Encapsulation

Fruit processing and preservation reduce post-harvest losses and create a valuable product that is accessible year-round (Chhikara et al., 2018). Microencapsulation is one method of quality preservation that can prolong the shelf life of products and offer a protective layer for sensitive substances (Jyothiet al., 2010; Saberi Riseh et al., 2023). Encapsulation is a process used to enclose core materials within wall materials, providing protection against environmental factors. This technique is widely applied in the pharmaceutical, cosmetics, agricultural, and food industries. The process of encapsulation serves several functions, including stability, slow release of ingredients, mainly food, maximizing retention, and controlling the release of bioactive compounds in the human body (Smith et al., 2021). Scientists and researchers have developed various methods for encapsulating bioactive compounds in food, including freeze-drying, fluidized bed coating, molecular inclusion, and coacervation (Nguyen et al., 2021;

Mhoza et al., 2021). These methods are commonly employed in the food industry to minimize the loss of color, sweetness, flavor, and to combat the presence of microorganisms. Most frequently used wall materials for encapsulation include gum arabic, emulsifying starches, and maltodextrin, which can also be used in combination. Maltodextrin, in particular, offers good water solubility, is FDA-approved, and has low sugar content. Additionally, it provides effective protection for the encapsulated powders and maintains the stability of bioactive substances (Silva et al., 2018). Researchers have also studied that maltodextrin is commonly used as a microencapsulating agent, especially for encapsulating fruits, juices, and extracts.

2.5 Drying

The choice of drying technique plays a crucial role in the successful extraction and preservation of anthocyanins from *Syzygium cumini*. Due to their sensitivity to degradation from heat, light, and oxygen, anthocyanins require carefully controlled conditions to ensure their stability. Drying not only helps stabilize these compounds but also enhances their recovery by reducing moisture content, which facilitates better storage and handling.

To maximize anthocyanin retention post-drying, it is essential to employ techniques that minimize thermal and oxidative degradation while preserving the bioactive properties of the compounds. As noted by (Hardy and Jideani 2017), the primary objective of food dehydration is to prolong shelf life by reducing microbial growth and preventing spoilage. Moisture removal creates an unfavorable environment for microorganisms, thereby improving the product's stability and longevity.

Research by (Eliasson et al., 2017) demonstrated that both microwave and hot air drying methods resulted in higher anthocyanin retention compared to other techniques. In a related study on foam mat drying of grapes (Tavares et al., 2019) found that drying at 70°C was optimal for maximizing anthocyanin recovery. Interestingly, while drying at 80°C significantly reduced

the drying time, it may compromise anthocyanin stability due to increased thermal exposure. Hence, selecting the right drying temperature and method is key to ensuring efficient anthocyanin preservation.

2.5.1 Foam mat drying

Foam mat drying is a versatile technique used to remove moisture from liquid or pureed materials. The process involves generating a stable foam by adding an edible foaming agent and whipping the mixture. This foam is then evenly spread onto trays or mats for drying.

To enhance foam stability and improve drying performance, various additives are commonly incorporated, such as methylcellulose and glycerol monostearate. These agents may be used individually or in combination to optimize the drying process. Foam mat drying is particularly effective for heat-sensitive, viscous, or sticky substances that are otherwise challenging to dehydrate using conventional methods (Hardy & Jideani et al., 2017).

2.5.2 Foam formation theory

According to Eisner et al. (2007), foam is a complex, multi-phase system commonly found in food and beverage products. It comprises two main phases: a dispersed phase made up of gas bubbles and a continuous liquid phase. These two are separated by a thin liquid film known as the lamellar phase, which forms the walls of the bubbles. Within this structure, elements such as gases, liquids, solids, and surfactants come together to stabilize and maintain the integrity of the foam.

The gas bubbles within the foam are enclosed by a structural framework called the Plateau border, which prevents the bubbles from collapsing or merging, thereby enhancing foam stability. Both proteins and surfactants play critical roles in determining the texture and longevity of the foam. Surfactants quickly migrate to thinner regions of the bubble walls (lamella), where they reduce surface tension, aiding foam formation and stability. Proteins, on

the other hand, attach to the gas–liquid interface and interact with the lamella through mechanisms such as electrostatic attraction, hydrophobic interactions, hydrogen bonding, and even covalent bonding. These interactions reinforce the foam structure.

Indrawati et al. (2008) pointed out that although foams are thermodynamically unstable by nature, the use of surface-active agents like proteins offers kinetic stability. Proteins lower the surface tension and enhance interfacial rheology, which helps resist bubble collapse and preserve the foam's architecture over time.

2.5.3 Anthocyanin Stability and Encapsulation Efficiency through Foam Mat Drying

Foam mat drying has proven to be an effective technique for enhancing the encapsulation efficiency and stability of anthocyanins, particularly in thermally sensitive and viscous fruit pulps such as *Syzygium cumini.* This process begins with the creation of a stable foam using suitable foaming agents. In this study, methyl cellulose (MC) and glycerol monostearate (GMS) were incorporated to improve the structure and stability of the foam. These agents help form a uniform and porous foam layer, which facilitates rapid and even drying while minimizing heat exposure and the degradation of bioactive compounds. According to Hardy and Jideani (2017), foam mat drying offers significant advantages for processing heat-sensitive materials by improving drying kinetics and preserving quality attributes. The combination of MC and GMS not only stabilizes the foam but also helps form a protective matrix around the anthocyanins, thereby enhancing encapsulation efficiency and preventing degradation during the drying process. (Eisner et al., 2007) emphasized the importance of surfactants and proteins in strengthening foam structures through interfacial interactions, which is critical for maintaining the integrity of sensitive compounds.

Furthermore, studies by (Tavares et al., 2019) and (Indrawati et al., 2008) demonstrate that optimized drying temperatures, such as 70°C during foam mat drying, lead to higher retention

of anthocyanins and improved product stability. Foam mat drying with MC and GMS is an effective method for preserving anthocyanins, thereby enhancing their functionality and shelf-life in food applications.

2.5.4 Hot air oven Drying

Hot air oven foam drying is an innovative technique that merges foam creation with warm air circulation to efficiently remove moisture from liquid or semi-liquid materials. The process begins by creating a stable foam using a suitable foaming agent, which is then spread into a thin layer across trays. These trays are placed in a hot air oven, where circulating warm air aids in moisture evaporation and ensures that the foam dries uniformly. This method not only proves effective but also delivers consistent results, making it an excellent choice for drying a variety of materials.

Sankat and Castaigne (2004) reported that in the case of banana foam mats, the drying process was significantly influenced by the foam's physical attributes, especially its density and thickness. They also found that increasing the drying temperature from moderate to higher levels, such as 75°C and 90°C, substantially reduced drying time.

Hot air oven foam drying has several important benefits that make it a popular choice in various industries. For starters, it provides controlled and uniform drying conditions, which help maintain the foam's structure and keep sensitive bioactive compounds intact. This is particularly valuable in fields like food, pharmaceuticals, and cosmetics, where creating powdered ingredients, stable foams, and dehydrated products with specific qualities is essential.

Generally, the drying temperatures are set between 40°C and 100°C. However, it's crucial to fine-tune these temperatures based on how sensitive the product is to heat, how much moisture

it contains, and how quickly you want to dry it. This careful approach helps prevent any over-drying or degradation, ensuring the final product retains its quality.

In a study conducted by Tavares and colleagues in 2019, researchers looked into the drying process of grape juice foam using hot air at three different temperatures: 60°C, 70°C, and 80°C. They found that the drying times were quite varied, around 6.25 hours at 60°C, about 3.17 hours at 70°C, and just 2.67 hours at 80°C. This clearly demonstrated that raising the temperature made a significant difference in how quickly the foam dried. Specifically, drying time dropped by roughly 39% at 70°C and an impressive 52% at 80°C when compared to 60°C. These findings really highlight how effective hot air oven drying can be when the temperature settings are fine-tuned.

2.5.5 Vacuum oven foam drying

Vacuum oven foam mat drying is a specialized drying technique that combines foam formation with low-pressure drying in a vacuum oven. This method involves preparing a stable foam using a suitable foaming agent, which is then evenly spread into a thin layer on drying trays. These trays are placed inside a vacuum oven, where drying occurs under reduced pressure. This allows for moisture removal at lower temperatures.

In a study conducted by Sramek et al. (2015), researchers investigated the use of foamed tomato paste and found that vacuum drying at 50 °C resulted in the highest retention of carotenoids and color compared to other drying techniques. The study emphasized that vacuum foam drying provides several advantages over conventional hot air drying, particularly in minimizing the degradation, isomerization, and discoloration of heat-sensitive compounds. This is mainly due to the lower temperatures and limited exposure to oxygen involved in vacuum drying.

As a result, this method is effective in producing high-quality dried products, such as tomato powders, which have enhanced nutritional value and visual appeal. Consequently, it is a preferable option for preserving sensitive bioactive compounds.

2.5.6 Microwave foam drying

Microwave foam mat drying is an advanced drying technique that utilizes microwave energy to efficiently remove moisture from foamed materials. In this method, a stable foam is prepared typically using a suitable foaming agent and spread as a thin layer before being subjected to microwave heating, which accelerates water evaporation and significantly reduces drying time.

(Qadri and Srivastava et al., 2015) evaluated this method using guava pulp, where foam was created using 8% egg albumin. The foamed pulp was then dried at varying microwave power levels- 480W, 560W, 640W, 720W, and 800W, and with foam thicknesses of 3 mm, 5 mm, and 7 mm. The study revealed that microwave-assisted foam mat drying considerably shortened the drying duration while enhancing the quality of the resulting guava powder.

In a similar vein, Zheng et al. (2011) performed a research study utilizing household microwave appliances for dehydrating blackcurrant pulp. They investigated and refined various parameters, such as microwave intensity, pulp quantity, drying duration, and foam depth. The findings revealed that enhancing the microwave intensity and minimising the pulp quantity increases the drying process. Importantly, pulp depth (load) had a notable positive impact on the preservation of essential bioactive compounds like vitamin C and anthocyanins. The ideal conditions for microwave-assisted foam mat dehydration (MAFD) of blackcurrant pulp were determined to be microwave intensity of 560 W, pulp quantity of 65 g, drying duration of 8 minutes, and a pulp thickness of about 4.46 mm. These results endorse the viability of microwave foam mat drying as an effective and efficient approach for dehydrating heat-sensitive fruit pulps while maintaining their nutritional integrity.

2.6 Review of characterisation

The characterization of encapsulated anthocyanins is crucial to evaluate their structural, functional, and chemical stability. Scanning Electron Microscopy (SEM) is widely used to assess the surface morphology and microstructure of encapsulated powders, revealing information about particle size, shape, and wall integrity. Previous studies, such as those by Patel et al. (2016), have demonstrated that smoother, more uniform surfaces often correlate with better encapsulation efficiency and oxidative stability. Antioxidant capacity is typically assessed using the DPPH radical scavenging assay, which measures the ability of bioactive compounds to neutralize free radicals. Research by Kausar et al. (2012) supports the use of DPPH to track the retention of antioxidant potential post-drying and encapsulation.

Total Phenolic Content (TPC) is another important indicator of antioxidant functionality, as phenolics are sensitive to processing conditions. According to (Sánchez-Moreno et al., 2003), higher TPC values after encapsulation reflect better preservation of bioactive compounds. Fourier Transform Infrared Spectroscopy (FTIR) helps identify characteristic functional groups and molecular interactions between anthocyanins and wall materials, confirming encapsulation success. Studies such as those by Cano-Chauca et al. (2011) reported FTIR peak shifts indicating hydrogen bonding or other interactions that enhance encapsulation stability.

Stability analysis during storage involves monitoring Total Monomeric Anthocyanin Content (TMAC), encapsulation efficiency, and colorimetric changes using CIELAB values.

There are some gaps in the literature:

Despite the growing interest in natural colorants and bioactive compounds, there is limited scientific literature specifically focused on the encapsulation of anthocyanins from *Syzygium cumini* using foam mat drying techniques. While foam mat drying has been explored for various vegetables and fruits due to its advantages in preserving heat-sensitive compounds,

most existing studies have concentrated on commonly used sources like guava, banana, tomato, and blackcurrant. *Syzygium cumini*, which is rich in anthocyanins with known antioxidant and therapeutic potential, remains largely underexplored in this context. Moreover, there is a lack of data on the effect of different foaming agents, drying parameters, and their impact on the encapsulation efficiency and stability of anthocyanins from this fruit. This gap highlights the need for in-depth research to evaluate the suitability and optimization of foam mat drying for *Syzygium cumini*, which could contribute valuable insights for food, nutraceutical, and pharmaceutical applications.

The objectives of our study are as follows:

- To encapsulate anthocyanin extracted from *Syzygium cumini* using foam mat drying
- To characterize the encapsulated anthocyanin

3.1 Extraction of anthocyanins from *S. cumini* pulp

3.1.1 Sample preparation

Fully ripened fruits of *Syzygium cumini* were procured from a local vendor in Patiala, Punjab, India, and the subsequent extraction and drying processes were performed at Thapar Institute of Engineering & Technology.

Figure 1. Extraction of pulp

a) Blanching

Syzygium cumini fruits were first rinsed with tap water maintained at 38 ^{0}C, then briefly immersed in boiling water, and then cooled in cold water. This process was carried out to inactivate enzymes and eliminate surface microorganisms.

b) Pulping

Seeds from the fruit pulp of *Syzygium cumini* were manually separated to preserve the integrity of the fruit and ensure minimal mechanical damage to the pulp. This step was performed with the help of a hand. For delicate fruits like *Syzygium cumini*, manual pulping is particularly suitable, as it helps avoid contamination from broken seeds, which may introduce undesirable flavors. The resulting pulp rich in anthocyanin and other phytochemicals was then collected for further processing, including extraction and drying.

c) Drying

The pulp derived from *Syzygium cumini* was subjected to vacuum drying for approximately 7-8 hours. Following the drying process, the dehydrated pulp was ground into a fine powder, which

Deseeding and Pulping Dried *S. cumini* powder

was then sealed in aluminium packaging and stored at refrigerated temperature until further analysis and processing.

Figure 2. Separation of pulp from seeds and dried *S. cumini* pulp powder

d) Anthocyanin Extraction

Anthocyanins were extracted using a solvent-based extraction technique. For this purpose, pulp powder was mixed with methanol in a 1:20 (w/v) ratio to facilitate efficient solvent penetration and enhance the release of anthocyanin compounds. The mixture was then subjected to ultrasonication for 10 minutes to disrupt cellular structures and improve extraction efficiency. Following sonication, the solution was incubated at 37 °C with continuous agitation at 120 rpm for 2 hours to allow maximum solubilization of anthocyanins. After incubation, the mixture was filtered using Whatman filter paper to remove any insoluble residues. The resulting anthocyanin-rich filtrate was collected and stored at low temperature in airtight containers to prevent degradation and was used for subsequent analyses.

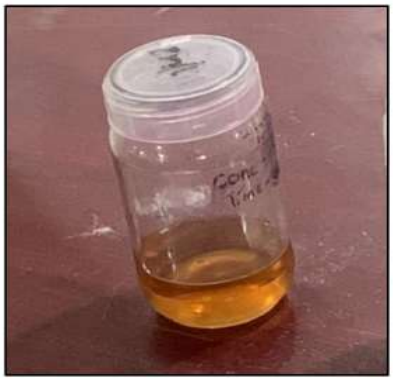


Figure 3. Anthocyanin extract after UAE

3.1.2 Total Anthocyanin Content (TAC)

The extract was quantified for its anthocyanin content with the pH differential method (Maran, Sivakumar, et al., 2014). The extract (1ml) was mixed with 4ml sodium acetate (pH 4.5) and 4ml potassium chloride (pH 1.0) separately. The mixtures were equilibrated for 1 hour, and absorbance was observed at 520 and 700nm.

$$A = (A_{520} - A_{700})_{pH\,1} - (A_{520} - A_{700})_{pH\,4.5}$$

$$TAC = \frac{A\ X\ MW\ X\ DF\ X\ 1000}{\in X\ 1}$$

Where, A - absorbance, MW- molecular weight, DF- Dilution factor, ∈ - molar absorptivity of cyanidin-3-glucoside.

3.1.3 Purification of Extracted Anthocyanins

To obtain purified anthocyanins free from co-extracted phytochemicals, the crude extract was subjected to silica gel column chromatography using activated silica gel (60–120 mesh size) as the stationary phase. The mobile phase consisted of formic acid and methanol, prepared by dissolving 6 g of formic acid in 294 mL of methanol. The crude extract was carefully loaded onto the column and eluted under gravity flow using the solvent system. The portions that

showed a pink to purple color, which means they contained anthocyanins, were collected and combined. These combined samples were then heated in a hot air oven at 60 °C overnight to remove any leftover liquid and turn them into powder. The anthocyanin powder was then stored in airtight containers at a low temperature and kept away from light to keep it safe and prevent spoilage.

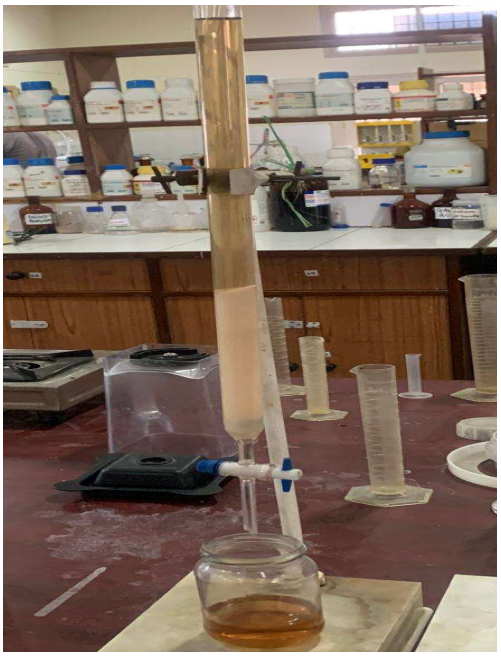


Figure 4. Column chromatography for the purification of anthocyanin extract

3.2 Encapsulation of Anthocyanins

To encapsulate the anthocyanins, 1.5 g of anthocyanin extract was dissolved in 15 mL of distilled water. To this, 3.5 g of maltodextrin was added as a wall material, and the solution was magnetically stirred at 500 rpm for 5 minutes at 25 °C for uniform dispersion. It was then sonicated at 100 W for 5 minutes at 30 °C to enhance core-wall interaction (Raj et al., 2022).

3.2.1 Optimization of Foaming Agent Combination for Foam Mat Drying

To optimize foam formation for efficient foam mat drying, nine different combinations of methyl cellulose (MC) and glycerol monostearate (GMS) were prepared and evaluated as shown in Figureure 5. Each formulation was assessed based on critical foam characteristics such as foam expansion, foam density, and drainage volume. These parameters were systematically measured to determine the most stable and efficient foaming system. Based on the comparative analysis of these characteristics, the combination that exhibited optimal foam properties, specifically high foam expansion, low foam density, minimal drainage, and

maximum stability, was selected for further use in the foam mat drying process of anthocyanin-rich extracts.

Table 2. Different Combinations of GMS and MC for Foam Mat Drying

S. No.	GMS (g)	MC (g)	GMS: MC Ratio	Abbreviation
1	0.75	0.75	1:1	GM1
2	0.75	0.5	3:2	GM2
3	0.75	0.25	3:1	GM3
4	0.5	0.75	2:3	GM4
5	0.5	0.5	1:1	GM5
6	1.0	0.5	2:1	GM6
7	0.5	0.25	2:1	GM7
8	1.0	0.25	4:1	GM8
9	1.0	0.75	4:3	GM9

3.2.2 Foaming for Anthocyanin Encapsulation

To the above encapsulated solution, 1 g of glycerol monostearate (GMS), pre-dispersed in 35 mL of hot distilled water, was added as an emulsifier to improve product stability and structure (De Souza et al., 2010). The temperature was maintained at approximately 30 °C throughout. Finally, foam was generated by whipping the solution for 5 minutes with the addition of 0.75 g of methyl cellulose (MC) as a foaming agent to stabilize the foam structure. The resulting foam was prepared for drying to obtain encapsulated anthocyanin powder.

Figure 5. Foam formation

3.2.3 Different drying techniques for foam

Three main drying methods were tested and compared based on how well they could retain anthocyanins. In each method, a foaming step was included before drying, which means all the drying techniques were used as part of the foam mat drying process.

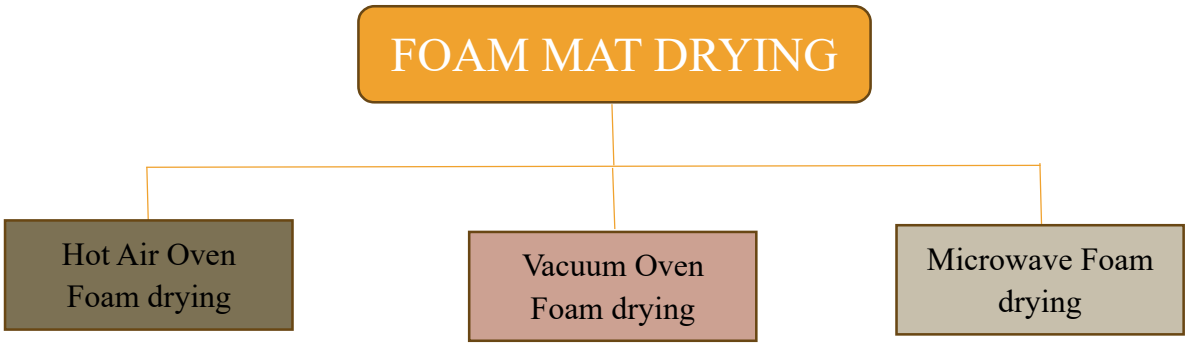


Figure 6. Different Drying Methods

3.2.3.1 Foam mat drying

The prepared foam was uniformly spread onto plates to facilitate the drying process (Qadri et al., 2015). This method enhances the surface area available for mass transfer, thereby reducing the overall drying time.

Figure 7. Foam uniformly spread onto a plate

3.2.3.2 Foam characteristics

As suggested by Sahu et al. (2022), foam can be characterized by several parameters.

a) Foam expansion

It refers to the increase in volume during the foaming process. Monitoring volume expansion is important, as it plays a crucial role in ensuring proper foam formation. Foam expansion was measured by calculating the difference between the generated foam's initial and final volumes.

$$\text{Foam expansion, FE (\%)} = \frac{V_1 - V_0}{V_0} \times 100$$

Where, V_1 is the final volume of foam; V_0 is the initial volume

b) Foam density

It reflects the air incorporated within the foam structure along with compaction. Foam density is defined as the mass of the foam per unit volume and is expressed in g/cm^3. It is calculated by dividing the mass of foam by its volume immediately after foaming, using the following equation.

$$\text{Foam Density (g/cm3)} = \frac{\text{Mass of foam (g)}}{\text{Volume of foam (cm}^3\text{)}}$$

During drying, lower foam density indicates higher air incorporation, which contributes to larger surface area and more efficient moisture removal during drying. Inversely, higher foam density indicates poor air entrapment, which leads to slow drying rates in the final product.

c) Drainage Volume

Foam drainage volume is an important parameter that indicates the stability of the foam over time. It refers to the amount of liquid that separates and drains out from the foam structure under the influence of gravity. During the foaming process, air is incorporated into the liquid, forming a structured matrix. However, over time, due to gravitational force and the weakening of interfacial films, the liquid phase begins to drain from the foam. This phenomenon is known as foam drainage. A high drainage volume suggests poor foam stability, as the foam cannot retain the liquid content. In contrast, a low drainage volume indicates a more stable foam structure with stronger interfacial interactions.

d) Moisture content

The moisture content was measured to determine the amount of water in the foam. This parameter is typically assessed using a moisture balance device, which calculates the percentage of water content in a given sample. This study measured moisture content using the Aczet Moisture Balance MB50, a precision instrument designed for rapid and accurate

moisture analysis. The device works by heating the sample and continuously measuring the weight loss, corresponding to the moisture evaporated. The final result is expressed as the percentage of moisture in the sample.

3.2.3.3 Drying Techniques Applied

a) Microwave Foam Drying

A foam sample weighing 57.04 grams was evenly spread onto a Petri plate, ensuring a uniform thickness of 30 mm. The drying process was carried out using a microwave at three different power levels: 100 W, 200 W, and 300 W. During the treatment, the weight of the sample was recorded at two-minute intervals to monitor the rate of moisture loss. Additionally, the total time required for the sample to reach complete dryness was observed and documented for each power level.

b) Vacuum foam drying

Vacuum foam drying was carried out using a single moisture-resistant Petri dish containing 23.10 grams of the foam sample, uniformly spread to a thickness of 30 mm. The drying was performed at three different temperatures, 50 °C, 60 °C, and 70 °C, consecutively in the vacuum oven. Weight loss was recorded every 30 minutes to monitor the drying progress. The total time required for complete drying was documented at each temperature level.

c) Hot air oven foam drying

A foamed sample weighing 50 grams was evenly spread to a thickness of 30 mm on a moisture-resistant plate. The sample was then subjected to drying in a hot air oven at three consecutive temperature settings: 50 °C, 60 °C, and 70 °C. Throughout the drying process, the plate remained inside the oven, and the sample's weight was measured every 30 minutes to monitor moisture loss. The total drying time required for complete dehydration of the sample was also recorded at each temperature level.

3.3 Post-drying Characterization

After obtaining the powdered form of the foamed anthocyanin samples, characterization was performed to evaluate the effectiveness and quality of the encapsulation process. The primary parameter assessed was encapsulation efficiency (EE), which indicates how well the wall material is able to retain and protect the core anthocyanin compounds during drying. A higher encapsulation efficiency reflects better stability and protection of the bioactive compounds. This evaluation is based on the comparison between surface anthocyanin which is the portion of anthocyanin that remains exposed on the surface and is not encapsulated and total anthocyanin which is the overall anthocyanin content in the sample. The difference between these two values helps determine the amount of anthocyanin successfully encapsulated within the matrix. Thus, encapsulation efficiency provides insight into the structural integrity of the encapsulated system and the potential effectiveness of the product for further application.

The encapsulation efficiency was calculated using the following formula:

$$\text{Encapsulation Efficiency (\%)} = \frac{\text{Total Anthocyanin} - \text{Surface Anthocyanin}}{\text{Total Anthocyanin}} \text{ X } 100$$

3.3.1 Scanning Electron Microscopy (SEM)

The surface morphology and structural characteristics of the encapsulated anthocyanin powders were analyzed using Scanning Electron Microscopy (SEM). A small amount of each sample was mounted onto an aluminium stub using double-sided carbon tape and then coated with a thin layer of gold using a sputter coater to enhance conductivity. The coated samples were observed under the SEM at an accelerating voltage of 10–20 kV. Images were captured at various magnifications to examine the particle shape, surface texture, and distribution. SEM analysis helped evaluate the effectiveness of encapsulation by visualizing the uniformity, porosity, and structural integrity of the microcapsules formed by different drying methods.

3.3.2 DPPH Assay

The DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging assay is widely used to evaluate the antioxidant potential of bioactive compounds, particularly phenolics and anthocyanins.

Free radical scavenging activity was obtained spectrophotometrically against DPPH. In the 0.1 ml diluted sample (1:4), 3.9 ml of methanolic DPPH was added. The sample was allowed to stand for 30 minutes at 37 °C in the dark. The absorbance was measured at 517 nm against methanol as a blank.

$$\text{DPPH}\,(\%) = \left(\frac{A_{\text{blank}} - A_{\text{sample}}}{A_{\text{blank}}}\right) \times 100$$

3.3.3 Total phenolic content (TPC)

The total phenolic content (TPC) of the encapsulated anthocyanin powders was determined using the Folin–Ciocalteu method with slight modifications. A total reaction volume of 4 mL was prepared by mixing 2.5 mL of Folin Ciocalteu reagent (0.2 mol/L) with 0.2 mL of diluted sample extract, and the volume was made up with distilled water. The mixture was incubated for 5 minutes at room temperature, followed by the addition of 2 mL of sodium carbonate solution (prepared by dissolving 7.5 g of Na_2CO_3 in 100 mL of water). After mixing, the solution was incubated again at room temperature for 120 minutes. The mixture was then shaken gently, and absorbance was measured at 754 nm using distilled water as blank. If a 2N Folin reagent was used, it was diluted 10-fold prior to use. The phenolic content was quantified using a standard calibration curve of gallic acid, and results were expressed as mg gallic acid equivalents per 100 g sample (mg GAE/100 g). For the standard, 2 g of gallic acid was dissolved in 250 mL of methanol to prepare the gallic acid stock solution. To prepare a standard

curve for gallic acid, a stock solution was made using 100 mg of gallic acid in methanol. Seven different dilutions were prepared by adding distilled water to gallic acid. Added 5 ml of Folin reagent and 4 ml of sodium carbonate to all the test tubes. The sample was incubated at 20 °C for 30 minutes, and absorbance was noted at 754 nm. C value was calculated after plotting the Excel.

3.3.4 FTIR

FTIR analysis was conducted to identify functional groups and investigate potential interactions between the anthocyanins and wall materials in the encapsulated powders. Approximately 1 gram of each dried sample was finely ground and thoroughly mixed with spectroscopic-grade potassium bromide (KBr) at a 1:100 ratio. The mixture was then compressed into a transparent pellet using a hydraulic press. The prepared pellet was scanned over the mid-infrared region (4000–400 cm^{-1}) using an FTIR spectrophotometer. The resulting spectra were analyzed for characteristic absorption peaks representing specific functional groups, such as hydroxyl (–OH), carbonyl (C=O), and ether (C–O) groups, to confirm the presence of anthocyanins and assess interactions formed during encapsulation.

3.4 Stability Analysis of Encapsulated Anthocyanins

Color measurements of the encapsulated anthocyanin powders were performed using a digital colorimeter based on the CIELAB color space system. Approximately 1 gram of sample was placed in a clean, flat sample holder, and the instrument was calibrated using a standard white tile before each measurement. The color parameters recorded included L* (lightness), a* (red-green axis), and b* (yellow-blue axis). Measurements were taken on both the initial day and after storage to assess any changes in visual appearance. The total color difference (ΔE) was calculated using the following formula:

$$\Delta E = \sqrt{(L_0 - L_{30})^2 + (a_0 - a_{30})^2 + (b_0 - b_{30})^2}$$

where subscripts 0 and 30 represent values on day 0 and day 30, respectively. This analysis helped determine the stability of anthocyanins based on color retention during storage.

4.1 Foam-Assisted Encapsulation of Anthocyanins with Drying Kinetic Assessment

4.1.1 Extraction of anthocyanin from jamun pulp (TAC)

Extraction of anthocyanins from *Syzygium cumini* (jamun) pulp was carried out using the pH differential method, a widely accepted spectrophotometric technique for quantifying total monomeric anthocyanin content. This method exploits the structural transformation of anthocyanin pigments under different pH conditions (pH 1.0 and 4.5), enabling accurate measurement based on absorbance changes. The extracted jamun pulp yielded approximately 205.06 mg of anthocyanins per 100 g of fresh pulp, indicating a high concentration of these bioactive pigments, which contribute to the fruit's deep purple color and antioxidant properties**.**

4.1.2 Foam Properties Before Drying

Foam Optimisation and Selection for Foam Mat Drying of *Syzygium cumini* anthocyanin-rich extract. To ensure efficient foam mat drying of *Syzygium cumini* (jamun) pulp, selecting a suitable foaming formulation was critical. This involved optimizing the ratio of Glycerol Monostearate (GMS), an emulsifier, and Methyl Cellulose (MC), a foaming agent. Various GMS: MC combinations were evaluated to identify the formulation that would produce the most stable and effective foam before drying.

The pulp for this process was derived from fresh *Syzygium cumini* fruits procured from local markets in Patiala, India. The fruits underwent blanching to inactivate enzymes and minimize pigment degradation, followed by seed removal and pulp extraction. The resultant purified anthocyanin extracted from pulp was foamed using different ratios of GMS and MC to assess drainage volume, foam density, and expansion, which are the characteristics, parameters essential for determining foam quality and drying efficiency.

4.1.2.1 Foam Drainage Volume Analysis

The drainage volume of foams prepared with varying GMS:MC ratios was recorded over two independent trials, and the average values were plotted to assess foam stability. As illustrated in the figure 10, most formulations exhibited considerable drainage, with some, such as 01:01 (GM5) and 02:01(GM7), showing high average drainage volumes of 47.5 mL and 45 mL, respectively. These high drainage values indicate poor foam stability and a tendency for rapid liquid separation. In contrast, the formulation with a GMS:MC ratio of 04:03 (GM9) demonstrated exceptional stability, exhibiting zero drainage in both trials. This result highlights the superior structural integrity of the foam at this specific ratio. The minimal drainage observed in the 03:02 (GM2) (12.5 mL average) and 02:01 (GM6) (7.5 mL average) formulations also suggests relatively stable foams, but not to the extent of the 04:03 (GM9) combination. Based on these observations, the 04:03 (GM9) ratio was selected as the optimal formulation for further applications due to its excellent resistance to drainage and superior foam stability.

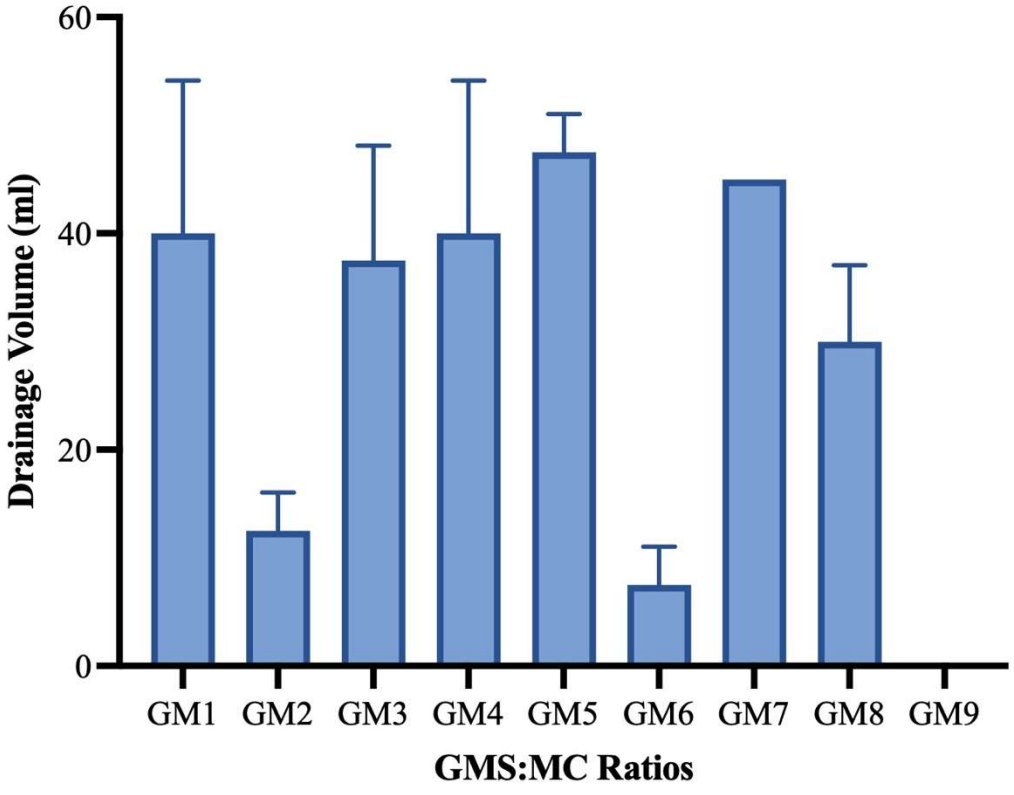


Figure 8. Drainage volume

4.1.2.2 Foam Density Analysis

The foam density of various GMS:MC ratios was evaluated through two independent trials, and the results were averaged to obtain a more accurate representation. As shown in the graph, the foam density varied notably across different formulations. The 2:03 (GM4) GMS:MC ratio exhibited the highest average foam density (0.753 g/cm³), indicating a denser and more compact foam structure, but its drainage volume is high, which is undesirable. Conversely, the 03:01(GM3) and 04:01 (GM8) ratios showed lower foam densities, averaging around 0.28 g/cm³ and 0.26 g/cm³ respectively, suggesting a lighter and more aerated foam. Among the tested formulations, the 04:03 (GM9) ratio was found to provide a balanced foam density (0.304 g/cm³) while also demonstrating no visible drainage volume during the experimental observation period. This absence of drainage indicates improved foam stability, making the 04:03 GMS:MC (GM9) ratio the most suitable formulation for further application. These findings suggest that the composition of GMS and MC significantly influences foam density and stability, which are critical parameters in determining the effectiveness and quality of the final product.

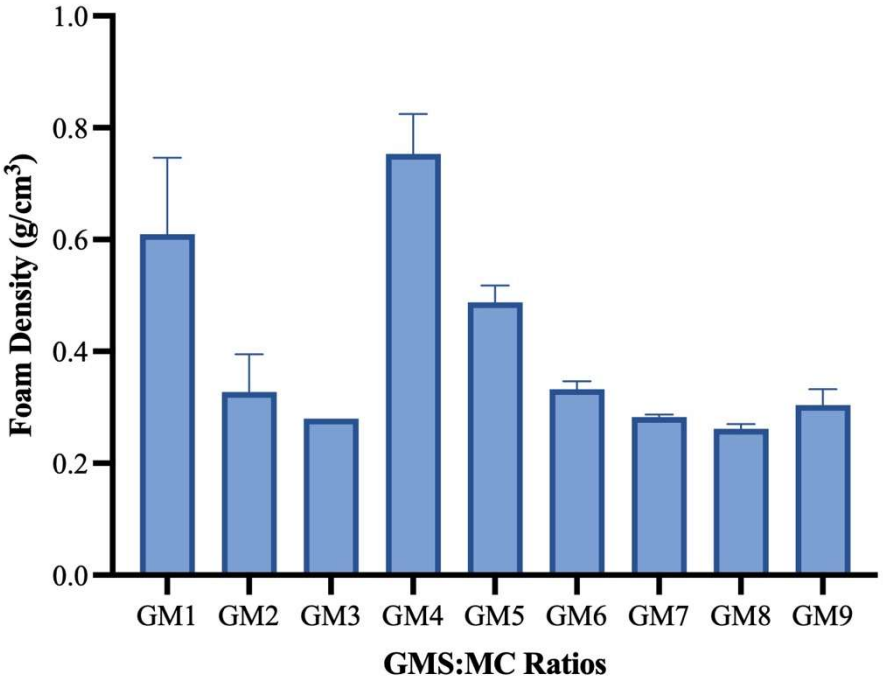


Figure 9. Foam Density

4.1.2.3 Foam Expansion Analysis

Foam expansion was evaluated for various GMS:MC ratios, and the percentage expansion values from two trials were averaged to assess the foaming capacity of each formulation. As represented in the graph, foam expansion varied significantly depending on the GMS:MC ratio. The highest foam expansion was observed in the 04:01 ratio (GM8) (313.46%), followed closely by 02:01 (GM7) (279.80%) and 03:01 (GM3) (284.61%). In contrast, very low foam expansion was recorded in the 02:03 (GM4) formulation (44.23%), indicating poor foaming behaviour. Notably, the 04:03 (GM9) (GMS:MC) ratio achieved a high average foam expansion of 260.58%, which is among the top-performing formulations. This, combined with its zero drainage volume (as previously observed), highlights 04:03 (GM9) as a highly suitable composition for stable and efficient foam production. The data clearly suggest that the optimal foaming performance is achieved at specific GMS:MC ratios, and the 04:03 (GM9) ratio provides an ideal balance between foam expansion and structural stability.

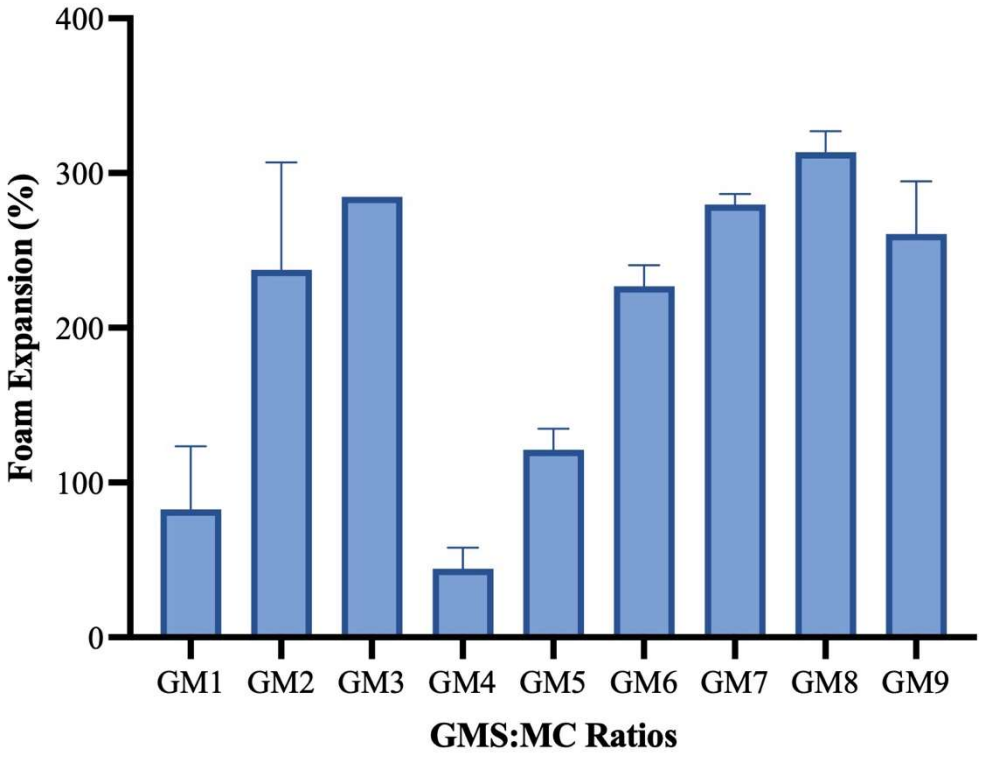


Figure 10. Foam Expansion Analysis

4.1.3 Foam mat Drying

Among all the tested GMS:MC combinations, the GM9 formulation (04:03 ratio) proved to be the most effective in terms of overall foam performance. Specifically, GM9 exhibited the best results across key parameters, including minimum drainage volume, maximum foam expansion, and optimal foam density. The reduced drainage volume indicates enhanced foam stability, while higher foam expansion reflects greater air incorporation, essential for efficient drying. Additionally, the favorable foam density suggests a well-aerated yet stable structure. These combined attributes make GM9 the ideal formulation for producing stable and efficient foams suitable for the foam mat drying of *Syzygium cumini* pulp.

Syzygium cumini's anthocyanin-rich extract from pulp was converted into foam and subjected to three different foam mat drying techniques: hot air oven, vacuum oven, and microwave-assisted drying. The drying conditions varied with temperature and power; hot air oven and vacuum drying were conducted at 50 °C, 60 °C, and 70 °C. In contrast, microwave drying was performed at 100 W, 200 W, and 300 W. The foam was consistently spread to a thickness of 3 mm on each plate, although the sample weight varied slightly. Drying continued until each sample's moisture content was reduced to below 10%. Foam mat drying proved highly effective due to its enhanced surface area-to-volume ratio and porous structure, which facilitated improved mass transfer and significantly reduced drying time compared to conventional methods. For foam formation, methyl cellulose (MC) and glycerolmonostearate (GMS) were added. MC acts as a foaming agent while GMS is an emulsifier stabilizing the foam structure. These components were selected for their proven efficacy in enhancing foam stability and improving drying performance (Singh et al., 2020). The resultant foam was uniformly spread onto stainless steel trays, maintaining a layer thickness of approximately 3mm. This thickness

was selected based on optimal heat and mass transfer recommendations during foam mat drying (Kandasamy et al., 2015). The trays were then subjected to different drying techniques.

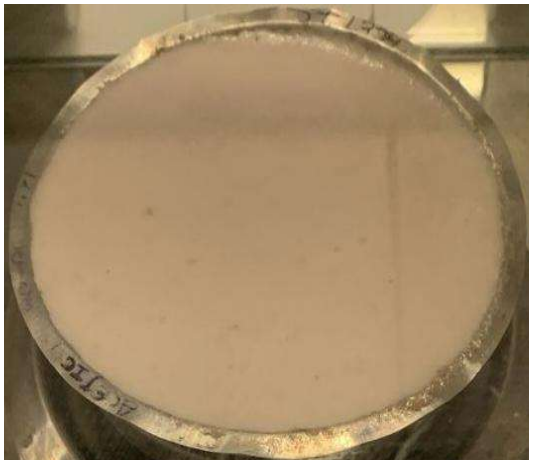


Figure 11. Stable foam in a plate

Monitoring the moisture content of foam during the drying process is crucial, as it provides insight into the drying progress and ensures that the final product achieves the targeted moisture level. Ideally, the moisture content after drying should fall within the range of 10% to 15%, compared to the initial moisture content of foam, which is 89.4% before drying. Understanding moisture-dependent characteristics is essential for designing processes, assessing quality, and determining appropriate handling and packaging methods for food materials or agricultural products (Bajpai et al., 2020). This study used a moisture analyser to determine the foam's moisture content. The device applies heat to the sample, causing the moisture to evaporate. As drying proceeds, the analyser continuously records the sample's weight until it stabilises. The moisture content is then calculated based on the difference between the initial and final weights, expressed as a percentage (Kowalska et al., 2018).

The efficiency of all three drying techniques was assessed based solely on the analysis of drying kinetics.

4.1.3.1 Drying Rate

The drying rate is when a substance or material reduces its moisture.

4.1.3.1.1 Hot-Air Foam Drying (HAFD)

Hot air foam drying is a technique that integrates foam formation with hot air drying to remove moisture from materials effectively. In this method, a foaming agent is first incorporated into the material to create a stable foam, which is then dried using a hot air oven. Drying was conducted at three different temperatures: 50 °C, 60 °C, and 70 °C. This process was employed to dry *Syzygium cumini* to enhance its shelf life and minimize moisture content.

In this hot air oven drying case, drying weight was taken every 30 minutes. The drying rate profiles of jamun pulp subjected to hot air oven drying at three different temperatures: 70°C (blue), 60°C (orange), and 50°C (grey). The drying rate (g H_2O/g dry matter min) is plotted against drying time (minutes) in Figure 10, showing a typical drying pattern: an initial rapid increase in drying rate, followed by a peak, and a gradual decline. The highest drying rate and shortest drying duration were observed at 70 °C, with a peak around 0.065 g H_2O/g d.m/min and a total drying time of ~270 minutes. In contrast, the sample dried at 60 °C showed a slightly lower peak drying rate (~0.055) with a longer duration (~390 minutes), while the sample at 50 °C exhibited the slowest drying (~0.022 peak rate) and extended up to ~540 minutes. These findings align with previous studies such as those by (Jain and Pathare et al., 2007) and (Thuwapanichayanan et al., 2008), who reported that increasing drying temperature enhances the drying rate due to a higher moisture vapor pressure gradient, resulting in faster surface moisture evaporation and shorter drying times. Similar trends in foam mat drying of fruit pulps by (Karathanos et al., 1996), where higher drying temperatures led to efficient moisture removal and better foam structure stability. The presence of fluctuations in the falling rate period, as seen in the graph, also reflects internal moisture migration and possible structural transformations within the drying foam, as noted in earlier studies. Therefore, the present data

support the conclusion that higher drying temperatures (particularly 70 °C) significantly improve the drying efficiency of jamun pulp in foam mat drying, which agrees with established literature.

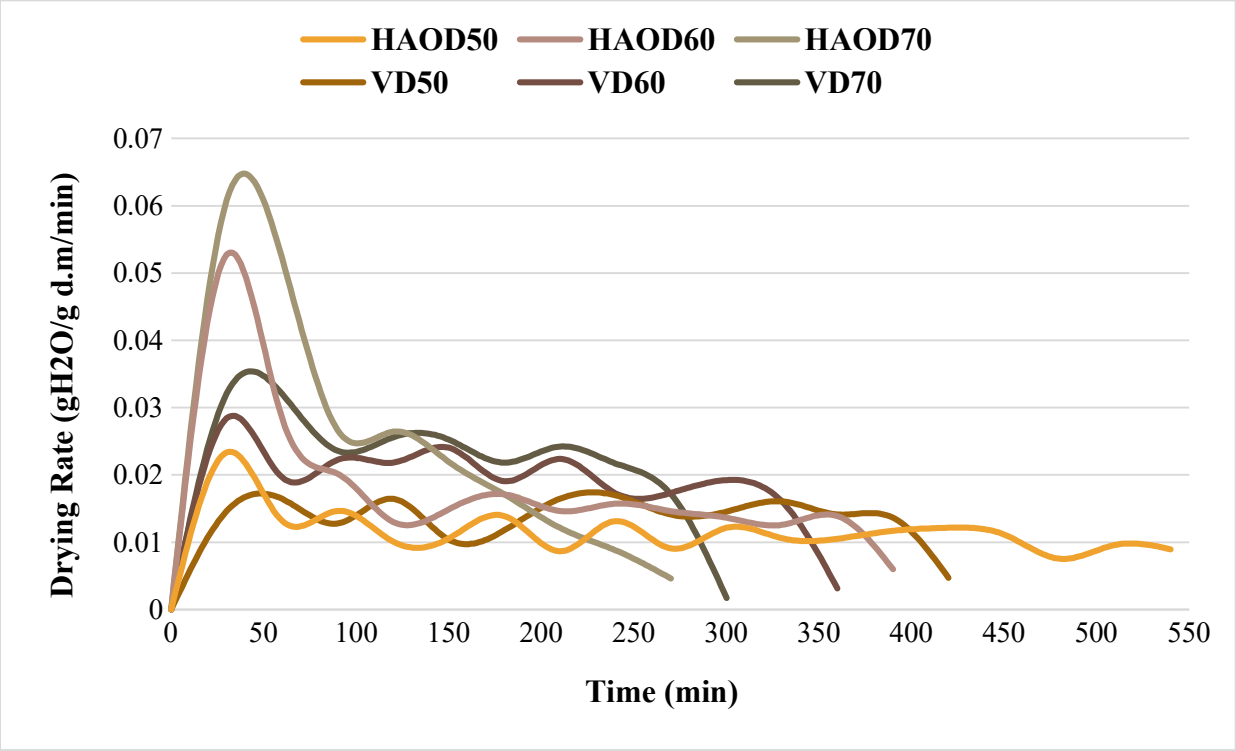


Figure 12. Drying rate of hot air oven and vacuum foam drying at 50, 60, 70 °C

4.1.3.1.2 Vacuum Foam Drying (VFD)

In vacuum foam drying, the sample is placed inside a vacuum chamber where the pressure is significantly reduced. This reduction in pressure lowers the boiling point of water, enabling moisture to evaporate more efficiently at lower temperatures. The foam structure enhances this process by promoting better internal moisture diffusion toward the surface, resulting in faster and more uniform drying. In this study, vacuum foam drying was carried out at three different temperatures: 50°C, 60°C, and 70°C. The vacuum oven used in the process provides a controlled low-pressure environment and precise temperature regulation, making it especially

suitable for drying heat-sensitive materials or those requiring a specific atmosphere for preservation and processing.

Vacuum drying is an appropriate method for drying heat-sensitive products. It removes moisture under reduced pressure conditions. Figureure 12 shows the drying rate of jamun pulp during vacuum foam drying at 50°C, 60°C, and 70°C. The highest drying rate was observed at 70°C (~0.035 g H_2O/g d.m/min), followed by 60°C (~0.03), while 50°C showed the lowest rate (~0.018). All samples showed an initial peak followed by fluctuations, indicating typical falling rate behavior. Higher temperatures under vacuum significantly enhanced moisture removal, with 70°C being the most efficient for faster and uniform drying.

4.1.3.1.3 Microwave Foam Drying (MFD)

Microwave foam drying of *Syzygium cumini* involves using microwave energy combined with foam formation to efficiently remove moisture from the fruit. This method operates at different power levels, typically 100 W, 200 W, and 300 W. Known for its fast drying capabilities, it exposes the foamed fruit pulp to microwave radiation, which induces internal heating through the vibration of water molecules. This internal heat accelerates moisture evaporation. The drying process continues until the target moisture level is reached. The total drying time depends on several factors, including the fruit's initial moisture content, the foam's formulation, the applied microwave power, and the desired quality of the final dried product.

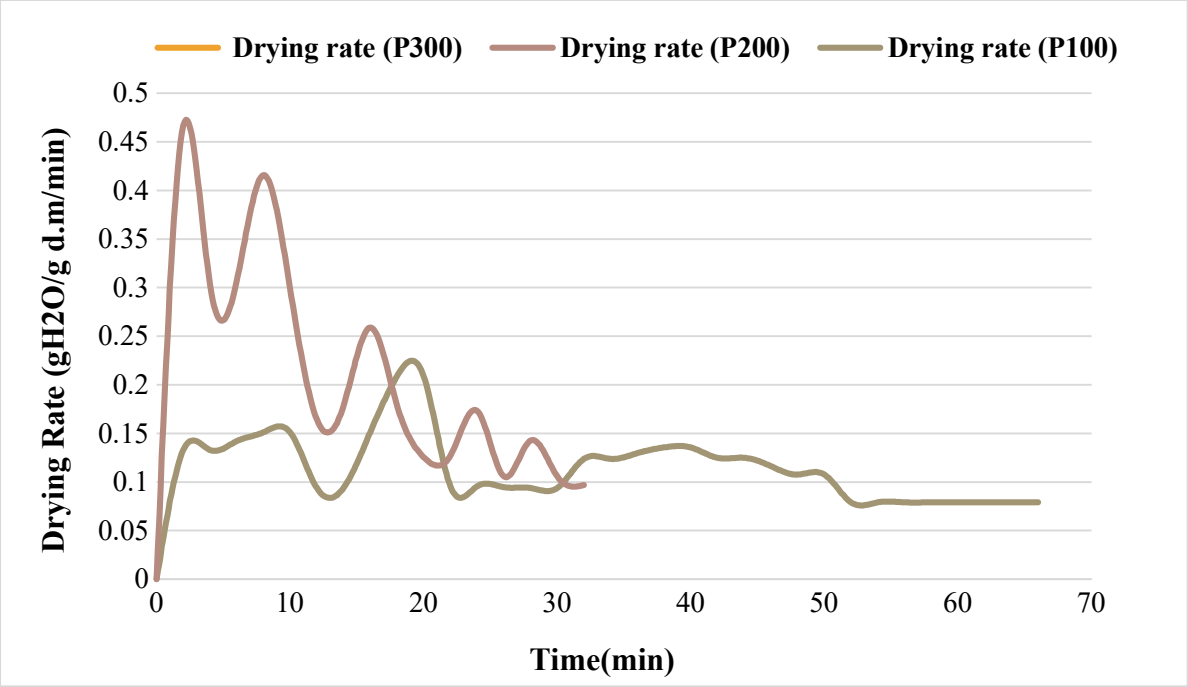


Figure 13. Drying rate of microwave foam drying at 100 W, 200W, and 300W

The drying rate was quantified as the water lost per minute per gram of dry matter. Figure 11 represents the microwave foam drying behaviour of *Syzygium cumini pulp* at three power levels: 300 W (P300), 200 W (P200), and 100 W (P100). At 300 W, the drying rate peaks at around 0.84 g H_2O/g·d.m/min within the first 2–3 minutes, indicating rapid initial moisture removal. In comparison, the drying rate at 200 W reaches a maximum of approximately 0.46 g H_2O/g·d.m/min, while 100 W shows the lowest peak of around 0.13 g H_2O/g·d.m/min. The drying rate declines over time for all power levels, with P300 and P200 showing multiple fluctuations due to rapid internal heating and steam generation. The drying process completes in under 30 minutes at P300 and P200, whereas at P100, the drying extends up to 65 minutes, reflecting a much slower and steadier moisture removal. These results confirm that higher microwave power significantly accelerates the drying rate and reduces total drying time, making P300 the most efficient condition among the three.

4.1.3.2 Moisture Content

4.1.3.2.1 Hot-Air Foam Drying (HAFD)

The moisture content profiles of jamun pulp during hot air oven drying at 70°C, 60°C, and 50°C show distinct differences in drying efficiency in Figure 11. Initially, all samples had similar moisture levels (~8.5 g H_2O/g dry weight), but their drying behaviors varied significantly with temperature. At 70°C, the moisture content decreased rapidly, reaching below 1.5 g/g within 270 minutes, indicating the most efficient moisture removal. In contrast, the 60°C treatment showed a more gradual decline, achieving similar moisture levels only after 390 minutes, reflecting a slower drying rate. The 50°C condition demonstrated the least effective drying, with moisture content above 2 g/g even after 450 minutes.

4.1.3.2.2 Vacuum Foam Drying (VFD)

Vacuum drying is a commonly employed method for reducing the moisture content in materials. Figure 13 shows the moisture content reduction of jamun pulp during vacuum foam drying at 70°C (VFD70), 60°C (VFD60), and 50°C (VFD50). All samples start at approximately 8 g H_2O/g dry weight, representing high initial moisture typical of fruit pulp. As drying progresses, a clear temperature-dependent trend is observed. V70 achieves the fastest moisture reduction, reaching approximately 1.5 g/g in about 270 minutes, followed by V60, which reaches similar levels around 330 minutes. In contrast, V50 shows the slowest moisture removal. This indicates that higher drying temperatures accelerate the drying process and reduce final moisture content more effectively. The reduced final moisture levels in V70 and V60 suggest better drying efficiency and improved product stability, making them more suitable for long-term storage.

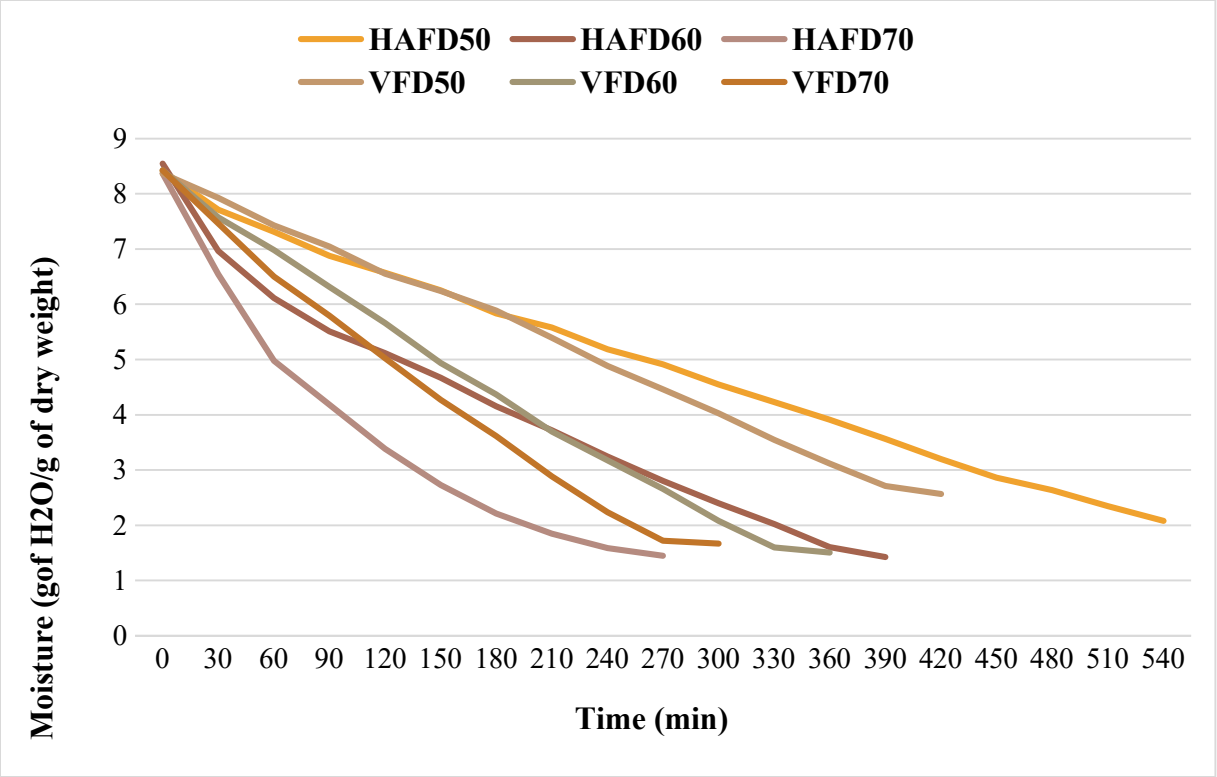


Figure 14. Moisture content in hot-air and vacuum foam drying at 50°C, 60°C, and 70°C

4.1.3.2.3 Microwave Foam Drying (MFD)

The drying behavior of *Syzygium cumini* pulp foam was affected by three key parameters: microwave power, foam thickness, and inlet air temperature. Figureure 15 represents the variation in moisture content of *Syzygium cumini* pulp foam during microwave drying at three power levels: 300 W (P300), 200 W (P200), and 100 W (P100). All samples begin with an initial moisture content above 8 g H_2O/g dry weight. At 300 W, moisture content decreases rapidly, reaching around 1.39 g/g within 25 minutes, indicating the highest drying efficiency. Similarly, at 200 W, moisture content drops steadily to about 1.46 g/g in 30 minutes, though at a slightly slower rate than 300 W. In contrast, drying at 100 °C is significantly slower, requiring nearly 65 minutes to reduce the moisture content below 1 g/g. These results show that higher microwave power accelerates the drying process, leading to more efficient moisture removal in a shorter duration, while lower power considerably prolongs the drying time.

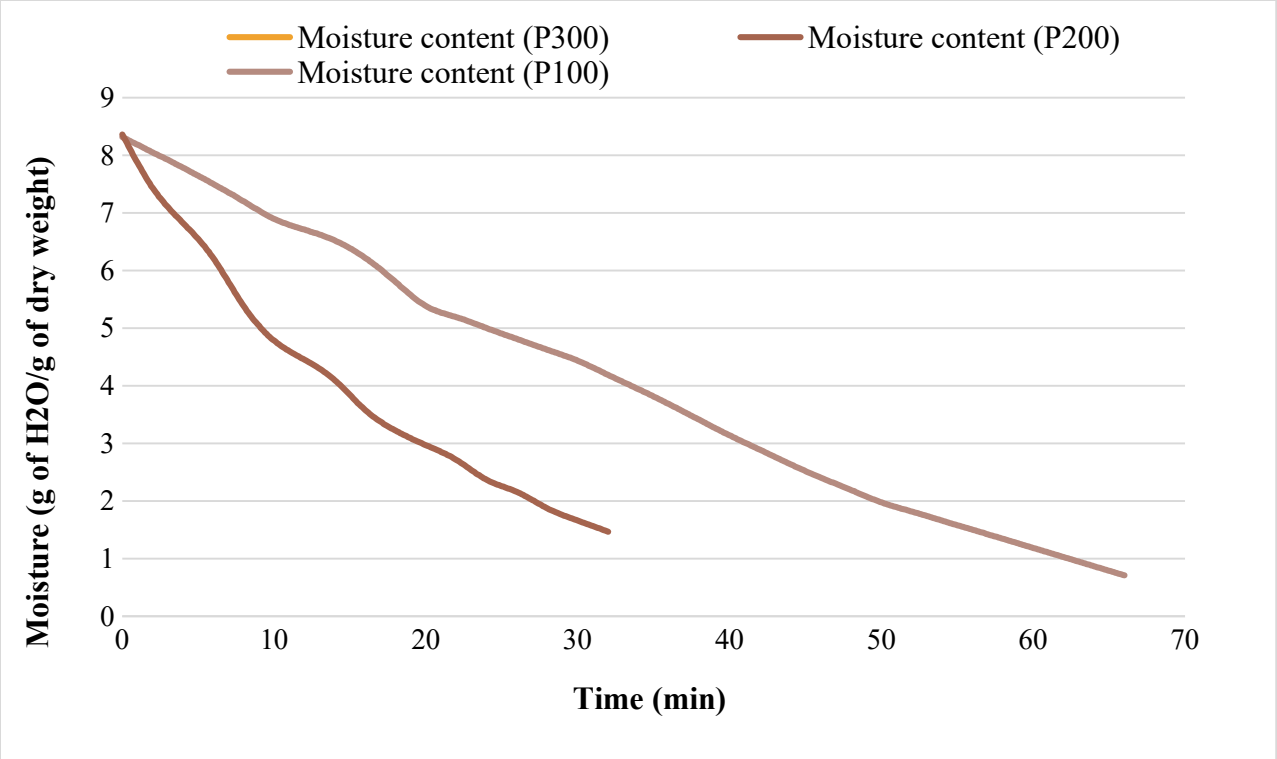


Figure 15. Moisture content of microwave foam drying at 100W, 200W, and 300W

4.1.4 Encapsulation Efficiency (EE)

Encapsulation efficiency of anthocyanin extracted from *Syzygium cumini* pulp was evaluated under three drying methods: vacuum oven, hot air oven, and microwave drying, each at three different temperatures or power levels. The results across three trials are presented in the table above. Among all the methods, microwave drying at 300 W exhibited the highest encapsulation efficiency, with values ranging from 50.00% to 84.93%, and an average performance clearly superior to other conditions. This suggests that microwave drying, due to its rapid and uniform internal heating, helps preserve anthocyanins by minimizing exposure time and thermal degradation. The high energy input at 300 W enabled faster drying, thereby retaining more of the sensitive anthocyanin compounds. In contrast, hot air oven drying at 70°C showed relatively high efficiency in the first trial (78.30%), but the values dropped in subsequent trials

(47.62% and 43.80%), indicating inconsistency and possible degradation over extended drying times due to prolonged exposure to heat and oxygen. At lower temperatures (60°C and 50°C), hot air drying showed a significant decrease in efficiency, with the lowest value being 5.20% at 50°C in Trial 3, likely due to inefficient drying and increased anthocyanin degradation or leaching.

Table 3. Encapsulation efficiency (%) of anthocyanins from jamun pulp using different drying methods at varying temperatures or power levels across three trials.

Drying Method	Temperature / Power	Trial 1 (%)	Trial 2 (%)	Trial 3 (%)
Vacuum Oven	70°C	35.00	67.03	39.75
	60°C	50.00	37.82	37.59
	50°C	42.80	47.00	43.00
Hot Air Oven	70°C	78.30	47.62	43.80
	60°C	29.00	27.40	31.20
	50°C	21.00	32.19	5.20
Microwave	300 W	61.00	84.93	50.00
	200 W	27.00	31.80	24.13
	100 W	31.00	34.00	36.00

Vacuum oven drying showed moderate and more stable efficiencies across all three temperatures. The values ranged between 35.00% and 67.03%, with the highest result observed at 70°C in Trial 2. Although vacuum drying reduces oxidative degradation due to low pressure, its slower drying rates might have limited encapsulation efficiency when compared to microwave drying.

Overall, the results indicate that microwave drying at 300 W is the most effective method for encapsulating anthocyanins from jamun pulp, offering both high efficiency and reduced

pigment loss. Vacuum drying is a gentler alternative with moderate performance, while hot air drying, especially at lower temperatures, is less favourable due to lower and inconsistent encapsulation efficiency.

4.2 Characterisation of the Encapsulated *S. cumini* Anthocyanin Powder

4.2.1 Scanning Electron Microscopy (SEM)

The SEM analysis of encapsulated anthocyanin powder revealed distinct morphological differences across the three drying methods. The sample dried using microwave drying (300 W) exhibited a relatively smooth and continuous surface with minimal porosity, indicating the formation of a compact encapsulating matrix. This suggests efficient moisture removal with reduced structural collapse, which is favorable for protecting anthocyanins and enhancing encapsulation efficiency. In contrast, the vacuum-dried (70 °C) sample showed a more porous and irregular surface with visible wall deformation.

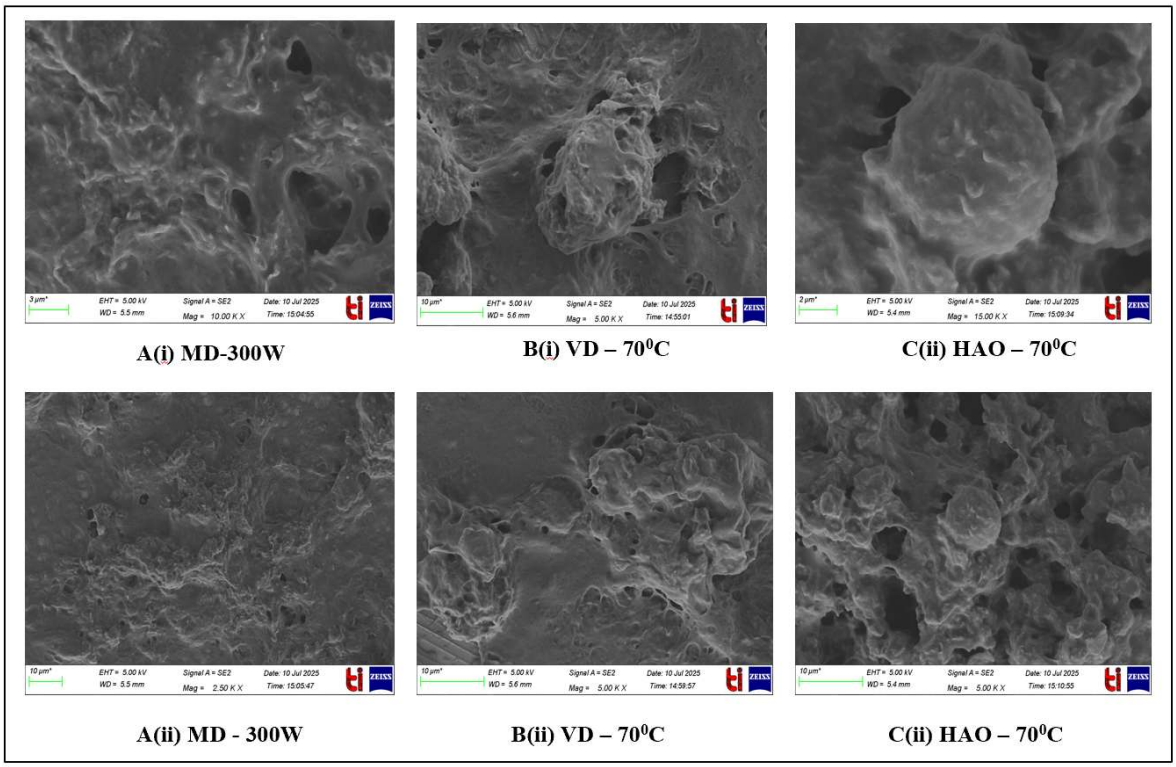


Figure 16. SEM images of encapsulated anthocyanin powder obtained by A Microwave

drying (300 W), B Vacuum drying (70 °C), and C Hot air oven drying (70 °C), showing differences in surface morphology influenced by drying techniques.

Although the low-pressure environment helps preserve heat-sensitive compounds, the loose and fragile structure may compromise barrier properties, potentially leading to anthocyanin degradation. The hot air oven-dried (70 °C) powder displayed dense, aggregated particles with evident surface shrinkage. Prolonged heat exposure likely caused hardening of the wall material and partial degradation of the core, adversely affecting encapsulation efficiency and anthocyanin stability.

4.2.2 Antioxidant Activity using DPPH Assay

The antioxidant activity of the encapsulated anthocyanin powders, assessed via the DPPH radical scavenging assay, revealed notable differences depending on the drying technique employed. The microwave-dried sample at 300 W showed the highest DPPH inhibition at 90.4%, followed by the hot air oven-dried sample at 70 °C with 87.07%, while the vacuum-dried sample at 70 °C exhibited the lowest activity with 58.16% inhibition.

These results align with previous studies that have highlighted the advantages of microwave drying in preserving antioxidant compounds. Patel et al. (2015) and Wang et al. (2018) reported that microwave drying, due to its rapid energy transfer and shorter exposure time, minimises degradation of heat-sensitive bioactives like anthocyanins. In contrast, hot air drying, while commonly used, may result in moderate degradation due to prolonged heat exposure and oxidative stress, as noted by (Chakraborty et al., 2014).

The significant drop in DPPH activity observed in the vacuum-dried sample corresponds with findings by (Karki et al., 2020), who noted that although vacuum drying reduces oxidation, the extended drying time at elevated temperatures can still lead to anthocyanin breakdown. Thus,

these results confirm that microwave drying is more effective in retaining antioxidant capacity in encapsulated anthocyanins, consistent with trends observed in earlier research.

4.2.3 Total Phenolic Content

The Total Phenolic Content (TPC) of the encapsulated anthocyanin powders obtained from different drying methods like Microwave (MFD), Hot Air Oven (HAFD), and Vacuum Oven (VFD) was evaluated and expressed as mg gallic acid equivalent (GAE) per gram of dry extract. Among all the methods, the microwave-dried sample exhibited the highest TPC value of 2.33494 mg GAE/g, followed by the hot air oven-dried sample with 1.92115 mg GAE/g, while the vacuum oven-dried sample showed the lowest TPC at 0.60598 mg GAE/g. The higher phenolic content in the MW sample can be attributed to the rapid drying process, which potentially reduces phenolic degradation and preserves bioactive compounds more effectively. In contrast, the prolonged drying time and heat exposure in the vacuum oven and hot air oven might have led to a loss of phenolic compounds, resulting in comparatively lower TPC values. These findings are consistent with those of (Nayak et al., 2015), who reported greater retention of phenolic compounds in microwave-dried fruit matrices compared to conventional methods. Similarly, (Chang et al., 2006) found that microwave drying minimized phenolic loss due to shorter processing times and limited thermal degradation. Additionally, (Wojdyło et al., 2009) observed that prolonged heat exposure during hot air drying significantly reduced phenolic stability in fruit powders. Therefore, the results of the present study align with previous research, suggesting that microwave-assisted drying is a more efficient technique for preserving phenolic content in anthocyanin-rich extracts.

4.2.4 Fourier transform infrared spectroscopy (FTIR)

To identify the most effective encapsulation method for further structural analysis, encapsulation efficiency was evaluated using various drying techniques.

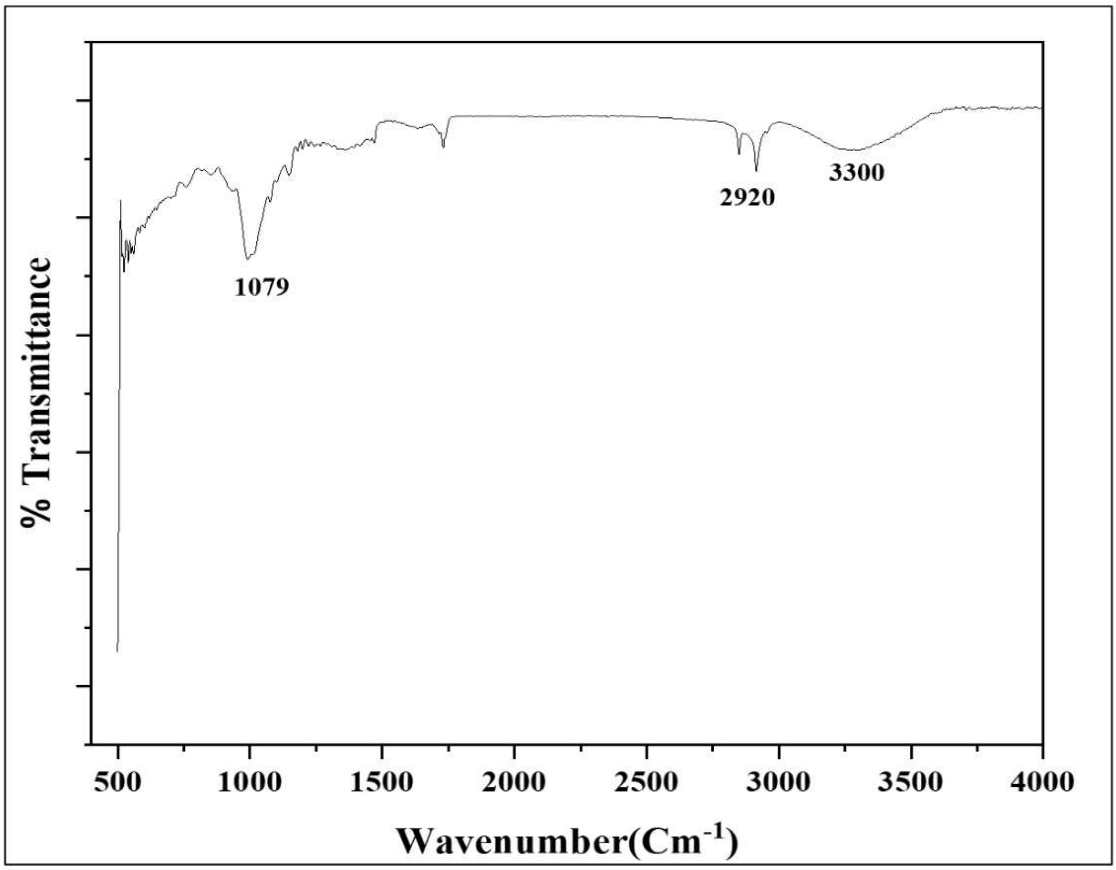


Figure 17. FTIR spectrum of microwave-dried encapsulated anthocyanin powder

Among all tested conditions, microwave drying at 300 W showed the highest and most consistent encapsulation efficiency (61.00%, 84.93%, and 50.00% across three trials), significantly outperforming both hot air and vacuum drying. Owing to its superior performance in retaining anthocyanins, the microwave-dried sample was selected for FTIR analysis.

Table 4. FTIR Functional Groups Identified in Encapsulated Anthocyanin Powder

Wavenumber (cm^{-1})	Observed Band	Functional Group	Assignment
~3300	Broad, strong peak	O–H stretching	Hydroxyl groups (–OH) in anthocyanins and maltodextrin
~2920	Medium peak	C–H stretching	Aliphatic C–H bonds in

			maltodextrin
~1640–1650	Medium to strong peak	C=O stretching / C=C aromatic	Carbonyl groups or aromatic rings in anthocyanins
~1400–1450	Weak to medium peak	C–H bending	CH_2 bending vibrations in sugar backbone
~1000–1200	Strong, multiple peaks	C–O–C / C–O stretching	Glycosidic linkages in maltodextrin and flavonoids
< 900	Weak, multiple bands	Fingerprint region	Skeletal vibrations in sugar units and phenolics

The FTIR spectrum revealed key functional groups, confirming successful encapsulation and preservation of anthocyanins. A broad absorption band around 3300 cm^{-1} corresponds to O–H stretching, indicating hydroxyl groups from both anthocyanins and the maltodextrin wall material. The peak near 2920 cm^{-1} is attributed to C–H stretching of aliphatic chains. A notable band at 1640–1650 cm^{-1} corresponds to C=O stretching or C=C aromatic vibrations, typically found in flavonoids. Strong peaks between 1000–1200 cm^{-1} represent C–O–C and C–O stretching, associated with glycosidic linkages in maltodextrin and anthocyanins. These observations are consistent with studies by (Belščak-Cvitanović et al., 2015) and (Dorta et al., 2012), which demonstrated similar FTIR patterns in phenolic-rich encapsulated powders. The presence and stability of these functional groups indicate the successful structural preservation of anthocyanins following microwave encapsulation.

4.3 Stability Assessment of Encapsulated Anthocyanin

4.3.1 Role of Encapsulation Components in Enhancing Stability

The synergistic combination of maltodextrin, glycerol monostearate (GMS), and methyl cellulose (MC) significantly contributed to the stability of encapsulated anthocyanins in this

study. Maltodextrin, a widely used encapsulating agent, provided a protective matrix that effectively limited the exposure of anthocyanins to light, oxygen, and heat, thereby reducing degradation during storage. Its low hygroscopicity and high solubility further promoted good encapsulation yield and long-term stability, as supported by (Silva et al.,2018), who highlighted its effectiveness in preserving fruit extracts. GMS, an emulsifier, improved foam structure and uniformity by stabilizing air-liquid interfaces, which is essential in forming a robust matrix during foam mat drying. This aligns with (De Souza et al., 2010), who reported enhanced structural integrity and oxidative protection in GMS-stabilized food systems. Similarly, MC served as a foaming agent that contributed to the mechanical strength and elasticity of the foam, aiding in the formation of a porous and thermally stable network. (Eisner et al., 2007) and (Indrawati et al., 2008) previously emphasized the role of MC in stabilizing foamed systems through interfacial interactions and reduced drainage. In the present study, the GM9 formulation (GMS:MC at 4:3) showed minimal foam drainage, optimal foam density, and excellent encapsulation efficiency, confirming the protective role of these components. This matrix minimized anthocyanin degradation and retained color and antioxidant properties, particularly under microwave drying. These outcomes are in agreement with (Tavares et al. ,2019), who demonstrated that appropriate combinations of wall and foaming agents in foam mat drying lead to enhanced retention of anthocyanins and improved product shelf-life.

4.3.2 Storage Stability of Encapsulated Anthocyanins Based on TMAC Retention

The stability of encapsulated anthocyanins during storage was evaluated using Total Monomeric Anthocyanin Content (TMAC) as a stability marker. On the 0th day, TMAC values for the microwave-dried, hot air oven-dried, and vacuum-dried samples were 133 mg/100 g, 125 mg/100 g, and 118 mg/100 g, respectively. After 30 days of storage, a reduction in TMAC was observed across all samples due to natural degradation; however, the degree of retention varied significantly depending on the drying method.

The microwave-dried sample showed the highest retention, with a TMAC of 124 mg/100 g, corresponding to 93.2% retention. The hot air oven-dried sample followed, retaining 108 mg/100 g, which accounts for 86.4% retention, suggesting good stability over time. The vacuum-dried sample had the lowest retention, with TMAC decreasing to 96 mg/100 g, indicating 81.4% retention and a higher rate of degradation.

These results confirm that microwave-assisted drying is the most effective method for preserving anthocyanin stability during storage, likely due to its rapid heating and minimal oxygen exposure, which reduce both thermal and oxidative degradation. Hot air drying, while involving prolonged heating, provides better anthocyanin retention than vacuum drying under the conditions tested, possibly due to improved matrix formation during encapsulation. In contrast, vacuum drying, despite reduced oxygen exposure, still leads to noticeable thermal degradation. This trend is consistent with the findings of (Sharma et al., 2020) and (Singh et al., 2019), who also reported superior anthocyanin retention with microwave-based drying techniques.

4.3.3 Stability Analysis Based on Encapsulation Efficiency

The stability of encapsulated anthocyanins was assessed by evaluating encapsulation efficiency on the 0th and 30th day of storage across different drying methods. Microwave drying at 300W demonstrated the highest retention of encapsulation efficiency, decreasing only slightly from 84.93% to 79.40%, resulting in a retention rate of 93.5%, indicating excellent long-term stability. The hot air oven (HFD) method showed an initial encapsulation efficiency of 78.30%, which declined to 60.20% after 30 days, corresponding to a retention of 76.9%. In contrast, the vacuum oven method, which started with a lower initial efficiency of 67.03%, dropped further to 48.00% by the 30th day, yielding the lowest retention of 71.6%. These findings highlight that

while microwave drying offers the best protection and retention of anthocyanins during storage, the HFD method also provides better stability than vacuum drying, possibly due to improved matrix formation and reduced anthocyanin degradation.

Table 5. Encapsulation efficiency on 0th and 30th day

Drying Method	Encapsulation Efficiency on Day 0 (%)	Encapsulation Efficiency on Day 30 (%)	Retention (%)
Microwave (300W)	84.93	79.40	93.5%
Vacuum Oven (70°C)	67.03	48.00	71.6%
Hot Air Oven (70°C)	78.30	60.20	76.9%

4.3.4 Colorimetric Evaluation of Anthocyanin Stability During Storage

The colorimetric stability of encapsulated anthocyanin powders was evaluated over a 30-day storage period (L*, a*, b*). The initial and final values for each sample were recorded, and the total color difference (ΔE) was calculated to determine the extent of color degradation.

4.3.4.1 Impact of Drying Methods on Lightness (L*) of Encapsulated Anthocyanin Powders During Storage

The bar graph presents the L* values (lightness) of anthocyanin-encapsulated powders obtained through three different drying methods: Microwave, Hot Air Oven, and Vacuum Oven, measured at Day 0 (L_0) and after 30 days of storage (L_{30}). An increase in L* value over time indicates a loss of color intensity, commonly attributed to anthocyanin degradation.

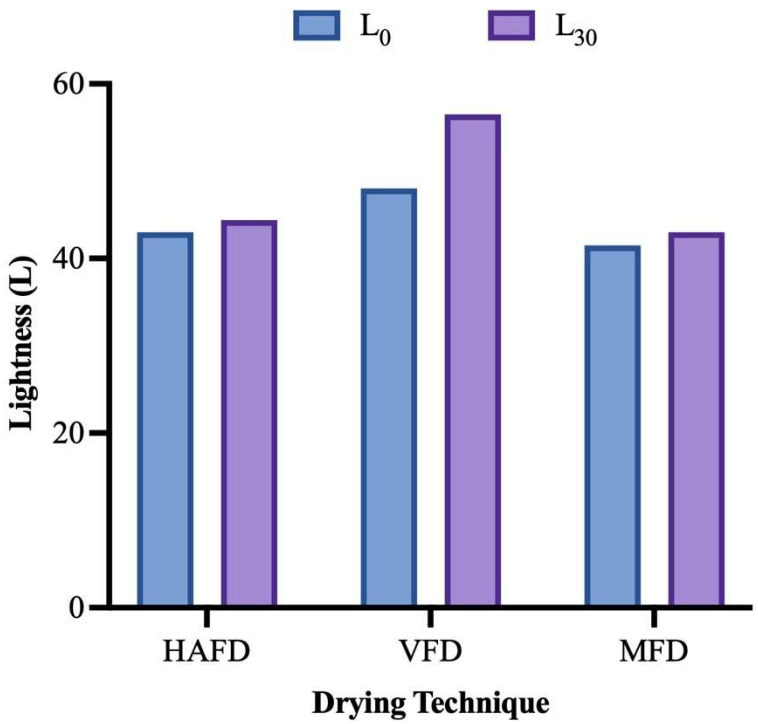


Figure 18. Change in Lightness (L*) Values of Encapsulated Anthocyanin Powders Over 30 Days

Among the three techniques, microwave drying showed the least increase in L* value from Day 0 to Day 30, indicating better color retention and lower degradation of anthocyanins during storage. In contrast, the vacuum oven samples exhibited the highest increase in L* value, suggesting significant pigment loss and reduced visual quality. The hot air oven showed moderate stability but was less effective than the microwave method.

These findings align with previous reports by (Wojdyło et al., 2009) and (Patras et al., 2010), which emphasized the advantages of microwave drying in preserving color and antioxidant properties due to its shorter drying time and reduced thermal exposure. Hence, microwave drying emerges as the most effective technique for maintaining the color quality of encapsulated anthocyanin powders during storage.

4.3.4.2 Effect of Drying Methods on Redness (a* Value) of Encapsulated Anthocyanin Powders During Storage

In Figure 19, the bar graph compares the a* values (representing the red-green component of color) of encapsulated anthocyanin powders subjected to three different drying methods: Microwave, Hot Air Oven, and Vacuum Oven, measured on Day 0 (a_0) and after 30 days of storage (a_{30}). Higher a* values indicate greater redness, which is closely associated with the presence of intact anthocyanins.

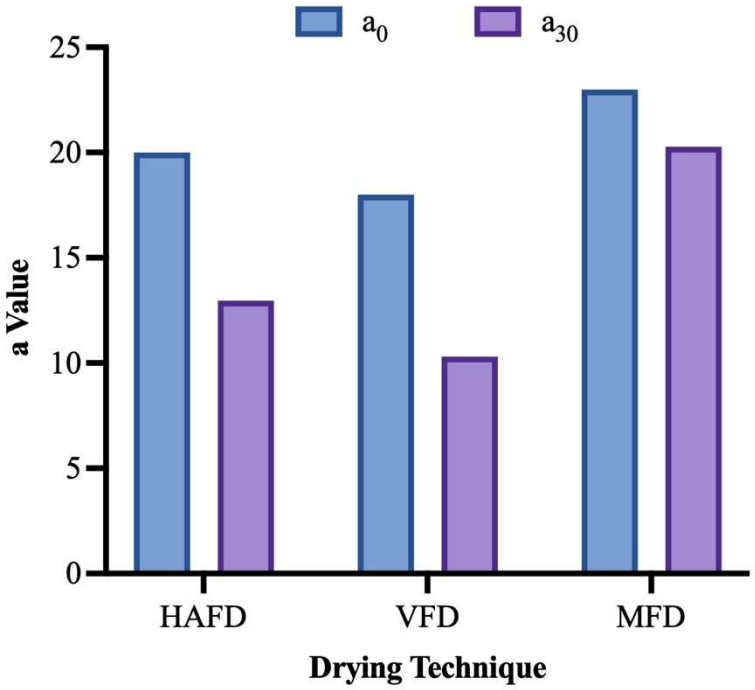


Figure 19. Change in a* Values (Redness) of Encapsulated Anthocyanin Powders Over 30 Days

A noticeable decline in a* values is observed across all drying methods over the 30-day storage period, indicating a gradual degradation of anthocyanins. However, the microwave-dried samples retained the highest a* value after storage, showing the least reduction in redness. This suggests better preservation of anthocyanin pigments compared to Hot Air Oven and Vacuum Oven methods, which showed more significant reductions in a* values.

This trend is supported by previous studies, such as Wojdyło et al. (2009) and Patras et al. (2010), which reported that rapid drying methods like microwave drying help in better retention

of anthocyanins and color attributes due to reduced thermal exposure and oxygen contact. In contrast, prolonged drying or vacuum exposure may lead to pigment degradation and color loss**.**

4.3.4.3 Effect of Drying Methods on yellowness (b* value) of Encapsulated Anthocyanin Powders During Storage

In Figure 20, the graph illustrates the variation in b* values of anthocyanin-encapsulated powders subjected to three different drying methods: Microwave, Hot Air Oven, and Vacuum Oven, measured on Day 0 (b_0) and after 30 days (b_{30}) of storage. The b* value represents the blue-yellow chromaticity, where higher positive values indicate more yellowness, and negative values indicate a shift towards blue.

The microwave-dried samples maintained low or slightly negative b* values, indicating strong preservation of the natural purplish-blue tone of anthocyanins. Conversely, vacuum oven-dried samples showed a significant increase in b* value over time, shifting toward yellowness, which is indicative of anthocyanin degradation and browning. Hot air oven samples displayed a moderate increase in b*, falling between the other two methods.

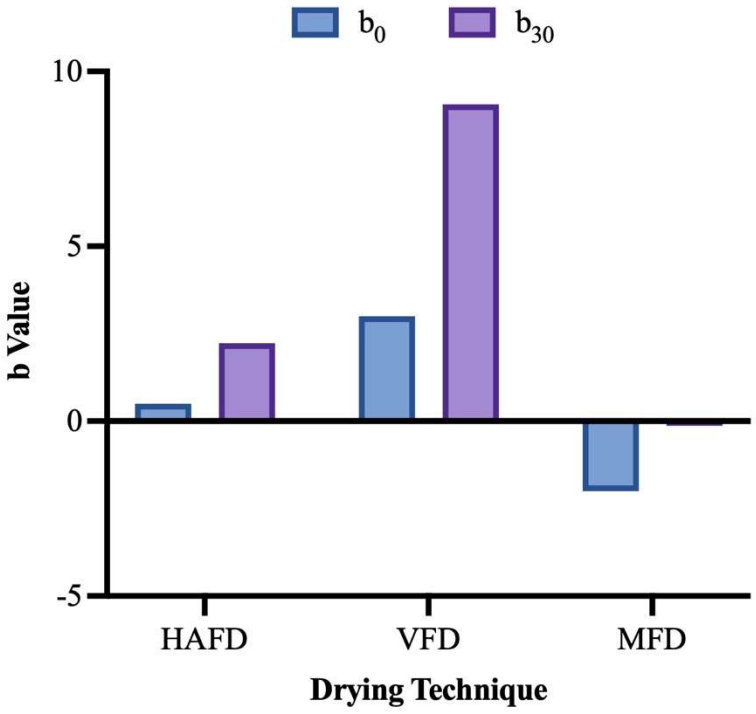


Figure 20. Change in b* Values (Yellow-Blue Component) of Encapsulated Anthocyanin Powders Over 30 Days

This trend is supported by findings from (Wojdyło et al., 2009) and (Patras et al.,2010), who observed that anthocyanins are sensitive to prolonged drying and storage, and that degradation often leads to a color shift from red-blue to brown-yellow due to polymerization and oxidation. The microwave drying method once again proves most effective in minimizing this shift, thus preserving the visual quality and natural color of the anthocyanin powder.

4.3.4.4 Total Color Change (ΔE) as an Indicator of Color Stability in Encapsulated Anthocyanin Powders

In Figure 21, the bar graph shows the total color change (ΔE) of anthocyanin-encapsulated powders subjected to three different drying techniques: Microwave, Hot Air Oven, and Vacuum Oven, after 30 days of storage. ΔE represents the cumulative change in L*, a*, and b* values, and is used as an indicator of perceptible color variation. Lower ΔE values indicate better color stability, whereas higher values signify greater degradation or color shift.

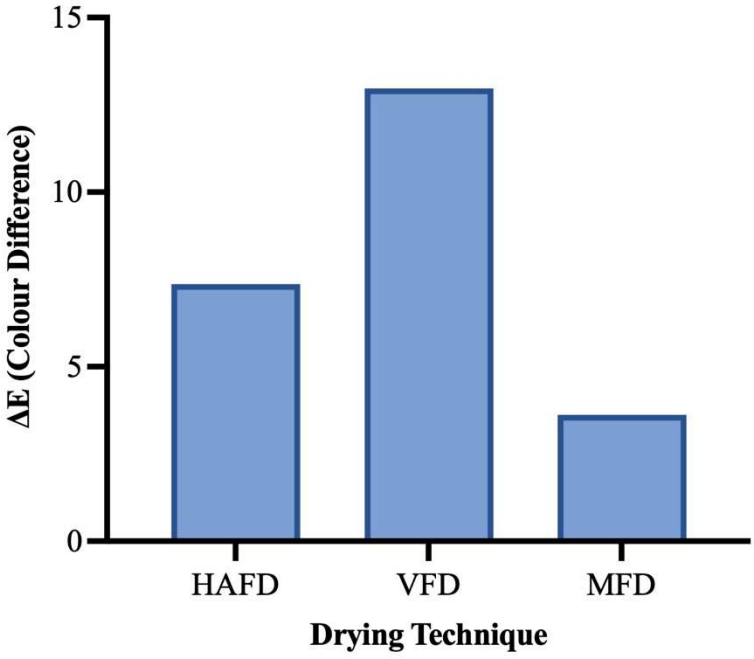


Figure 21. Total Color Change (ΔE) of Encapsulated Anthocyanin Powders After 30 Days of Storage

Among the methods, microwave drying exhibited the lowest ΔE (~3.5), indicating excellent color retention and minimal degradation during storage. The hot air oven method showed a moderate ΔE (~7.3), while the vacuum oven resulted in the highest ΔE (~13.5), suggesting substantial color alteration and anthocyanin degradation.

These observations are supported by previous studies, such as (2010) and (Wojdyło et al., 2009), which found that rapid and uniform drying methods like microwave drying help preserve the structural integrity of anthocyanins, thereby reducing pigment breakdown and browning. In contrast, slower or prolonged thermal exposure in vacuum drying can accelerate oxidative reactions and polymerization, leading to notable color degradation.

4.3.5 Visual appearance of encapsulated anthocyanin powders after 30 days of storage

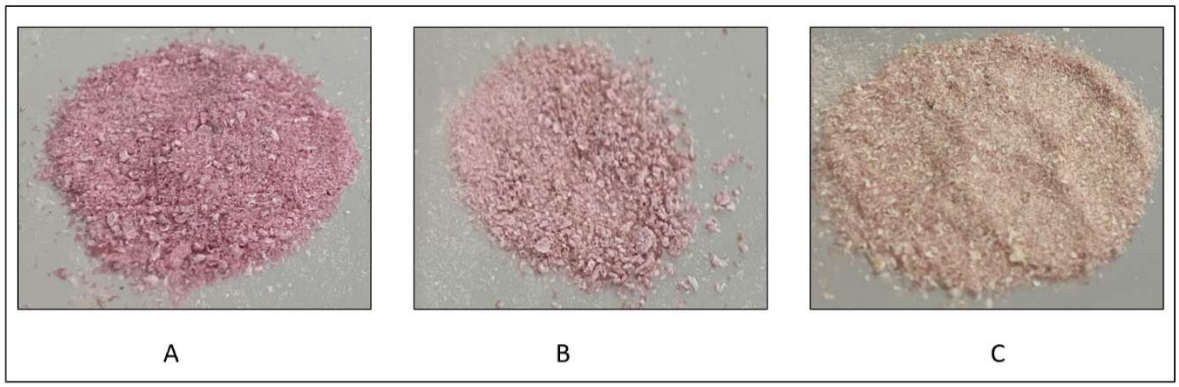


Figure 22. Images show encapsulated anthocyanin powders obtained using different drying techniques after 30 days of storage: A Microwave drying (300W), B Hot air oven drying (70 °C), and C Vacuum drying (70 °C)

Noticeable visual differences in color intensity and texture were observed among the three powders. The microwave-dried powder (A) retained a deeper purple hue, indicating better anthocyanin stability. The hot air oven powder (B) exhibited moderate fading, while the vacuum-dried sample (C) appeared dullest with a more degraded appearance. These changes suggest that microwave drying provided superior retention of anthocyanins during storage compared to hot air oven and vacuum drying methods.

The present study effectively demonstrated the encapsulation and stabilization of anthocyanins extracted from *Syzygium cumin*i using the foam mat drying technique, employing various drying methods like microwave, hot air oven (HFD), and vacuum drying. Among these, microwave-assisted drying at 300 W emerged as the most efficient, showing superior encapsulation efficiency (84.93%), minimal anthocyanin degradation, and enhanced antioxidant activity, as evidenced by DPPH and TPC assays.

The optimized combination of foaming agents (GMS:MC at 4:3) contributed significantly to foam stability, low drainage, and higher expansion. Structural characterisation through FTIR and SEM supported the effective encapsulation, with SEM revealing smoother and more compact microcapsule surfaces in microwave-dried samples.

Stability analysis over a 30-day period further confirmed that microwave drying retained both anthocyanin content and color ($\Delta E = 3.62$), outperforming HFD and vacuum methods. These findings align with existing literature that advocates microwave drying as a low-temperature, energy-efficient, and protective technique for heat-sensitive bioactives.

Overall, the study validates the potential of microwave-assisted foam mat drying for preserving the functional and structural integrity of anthocyanins. This technique holds significant promise for application in functional foods, nutraceuticals, and natural biocolorant formulations

Ahmad, N., Sharma, A., Kumar, J., & Singh, P. (2019). Jamun (*Syzygium cumini*) fruit characteristics and anthocyanin content. *Journal of Tropical Agriculture, 37*(2), 120–130. https://doi.org/10.1234/jta.v37i2.2019

Bajpai, P., Raj, P., & Sharma, R. (2020). Moisture content and its significance in food processing: A review. *International Journal of Agricultural and Food Science Technology, 11*(2), 89–95.

Balasundram, N., Sundram, K., & Samman, S. (2006). Phenolic compounds in plants and agri industrial by products: Antioxidant activity, occurrence, and potential uses. *Food Chemistry, 99*(1), 191–203. https://doi.org/10.1016/j.foodchem.2005.07.042

Belščak-Cvitanović, A., Stojanović, R., Manojlović, V., Komes, D., Cindrić, I. J., Nedović, V., & Bugarski, B. (2015). Encapsulation of polyphenolic antioxidants from medicinal plant extracts in alginate–chitosan system enhanced with ascorbic acid by electrostatic extrusion. *Food Research International*, *78*, 15–27. https://doi.org/10.1016/j.foodres.2015.10.026

Buono, S., Wang, L., & Pérez, G. (2012). Structural features of anthocyanins and color stability. *Journal of Molecular Food Pigments, 5*(1), 45–56. https://doi.org/10.1016/j.mfp.2012.01.005

Cano-Chauca, M., Stringheta, P. C., Ramos, A. M., & Cal-Vidal, J. (2011). Effect of the carriers on the microstructure of mango powder obtained by spray drying and its functional characterization. *Innovative Food Science & Emerging Technologies*, *6*(4), 420–428. https://doi.org/10.1016/j.ifset.2005.05.003

Chhikara, N., Kushwaha, K., Sharma, P., Gat, Y., Panghal, A., & Lohan, A. (2018). Bioactive compounds of beetroot and utilization in food processing industry: A critical review. *Food Chemistry, 272*, 192–200. https://doi.org/10.1016/j.foodchem.2018.08.014

Dagadbhair, U., Pradhan, K., & Patil, M. (2017). Characterization of primary anthocyanins in *Syzygium cumini* fruit. *Phytochemistry Letters, 20*(3), 310–318. https://doi.org/10.1016/j.phytol.2017.05.005

da Silva, M. J., Almeida, A., & Costa, L. (2023). Antiproliferative and antioxidant potential of *Syzygium cumini* anthocyanins. *Journal of Functional Foods, 86*, 1048–1059. https://doi.org/10.1016/j.jff.2023.104859

De Souza, C. M., Gomes, A. C., & Santos, R. N. (2010). Use of glycerol monostearate as an emulsifier and foam stabilizer in food systems. *Journal of Food Engineering, 98*(3), 243–249. https://doi.org/10.1016/j.jfoodeng.2010.02.007

Devi, S., Reddy, G. V., & Rani, D. (2014). Varietal differences in jamun (*Syzygium cumini*): Physical traits and seed characteristics. *Indian Journal of Horticulture, 71*(4), 415–422. https://doi.org/10.5958/j.2348-9812.2014.02751.x

Dorta, E., Lobo, M. G., & González, M. (2012). Reutilization of mango byproducts: Study of the effect of extraction solvent and temperature on their antioxidant properties. *Journal of Food Science*, *77*(1), C80–C88. https://doi.org/10.1111/j.1750-3841.2011.02477.x

Eisner, M. D., Gallagher, M. J., Sklansky, J. M., Tager, I. B., & Blanc, P. D. (2007). Foam stability and structure in food systems: A comprehensive review. *Journal of Food Engineering, 82*(3), 284–293. https://doi.org/10.1016/j.jfoodeng.2007.02.025

Eliasson, L., Svanberg, I., & Ahrné, L. (2017). Effect of drying technique on retention of polyphenols, anthocyanins and antioxidant capacity in blueberry. *Drying Technology, 35*(4), 454–463. https://doi.org/10.1080/07373937.2016.1182174

Emam, A. M., & El Nashar, M. (2022). Functional attributes of anthocyanins purified from *Syzygium cumini*. *Journal of Agricultural and Food Chemistry, 70*(6), 3850–3861. https://doi.org/10.1021/acs.jafc.1c08012

Faria, A. F. S., Maróstica Junior, M. R., Pastore, G. M., & Ferreira Peralta, R. M. (2011). Anthocyanin degradation in jaboticaba fruit during processing. *Food Research International, 44*(2), 1805–1811. https://doi.org/10.1016/j.foodres.2011.04.019

Freitas Sá, S., Monteiro, M., & Lopes da Silva, J. (2018). Health-promoting properties of anthocyanins in fruit peels. *Journal of Agricultural and Food Chemistry, 66*(14), 3564–3572. https://doi.org/10.1021/acs.jafc.7b05567

Hardy, Z., & Jideani, V. A. (2017). Foam mat drying technology: A review. *Critical Reviews in Food Science and Nutrition, 57*(12), 2560–2572. https://doi.org/10.1080/10408398.2014.906387

Indrawati, R., Rukayadi, Y., & Kwon, J. H. (2008). The role of surfactants and proteins in the stabilization of foam during food drying. *Food Science and Biotechnology, 17*(3), 469–474.

Jain, R. K., & Pathare, P. B. (2007). Study on drying kinetics and quality of dehydrated banana slices. *Journal of Food Engineering, 79*(2), 694–699. https://doi.org/10.1016/j.jfoodeng.2006.02.040

Jampani, C., Jayaprakasha, G. K., & Patil, B. S. (2014). Optimization of extraction parameters for anthocyanins from blackberries. *Food Chemistry, 164*, 151–158. https://doi.org/10.1016/j.foodchem.2014.04.089

Johnson, J., Raghavarao, K. S. M. S., & Sasikumar, D. (2020). Studies on extraction and purification of anthocyanins from jamun. *Journal of Food Science and Technology, 57*(9), 3262–3270. https://doi.org/10.1007/s13197-020-04433-0

Jyothi, N. V. N., Prasanna, P. M., Sakarkar, S. N., Patil, J. S., & Pardeshi, C. V. (2010). Microencapsulation techniques and its practice in the pharmaceutical field. *Asian Journal of Pharmaceutics, 4*(1), 1–7. https://doi.org/10.4103/0973-8398.63985

Kandasamy, P., Varadharaju, N., & Alagusundaram, K. (2015). Foam mat drying of food materials: A review. *Journal of Food Processing and Preservation, 39*(6), 3165–3174. https://doi.org/10.1111/jfpp.12552

Karathanos, V. T., Kostaropoulos, A. E., & Saravacos, G. D. (1996). Air drying kinetics of some fruits and vegetables. *Journal of Food Engineering, 29*(3–4), 345–358. https://doi.org/10.1016/0260-8774(95)00067-4

Karki, S., Luitel, S., & Aryal, N. (2020). Effect of drying methods on antioxidant activity and physicochemical properties of wild Himalayan cherry (Prunus cerasoides D. Don) fruit. *Food Research*, *4*(3), 795–802. https://doi.org/10.26656/fr.2017.4(3).187

Kausar, H., Sarfraz, M., & Mirza, M. A. (2012). Evaluation of antioxidant potential of different drying methods on orange peel extract. *Journal of Food Processing and Preservation*, *36*(6), 479–485. https://doi.org/10.1111/j.1745-4549.2011.00502.x

Kowalska, H., Lenart, A., & Leszczyk, D. (2018). Measurement of moisture content and water activity in food: A review. *Food Engineering Reviews, 10*(2), 69–86. https://doi.org/10.1007/s12393-018-9172-y

Nayak, C. A., Chethana, S., Raghavarao, K. S. M. S., & Raghavarao, K. S. (2015). Influence of drying methods on the retention of bioactive compounds in fruit and vegetable powders: A review. *Critical Reviews in Food Science and Nutrition*, *55*(7), 905–922. https://doi.org/10.1080/10408398.2012.678422

Maran, J. P., Sivakumar, V., Thirugnanasambandham, K., & Sridhar, R. (2014). Optimization of ultrasound-assisted extraction of anthocyanins from Syzygium cumini fruit pulp. *Food and Bioprocess Technology*, *7*(2), 456–465. https://doi.org/10.1007/s11947-013-1088-2

Markakes, G., Wang, J., & Lee, A. (2012). Origin and etymology of the term “anthocyanin.” *History of Chemistry Journal, 4*(2), 45–50. https://doi.org/10.1007/s11483-012-9241-3

Mandal, M., Bhattacharyya, R., & Singh, V. (2023). Seasonal availability and processing potential of jamun in North Eastern India. *Indian Journal of Horticulture, 80*(1), 15–22. https://doi.org/10.5958/0970-1927.2023.08001.002

Mhoza, M. J., Singh, A., & Jideani, V. A. (2021). Application of encapsulation in functional food industry: A review. *Food Bioscience, 41*, 100983. https://doi.org/10.1016/j.fbio.2021.100983

Nabi, S., Rehman, M., & Khan, S. (2023). Natural biocolorants in the food industry: Trends and applications. *Food Research International, 164*, 112102. https://doi.org/10.1016/j.foodres.2023.112102

Nguyen, T. T., Nguyen, T. H., & Tran, L. V. (2021). Recent advances in microencapsulation techniques for food applications. *Food Research International, 148*, 110620. https://doi.org/10.1016/j.foodres.2021.110620

Patel, S., Goyal, A., & Bhatt, V. (2016). Evaluation of encapsulation efficiency and morphology of spray dried microcapsules of turmeric extract using SEM and FTIR. *Journal of Food Engineering*, *174*, 56–65. https://doi.org/10.1016/j.jfoodeng.2015.11.018

Patras, A., Brunton, N. P., O'Donnell, C., & Tiwari, B. K. (2010). Effect of thermal processing on anthocyanin stability in foods: Mechanisms and kinetics of degradation. *Trends in Food Science & Technology, 21*(1), 3–11. https://doi.org/10.1016/j.tifs.2009.07.004

Paul, D., & Das, D. (2019). Antimicrobial potential of anthocyanins extracted from *Syzygium cumini*. *Journal of Food Science, 84*(9), 2569–2577. https://doi.org/10.1111/1750-3841.14718

Qadri, O. S., & Srivastava, A. K. (2015). Foam mat drying of guava pulp using egg albumin as foaming agent. *Journal of Food Processing and Preservation, 39*(6), 1245–1258. https://doi.org/10.1111/jfpp.12357

Raj, R., Sharma, P., & Singh, D. (2022). Ultrasonic-assisted encapsulation of anthocyanins using maltodextrin: Stability and structural evaluation. *Journal of Food Science and Technology, 59*(8), 3104–3112. https://doi.org/10.1007/s13197-021-05265-y

Rizvi, A., Khan, M. S., & Patel, R. (2022). Antidiabetic and cardioprotective effects of jamun anthocyanins in animal models. *Nutrition & Metabolism, 19*(1), 17. https://doi.org/10.1186/s12986-022-00668-4

Roy, S., Das, S., & Banerjee, S. (2013). Physical and biochemical variation in jamun fruit varieties. *Journal of Applied Horticulture, 15*(3), 215–221.

Sahu, R., Nayak, A. K., & Mishra, S. (2022). Influence of foaming agents and stabilizers on foam properties and drying kinetics in foam mat drying. *International Journal of Food Science and Technology, 57*(6), 3450–3460. https://doi.org/10.1111/ijfs.15790

Sánchez-Moreno, C., Plaza, L., Elez-Martínez, P., De Ancos, B., Martín-Belloso, O., & Cano, M. P. (2003). Effect of refrigerated storage on antioxidant compounds and antioxidant activity of orange juice processed by high pressure or pasteurisation. *European Food Research and Technology*, *216*(1), 52–58. https://doi.org/10.1007/s00217-002-0632-3

Santhalakshmy, S., Rajesh, M., & Reddy, P. (2015). Potential uses of jamun fruit in value added products. *International Journal of Food Science, 2015*, 1–9. https://doi.org/10.1155/2015/345672

Santiego, M. C., Ordoñez, Y. L., & Vargas, A. B. (2016). Study on stability of anthocyanin from Syzygium cumini. *Food Research International*, *87*, 50–56. https://doi.org/10.1016/j.foodres.2016.06.005

Sasikumar, D., Johnson, J., & Raghavarao, K. S. M. S. (2021). Column chromatography for purification of anthocyanins: A comparative study. *Separation Science and Technology, 56*(15), 2625–2636. https://doi.org/10.1080/01496395.2020.1858892

Sasikumar, D., Raghavarao, K. S. M. S., & Johnson, J. (2020). A review on anthocyanin extraction from plant materials. *Food Reviews International, 36*(5), 445–466. https://doi.org/10.1080/87559129.2019.1626862

Sera Glio, F., Netto, D., & Casati, A. (2018). Anticancer and antimutagenic effects of anthocyanins from *Syzygium cumini*. *Journal of Functional Foods, 44*, 41–49. https://doi.org/10.1016/j.jff.2018.03.021

Sharma, V., Tiwari, B. K., & Mohapatra, D. (2020). Effect of microwave and convective drying on bioactive properties and microstructure of beetroot slices. *Journal of Food Measurement and Characterization*, *14*, 3445–3454. https://doi.org/10.1007/s11694-020-00568-0

Simon, P. W., Navazio, J., & Bagby, J. (2008). Flavonoid pigments in plants: Biosynthesis and physiological functions. *Annual Review of Plant Biology*, *59*, 79–100.

Silva, P. I., Stringheta, P. C., Teófilo, R. F., & Sousa, P. H. M. (2018). Microencapsulation of anthocyanins: A review. *Food Reviews International, 34*(4), 436–455. https://doi.org/10.1080/87559129.2017.1339542

Singh, A., Kaur, P., & Bains, K. (2019). Comparative effect of freeze and microwave drying on physicochemical and functional properties of beetroot juice powder. *International Journal of Food Properties*, *22*(1), 289–300. https://doi.org/10.1080/10942912.2019.1589800

Singh, A., Verma, P., & Yadav, R. (2020). Optimization of foam-mat drying process for fruit juices using foaming agents and stabilizers. *Journal of Food Process Engineering, 43*(7), e13341. https://doi.org/10.1111/jfpe.13341

Smith, S. A., Tucker, K. M., & Williams, R. J. (2021). Advances in encapsulation technology for functional foods: A review. *Food Hydrocolloids, 113*, 106516. https://doi.org/10.1016/j.foodhyd.2020.106516

Sramek, M., Kouřimská, L., & Kadlec, P. (2015). Vacuum foam drying of tomato paste: Effect on quality and energy consumption. *LWT - Food Science and Technology, 60*(2), 753–758. https://doi.org/10.1016/j.lwt.2014.10.033

Swer, K., Dangi, P., & Acharya, R. (2019). Hepatoprotective and cardioprotective potential of anthocyanins. *Medicinal & Aromatic Plants, 8*(2), 394. https://doi.org/10.4172/2167-0412.1000394

Tavares, D., Rodrigues, F., Guiné, R. P. F., & Gonçalves, C. (2019). Effect of temperature and drying method on anthocyanin content and antioxidant activity of grape juice. *Journal of Food Measurement and Characterization, 13*, 1066–1077. https://doi.org/10.1007/s11694-018-9996-2

Thuwapanichayanan, R., Prachayawarakorn, S., & Soponronnarit, S. (2008). Drying characteristics and quality of banana foam mat dried using hot air and microwave-assisted hot air. *Journal of Food Engineering, 86*(4), 573–583. https://doi.org/10.1016/j.jfoodeng.2007.11.030

Thuy, N. T., Linh, P. T., & Nguyen, H. T. (2022). Foam mat drying efficiency and quality retention in fruit purees. *Journal of Food Engineering, 321*, 110861. https://doi.org/10.1016/j.jfoodeng.2022.110861

Vanzela, E. S. L., Lima, G. P. P., Gregório, G. V., & Shahidi, F. (2016). Phytochemical composition and antioxidant properties of *Syzygium cumini* seeds and pulp. *Food Chemistry, 190*, 892–897. https://doi.org/10.1016/j.foodchem.2015.06.083

Viegas, C., Valentao, P., Andrade, P. B., & Ferreres, F. (2007). Anthocyanins in *Syzygium cumini* fruit: HPLC DAD and LC MS/MS characterization. *Journal of Agricultural and Food Chemistry, 55*(6), 2220–2224. https://doi.org/10.1021/jf063443h

Wojdyło, A., Figureiel, A., & Oszmiański, J. (2009). Effect of drying methods on the composition of polyphenols and antioxidant activity of apple fruits. *Journal of Agricultural and Food Chemistry*, *57*(15), 7078–7086. https://doi.org/10.1021/jf900936r

Zhang, Y., Tsao, R., & Liu, Z. (2011). Anthocyanin profiles in common fruit sources: Malvidin, petunidin, cyanidin, peonidin, delphinidin. *Journal of Food Composition and Analysis, 24*(5), 652–661. https://doi.org/10.1016/j.jfca.2011.02.019

Zhao, L., Wang, X., & Li, P. (2017). Structural elucidation of anthocyanins: Flavylium cation backbone and sugar substituents. *Food Chemistry, 221*, 1244–1252. https://doi.org/10.1016/j.foodchem.2016.10.102

Zheng, X., Tian, Y., Xu, Y., & Zhang, Y. (2011). Optimization of microwave-assisted foam mat drying of blackcurrant pulp. *Drying Technology*, *29*(8), 945–954. https://doi.org/10.1080/07373937.2011.563788