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Investigation of the Effects of Energy-Efficient Drying Techniques and Extraction Methods on the Bioactive and Functional Activity of Banana Inflorescence

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Abstract: Plant-derived foods with therapeutic potential have strong connection with both the pharmaceutical and nutraceutical industries. The effectiveness of these therapeutic properties is heavily influenced by the thermal treatment during drying and extraction methods. Traditional convective drying is a very energy incentive and lengthy process. Although some advanced and hybrid drying methods have been developed, these have not been applied in drying of banana inflorescence. In this study, we investigated the effects of freeze-drying (FD) and intermittent microwave convective drying (IMCD), as well as traditional convective oven drying (CD), on the polyphenol profile of banana inflorescence when extracted using the energy-efficient Accelerated Solvent Extraction method (ASE). Our findings revealed that the freeze-dried banana inflorescence powder exhibited the highest extraction of bioactive compounds when using 75% methanol at 100 °C as a solvent. It recovered 2906.3 ± 20.83 mg/100 g of the phenolic compounds and 63.12 ± 0.25% antioxidant activity under the optimal extraction conditions. While IMCD was found to be the second-best drying method in terms of preserving bioactive compounds, its operational time and cost were significantly lower compared to freeze-drying. Furthermore, our study confirmed the presence of medicinal compounds such as gallic acid, protocatechuic acid, caffeic acid, coumaric acid, catechin, ferulic acid, kaempferol, and quercetin in banana inflorescence. The development of innovative functional foods and pharmaceutical ingredients through green extraction methods and optimal drying conditions holds significant potential to save energy in the process, enhance human health, and promote environmental sustainability and circular economy processes. These efforts align with supporting Sustainable Development Goals (SDGs) 3 and 12.

Keywords: freeze-drying; convective oven drying; intermittent microwave convective drying; phenolics; Accelerated Solvent Extraction; antioxidants; banana inflorescence

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1. Introduction

Functional foods and pharmaceutical products derived from natural plants have revolutionized human health, contributing to increased life expectancy, reduced reliance on synthetic antibiotics [1], and alleviation of various physical syndromes [2]. Medicinal plants, long recognized for their sustainable, protective, and efficient qualities, possess a natural antioxidant capacity, owing to their richness in phenolic compounds such as phenolic acids, flavonoids, anthocyanins, triterpenes, and plant steroids [3]. These phenolic compounds exhibit significant antioxidant potential, rendering them therapeutic agents

in combating numerous non-communicable diseases, including cancer, diabetes, obesity, cardiovascular diseases, and hypercholesterolemia [4].

Banana (*Musa* spp.) stands as a highly sought-after fruit crop, experiencing an annual production growth rate of 4.5% globally due to its nutritional and health-enhancing components. Despite the widespread consumption of its fruit, the banana plant yields substantial by-products [5], including the pseudostem, roots, leaves, and flowers, often left unutilized or discarded as waste [6]. Among these by-products, the banana flower, also known as the "inflorescence", remains underutilized within food and agriculture worldwide [7].

The banana inflorescence is an edible by-product, which was used as a medicinal herb and medicinal food in the past [6,8–11]. This demonstrated its potential to develop a food ingredient, pharmaceutical product, and nutraceutical product using Banana inflorescence as a raw material [12]. However, banana inflorescence is highly perishable and has a poor shelf life, which can result in spoilage and poor-quality produce. Therefore, it is important to dry the banana inflorescence to increase its shelf life and preserve its quality [13] for future food product development [14].

The previous literature demonstrated the potential of banana inflorescence flour as a food ingredient [15], as it demonstrated highly accepted food properties, including physical characteristics and chemical composition [15,16]. However, the properties of a food product are highly influenced by the method of drying [17,18]. In the literature, no attention has been given to the investigation of the effect of drying on the physical and chemical properties of banana inflorescence powder so far.

Moreover, research on banana inflorescence has revealed the presence of bioactive compounds [9] exhibiting various therapeutic potentials in humans [10], such as antioxidant [11], antibacterial, anti-aging, anti-inflammatory, anticancer [19], antimicrobial, and cardiovascular protective activities [20]. Nevertheless, the determination of bioactive compounds is heavily influenced by factors including thermal treatment, selection of the drying parameters, sample preparation process, extraction techniques, solvent types and concentrations, extraction temperatures, duration, and genetic variability among plants [21].

According to the literature on other plant food materials, the drying and extraction methods [19] are particularly critical steps affecting the retention of bioactive compounds and physical characteristics in plant matrices [22–24]. While some studies suggest that elevated temperatures can enhance the recovery of bioactive compounds by releasing bound compounds, published results remain inconsistent and sample-specific. Moreover, there is a gap in this research field, as less attention has been given to investigate the impact of different drying methods and extraction solvents and their concentrations on the bioactivity compounds of banana inflorescence.

Additionally, there has been no exploration into the optimal extraction parameters using an energy-efficient and sustainable method such as pressurized liquid extraction. Accelerated Solvent Extraction (ASE) plays a pivotal role in this context by significantly enhancing the efficiency and sustainability of the extraction process. ASE uses high pressure and temperature conditions to expedite the extraction of valuable compounds from natural materials, resulting in reduced energy consumption and processing time. This not only saves energy but also aligns with the principles of the circular economy by enabling the recovery of bioactive compounds from plant by-products, such as banana inflorescence. Due to optimized solvent usage and enhanced recovery processes, ASE is considered a green extraction method. ASE supports the creation of closed-loop systems where materials are continually recycled and reused, thereby reducing the environmental footprint of industrial activities.

Furthermore, while recent studies have characterized phenolic compounds in banana inflorescence, there is a notable absence of research on phenolic compound characterization from Australian-grown banana cultivars. Given potential variations induced by genetic diversity and environmental factors in Australian-grown bananas, it is imperative to characterize the physical and morphological structure of phenolic compounds in the Cavendish cultivar, the main commercial cultivar that represents 94% of Australian bananas [25].

However, to date, these Cavendish inflorescence are not considered for any value addition product development and remain a waste-inducing environmental problems.

Developing a food ingredient or pharmaceutical product from banana inflorescence by proper drying and extraction is the best alternative to utilizing waste banana inflorescence. High-quality natural raw materials for food fortification, which have bioactive properties and excellent physical properties, are highly favourable by the food and pharmaceutical industries. However, there is a gap in this research field, as less attention has been given to investigating the physical and chemical characteristics of banana inflorescence at different drying methods.

To address these gaps, this study aims to (a) investigate the physical properties and retention capacity of bioactive compounds in convective oven drying, freeze-drying, and intermittent microwave convective drying of banana inflorescence; (b) determine the optimal extraction solvent type and concentration using accelerate solvent extraction; and (c) determine the bioactive compounds in Cavendish banana inflorescence. This study will conclude the energy saving drying method and extraction parameters for the retention of bioactive compounds from banana inflorescence. Overall, this study seeks to explore alternative methods for utilizing plant food by-products, investigating the phytochemical composition of Australian banana inflorescence in sustainably promoting health, supporting the global sustainability goals.

2. Materials and Methods

2.1. Raw Materials

In this study, banana inflorescences were collected from multiple farms located in Wamuran, Queensland, Australia, at the debelling stage as shown in Figure 1. This process involved the cutting of inflorescences from the bunch, post the opening of the last fruits. To mitigate the effects of heat stress and photodegradation of bioactive compounds, the debelling process was carried out in the evening, and the inflorescences were covered with black polythene during transportation to the laboratory. Upon arrival at the laboratory, the inflorescences were subjected to a cleaning process to eliminate surface impurities and contaminants. The outermost 5–6 discoloured bracts, which were significantly exposed to solar radiation, were subsequently removed to further clean the inflorescence.



Figure 1. Banana inflorescence of the Cavendish cultivar.

This study aimed to investigate the whole banana inflorescence, including both bracts and male flowers, to maximize the usage of banana by-products. Prior research was solely focused on separated banana bracts, thereby disregarding the male inflorescence, which is

also a promising source of bioactive compounds. Consequently, this study was conducted on the entire inflorescence without dividing the two.

The cleaned inflorescences were sectioned into three equal parts, and the middle section was chosen for further processing. The middle section represents 50% of bracts and 50% of male inflorescence. The selected middle section was sliced into small pieces of approximately 0.5 cm × 0.5 cm using a sharp knife. These small pieces were subsequently subjected to three different drying methods, namely convective oven drying, freeze-drying, and intermittent microwave convective drying, before the extraction process using the pressurised liquid extraction technique.

2.2. Chemicals and Regents

All chemicals used in this research were of analytical grade. All chemicals were purchased from Sigma Aldrich, Castle hill, NSW, Australia. Phenolic standards were used for the quantification are gallic acid, syringic acid, protocatechuic acid, caffeic acid, coumaric acid, catechin, ferulic acid, sinapic acid, kaempferol, and quercetin. Calibration curves were prepared by diluting standards in LC-MS-grade methanol. Folin–Ciocalteu reagent, 2,2-diphenyl-1-picrylhydrazyl radical (DPPH), and anhydrous sodium carbonate were used for the phenol and antioxidant assays. Methanol, ethanol, distilled water, N_2 gas, HNO_3, LCMS-grade water (LiChrosolv® water), acetic acid, and LCMS-grade methanol were also used for extraction and LC-MS analysis.

2.3. Drying Experiments

Drying is a widely employed food preservation technique in the agricultural industry, which involves the removal of moisture from a product to extend its shelf life [26]. The drying process significantly affects the physical characteristics of the product and the retention of phytochemicals [24], including bioactive compounds and their functionalities [23]. To achieve efficient drying, advanced methods such as convective oven drying and freeze-drying have become prevalent on a commercial scale, while fourth-generation drying methods that combine convective methods such as microwave drying [27] have gained popularity for enhancing product quality in recent years.

Previous cross-sectional studies have highlighted a possible relationship between drying parameters and the bioactive composition [13,26,28–31]. However, the literature on banana inflorescence has not adequately addressed the impact of various drying methods on bioactive compounds. Therefore, this study aims to investigate the influence of drying on the phenolic compounds and antioxidant activity through a comparative analysis of three drying methods: convective oven drying, freeze-drying, and intermittent microwave convective oven drying.

2.3.1. Convective Oven Drying (CD)

Oven drying was carried out as per the method explained for the Cavendish cultivar in the previous literature, with some modifications [32]. Briefly, banana inflorescence was cut into small pieces and spread on metal trays lined with aluminium foil. The trays were kept in an oven (Labtek ODWF24, USA) at 55 °C for 24 h. After collecting the samples, they were weighed, labelled, and stored in a dark and dry place until milling.

2.3.2. Freeze-Drying (FD)

The process of freeze-drying begins with freezing the samples. To achieve this, the samples were placed in a freezer set at −80 °C for a period of 4–6 h before operating the freeze dryer condenser and vacuum pump. Once the samples are frozen, they are then put inside the SP scientific Benchtop Pro freeze dryer, and the equipment is set until the temperature reaches its minimum (usually −80 °C) and the pressure reaches its lowest point (−200 µB). At this stage, the water contained in the sample starts to undergo sublimation. The cold condenser creates a surface for water vapor to adhere to and solidify. Although the sublimation process is slow, it removes the moisture from the 500 g of banana inflorescence

over a period of 5–6 days. Once the banana inflorescence is freeze-dried, it is stored in a dark and dry place until it is milled.

2.3.3. Intermittent Microwave Convective Drying (IMCD)

The intermittent microwave convective drying facility, as shown in Figure 2, was used to remove moisture from banana inflorescence within a short duration. Preliminary experiments were conducted to determine the on and off times and the duration of the drying process.

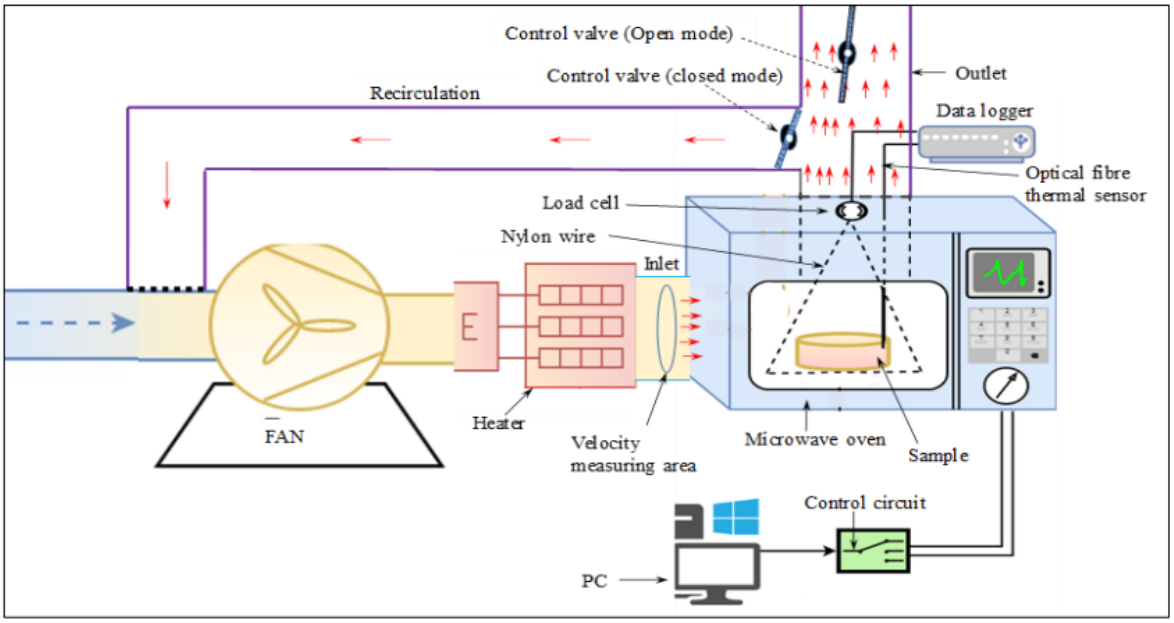


Figure 2. Schematic diagram of the intermittent microwave convective drying system.

The experiment was conducted for banana inflorescence at the temperature of 55 °C at the microwave power level of 80 W and the power ratio of 10 s on, 20 s off for 45 min for 1 kg of sample. The microwave-dried samples were stored in dark wrapping using aluminium foil until further experiments.

Milling

Milling is the process of cutting and grinding heterogeneous raw materials into fine particles, which will be carried out electronically. Within 7 days of the completion of the drying process, the dried samples were subjected to milling by using a Retsch miller (Germany). During the milling process, the dried banana inflorescence passes through the hopper into a grinding chamber, which has the rotor blades and the cutting bars to seize and grind the sample. After sieving, the fine ground powder will be collected in the receptacle. During the milling process, 2 mm sieve was used. The Retsch miller took 1–2 min to mill the freeze-dried samples, while 3–4 min for the convective oven-dried and microwave-dried samples. The milling time for freeze-drying is low, and the convective oven-drying and microwave oven-dried samples are slightly higher. This can be due to a combination of factors. The texture and porosity vary with different drying methods. Freeze-drying produces a highly porous structure by sublimating water directly from ice to vapor, making it easier to break down during milling. In contrast, oven-drying (including convective and microwave drying) often results in a denser, less porous structure, making the samples harder and requiring more time to mill. Another reason is the thermal effect. Oven drying involves exposure to higher temperatures, which can lead to changes in the material's texture and hardness. Heat can cause some materials to become tougher or more compact, making them more resistant to milling. Another cause is sample integrity. Freeze-dried samples often maintain their structural integrity better than oven-dried samples.

The gentle nature of freeze-drying prevents the collapse of cellular structures, resulting in samples easier to break mechanically. The fine grounded material, which is in powder form, was transferred to a sealer bag. The sealer bag was labelled and stored in a dark dry place in wrapped aluminium foil.

2.4. Experimental Design

The current study aimed to investigate the effect of different drying methods on the physical properties of dried banana inflorescence samples and bioactive properties of their subsequent extraction using the Accelerated Solvent Extraction method. Three drying methods, namely oven drying, freeze-drying, and intermittent convective oven drying, were employed to dry the banana inflorescence samples. The dried samples were then milled for extraction purposes. The milled banana powder was analysed for its physical properties and functional properties to determine the effect of the different drying methods. Subsequently, the milled samples were subjected to extraction in a closed environment using the Accelerated Solvent Extraction method with different solvents: water, methanol, and ethanol at three different temperatures (60 °C, 80 °C, and 100 °C). These solvents were selected due to their common application in both on the industrial scale and scientific experimental scale. Water was chosen as a low-cost solvent that could be a cost-effective option for the industrial scale. Ethanol and methanol are widely used in the food industry for the extraction of food ingredients such as tea [33], apples [34], and red raspberries [35]. Methanol is recognized as an acceptable solvent for food extractions. Since methanol is fully evaporated before bioactive compounds are added to food products, there is no residual methanol in the final product, eliminating any potential risk. This is supported by the Notification of the Ministry of Public Health (No. 151) B.E. 2536 (1993), which addresses prohibited substances in food. Additionally, methanol is considered a suitable extraction solvent according to the reports of the Scientific Committee for Food by the Commission of the European Communities [36]. The extracts with the highest concentration of phenolic compounds were selected for further characterisation of phenolics and bioactive compounds using LC-MS for each drying method. This approach enabled a comprehensive analysis of the different components present in the extract, providing a deeper understanding of the characteristics of the Cavendish banana inflorescence samples. The process is illustrated in Figure 3.

2.5. Physicochemical Properties of Banana Inflorescence Powder

2.5.1. Colour Parameters

The colour of milled banana inflorescence powder from different drying methods was measured by the instrumental measurement in triplicate using a colour reader (Konica Minolta CR-10 PLUS, Japan) and converted to a HEX value using nix sensor 2.0 software.

The chroma meter was precisely calibrated using a standard white reference tile prior to sample analysis. According to the colourimeter, the L axis stands for lightness (if L* = 0, black and L* = 100, white). The redness to greenness was presented on the a-axis as (if a*-value = +a*, redder and a*-value = −a*, greener). b*-value explained a change in colour from yellow to blue (if b*-value = +b*, yellower and b*-value = −b*, bluer).

2.5.2. Microstructure

The surface characteristics and microstructure of dried banana inflorescence were examined by Scanning Electron Microscopy (SEM) to determine the effect of different drying methods on the microstructure. The dried and milled samples were placed on pt-coated stubs and fixed before the analysis. The coated samples were cleaned using the plasma cleaner for 2 min to remove any impurities before placing them in the SEM-Phenom XL G2 (Thermo fisher Scientific). The observation was conducted under the phenom SEM and accelerated at 5 kV under the pressure of 0.1 Pa. The micro images were taken at 1000× magnification.

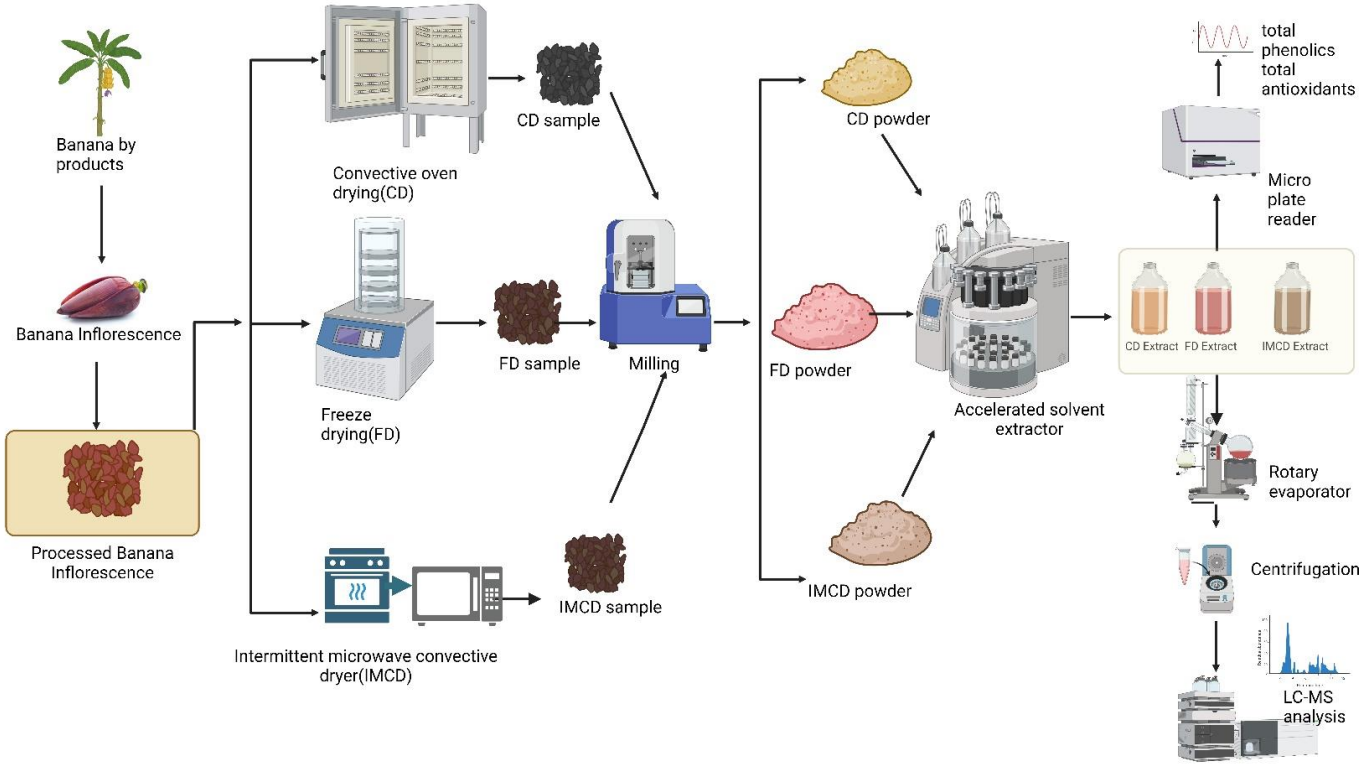


Figure 3. Experimental design.

2.5.3. Moisture Content

In the conducted study, the moisture levels were assessed using the procedures established by AOAC. Initially, the mass of the empty crucible was noted. Subsequently, 5 g of the sample was placed into the crucible, and the combined mass was documented. The sample, within the crucible, was then subjected to a temperature of 105 °C in an oven for a duration of 6 h. Post-heating, desiccators were employed to bring the sample's temperature to ambient. The mass of the sample-laden Petri dish was repeatedly measured until a consistent weight was observed over three measurements. To calculate the moisture content percentages, the following equation was applied.

$$\text{Total moisture content } \% = \frac{\text{Fresh weight(g)} - \text{Dry weight(g)}}{\text{Fresh weight(g)}} \times 100$$

2.5.4. Ash Content

The quantification of the sample's ash content was conducted in accordance with AOAC guidelines. A 2 g specimen was placed into a crucible, which was then transferred to a muffle furnace and heated at 600 °C for 6 h. After the heating period, the crucible was allowed to cool in a desiccator before its weight was measured. This procedure was repeated until the ash attained a whitish or greyish hue and the weight measurements stabilized across three successive readings. The ash amount was then calculated using the following formula:

$$\text{Ash content } \% = \frac{\text{Weight of residue(g)}}{\text{Weight of fresh sample(g)}} \times 100$$

2.5.5. pH

The pH value of the samples was measured by using a pH meter as per the method explained for the determination of pH for green banana flour [37]. This experiment involved mixing 1 g of banana inflorescence powder with 100 mL of distilled water. The mixture

was then boiled for an hour and filtered. After filtering, 20 mL of the resulting sample was used for the pH test.

2.5.6. Total Soluble Solids Content

Total soluble solids (TSS) were measured by using the refractometer (RFM 342 Bellingham and Stanley LTD, London, UK) and recorded the brix value for aqueous solutions of the different drying methods.

2.5.7. Drying Yield

The percentage yield of the drying process is calculated as the percentage of the final dried product compared to the amount of fresh raw material used.

2.5.8. Energy Dispersive X-ray Spectroscopy (EDS)—Mineral Analysis

The elemental composition of the banana inflorescence milled powder was examined through a scanning microscopy-Phenom XL G2 equipped with an energy-dispersive X-ray system. The process involved mounting the milled powder on aluminium stubs, which were then coated with a layer of carbon paint. These stubs were stored in a fume cabinet overnight to dry. Before the coating process, any residual substances were cleared using nitrogen gas. Then, the samples were carbon-coated with a 10 nm thickness carbon layer and placed in the SEM-EDX chamber. The EDS spectrum was captured under conditions of 15 kV, full backscatter, a vacuum pressure of 10 Pa, and at a magnification level of 1000×.

2.6. Functional Properties

2.6.1. Swelling Capacity

The swelling capacity of banana inflorescence powder was determined by the method explained by Padhi and Dwivedi [37] with some alterations. Briefly, the banana flour sample was aliquoted to a volume of 10 mL within a 100 mL graduated measuring cylinder. Distilled water was subsequently added to adjust the volume to 50 mL. The cylinder was then securely covered and inverted to ensure thorough mixing. Following a 2-min interval, the cylinder was inverted once more and allowed to settle for 30 min under stable conditions. Subsequently, the volume of the sample was measured and computed using the formula given below:

$$\text{Swelling capacity (weight of paste (g)/dry sample (g))} = \frac{\text{Swelling volume (mL)}}{\text{Weight of mucilage (g)}}$$

2.6.2. Bulk Density

The determination of the bulk density was conducted employing a modified protocol based on the methodology outlined by Alam et al. [38]. Initially, a 10 mL graduated glass cylinder was filled with 1 g of the sample material for measurement. Subsequently, the cylinder was subjected to gentle shaking and tapping five times to ensure uniform packing and to flatten the surface of the flour within. The bulk density of the sample was then calculated by dividing the mass of the sample by the volume of the measuring cylinder.

2.6.3. Tapped Density

The tapped density of the samples was assessed with a slight modification to the procedure detailed by Alam et al. [38]. Briefly, 1 g of sample powder was introduced into a 10 mL graduated glass measuring cylinder. Subsequently, the cylinder was subjected to gentle tapping using a glass rod while positioned on a soft and stable surface. Tapping was continued until no further change in volume was observed; at which point, the results were recorded. The tapped density was then computed by dividing the mass of the sample by the tapped volume achieved.

2.6.4. Water-Holding Capacity

For the determination of the water-holding capacity (WHC), precisely weighed samples (0.5 g) were transferred into centrifuge tubes, accompanied by the addition of 10 mL of distilled water. After stirring for 1 min using a vortex stirrer, the samples were left to equilibrate at room temperature for 30 min, followed by centrifugation at 3000 rpm for 30 min. Upon completion of centrifugation, the supernatant was carefully decanted, and the centrifuge tube was inverted for 1 min to facilitate complete drainage. The difference in weight of the sample before and after mixing with water was utilized for the calculation of the WHC, as per the formula provided below:

$$\text{Water holding capacity} = \frac{\text{Weight of wet sample(g)} - \text{Weight of dry sample(g)}}{\text{Weight of dry sample(g)}}$$

2.6.5. Oil-Holding Capacity

For the determination of the OHC, precisely weighed samples (0.5 g) were transferred to centrifuge tubes, followed by the addition of 5 mL of virgin coconut oil. Subsequently, the mixture was vigorously stirred for 1 min using a vortex stirrer, allowed to stand at room temperature for 30 min, and then subjected to centrifugation at 3000 rpm for 30 min. Upon completion of centrifugation, the supernatant was carefully decanted, and the centrifuge tube was inverted for 1 min to ensure thorough drainage.

$$\text{Oil holding capacity} = \frac{\text{Weight of oil abosorbed sample(g)} - \text{Weight of dry sample(g)}}{\text{Weight of dry sample(g)}}$$

2.6.6. CHN Analysis

CHN analysis was performed using the Thermo Flash SMART CHNSO analyser, USA. Homogenous fine granules of banana inflorescence were collected after milling. Briefly, the milled inflorescence was placed into a delicate tin container using a spatula until sufficiently filled, then delicately pressed the sample to make a sealed tin cover. For CHN, the sample was combusted at 950 °C with oxygen. Samples were measured in triplicate with CRM (Certified Reference Material) run approximately every 20 samples.

2.6.7. FTIR

To determine the functional groups of banana inflorescence at different drying methods, FTIR analysis was conducted as per the method stated for banana inflorescence [39]. The FTIR spectrum for CD, FD, and IMCD dried banana inflorescence in the range of 4000–375 cm^{-1} at a velocity of 0.6329 was measured by a Fourier transform infrared spectrometer Diamond ATR-IR (Nicolet iS50 Thermo Scientific, USA). The experiment was carried out at room temperature, and the spectrum was examined at the resolution of 4 cm^{-1} for 64 scans.

2.7. Bioactive Properties of Extracted Banana Inflorescence

To determine the bioactive characteristics of banana inflorescence at different drying methods, the samples need to be extracted. For this purpose, the extraction procedure is carried out using the ASE method.

As there is no information on the optimum conditions for banana inflorescence bioactive compound extractions using the ASE method, this study conducted the preliminary extractions from three different solvents (water, ethanol, and methanol) at three different drying methods (CD, FD, and IMCD) and three different concentrations (50%, 75%, and 100%) at three extraction temperatures (60 °C, 80 °C, and 100 °C) to determine the optimum extraction parameters. Water extracted is considered as the control.

2.8. Extraction

2.8.1. Extraction Method

Most studies on the extraction of nutrient and non-nutrient compounds from banana inflorescence have been carried out with traditional extraction methods such as conventional stirring and ultrasound-assisted extraction [12,16,32,40]. However, many other biological studies for bioactive compound extractions have used ASE, and it is a time-saving method with highly efficient extractions [41]. As the ASE method has not been previously studied for banana inflorescence, in this study, Dionex ASE 350, USA equipment was used for the first time. In this study, grounded banana inflorescence was extracted using the Dionex Accelerates Solvent Extractor 350 equipment as per the method explained by Azian et al. [41], with some modifications.

As there is no literature on banana inflorescence extraction using ASE, the protocol was developed with preliminary experiments. The programmed method involves applying a 1500 psi pressure with 60 s of purging time in one cycle and using 60% of the flush volume. To complete the extraction process, the extraction time was set for 3 cycles of 5 min each and an additional 5 min for preheating. Dionium stainless steel 36 mL extraction cells, bottom-lined with ASE filter glass fibre 34 (Thermo Scientific grade used). Then, 1 g of dried banana inflorescence mixed with 5.0 g of diatomaceous earth (DE) (Thermo Fisher Scientific, P/N 062819) was used to fill the volume of dionium stainless steel Dionex extraction cells up to 75%. After the extraction process, the collected extracts were filtered using sterile 0.22 µm PTFE syringe filters, labelled, and stored in a refrigerator at −4 °C for 3–4 days before analysis.

2.8.2. Optimised Extraction Process

Our preliminary studies were conducted on extracting banana inflorescence at 60 °C, 80 °C, and 100 °C to determine the temperature results in higher concentrations of phenolic compounds and antioxidant activity. The results revealed that 100 °C was the optimum temperature for extraction. Based on this, the experiment was designed as per the details given below.

Drying methods	CD, FD, IMCD
Extraction solvents	Methanol, Ethanol, Water
Extraction solvent concentrations	50%, 75%, 100%
Control	Fresh Banana inflorescence without drying

2.9. Total Phenolic Content (Folin–Ciocalteu Method)

The total phenolics content in the extracted banana inflorescence was measured by the Folin–Ciocalteu method [14], with some modifications. Folin–Ciocalteu regent (2N, # f9252, Merck) was used for this experiment. In brief, 790 µL of distilled water was added to 10 µL of banana inflorescence extract prepared in 1.5 mL Eppendorf tubes. Subsequently, 100 µL of Folin–Ciocalteu solution was introduced, and the tubes were allowed to stand at room temperature for 5–8 min. Following this, 150 µL of 20% sodium carbonate solution was added to each tube and thoroughly mixed. The samples were then placed in a dark environment at room temperature for 2 h. Following incubation, 200 µL aliquots from each tube were transferred onto a 96-well microtitration plate. The absorbance of these samples was measured at 765 nm using a UV spectrophotometer equipped with a Synergy Biotek HTX multimode microplate reader (serial number: 1608151C) and Gen 5.3 software version 3.00.19. The absorbance readings were compared against a gallic acid standard curve, and the results were expressed as the gallic acid equivalent (mg GAE/g sample).

2.10. Total Scavenging Activity (DPPH Analysis)

Antioxidant activity refers to the ability of a substance to prevent or slow down the oxidation of other molecules. Oxidation is a chemical reaction that can produce free radicals,

leading to chain reactions that may damage cells. Antioxidants are molecules that can donate an electron to a free radical without becoming destabilised, effectively neutralising the free radical and preventing cellular damage. The total antioxidant activity of banana inflorescence extract was measured by DPPH free radical scavenging activity according to the method explained by Yu et al. [3], with some modifications.

Briefly, a 0.1 mM solution of 2,2-diphenyl-1-picryhydrazyl (DPPH) was made by dissolving 39.43 mg of DPPH in 1000 mL of ethanol. This solution was then diluted tenfold. For the DPPH assay, 300 µL of the DPPH solution was mixed with 300 µL of the sample, standard, or blank solution. The mixtures were then incubated at room temperature for 30 min in the dark. Subsequently, the absorbance of each mixture was measured at 517 nm using a UV spectrophotometer equipped with a Synergy Biotek HTX multimode microplate reader and Gen 5.3 software. To generate the calibration curve, quercetin was used at various concentrations ranging from 1 µg/mL to 10 mg/mL. The results of the DPPH assay were expressed as µmol of ascorbic acid equivalents. The DPPH scavenging activity was calculated using the following equation:

$$\% \text{ DPPH radical scavengingctivity} = \left[\frac{(A_0 - A_1)}{A_0}\right] * 100$$

where A_0 is the absorbance of control without a sample (Blank), and A_1 is the absorbance of the sample.

2.11. Characterisation of Polyphenols Using LC-MS

The Folin–Ciocalteu test concluded that banana inflorescence is a source of polyphenols. Furthermore, it shows that methanol-extracted banana inflorescence at elevated temperatures resulted in a greater polyphenol concentration. The most abundant extracts were chosen for the quantitative determination of targeted phenolic compounds. These extracts were further studied for the characterisation of polyphenols as per the method explained by [42,43], with modifications. The phenolic compounds of banana inflorescence were characterised using UHPLC equipped with a photodiode array (PDA). The phenolic compounds isolation was conducted using the column Kinetex EVO C18, 100 A100 × 2.1 mm × 2.6 µm particle size, Phenomenex, Australia.

The mobile phase A (eluent A) was LCMS-grade water (LiChrosolv® water)/acetic acid (99:1, *v*/*v*), and the mobile phase B was methanol (eluent B). The gradient was programmed at 1–5% B (7 min), 5–20% B (26.6 min), 20–37.5% B (20 min), 37.5–80.5% B (5 min), and 80–100% B (0.5 min). The banana extract of 20 µL from each sample was injected to the autosampler at a flow rate of 0.5 mL/min. The peaks were detected in negative ion mode. The instrument control and data acquisition were conducted by Chromeleon software, and the analysis was done by Thermo—Xcalibur 3.0.63.3 software (Thermo Fisher Scientific, Inc.).

2.12. Quantification of Phenolic Compounds Using HPLC-PDA

The phenolic compounds were investigated at three different wavelengths: 280, 320, and 370 nm. The targeted polyphenols were quantified based on the calibration standard curve, and the results were expressed as mg/g of the sample. Fifteen standards were employed in preparing external calibration curves for the quantification.

The instrument control, data acquisition, and analysis were conducted by Thermo Xcalibur 3.0.63.3 software (Thermo Fisher Scientific, Inc.)

2.13. Statistical Analysis

The statistical differences were determined using Minitab 21.1 software (Minitab, LLC, USA). Analysis of variance (ANOVA) test and Turkey's test were carried out to measure the statistical difference. If $p < 0.05$, the results were considered significantly different. Data were reported as the average ± standard deviation.

3. Results and Discussions

3.1. Physical Properties of Dried Banana Inflorescence

3.1.1. Colour

Colour plays a crucial role in determining product quality and consumer preferences, especially in pharmaceutical products and food ingredients. In the case of banana inflorescences, the colour properties were analysed using a colorimeter. Table 1 compares the colour properties of banana inflorescences using different drying methods. The results revealed a significant difference ($p < 0.05$) among the drying methods and the a, b, L, C, and h values. Notably, it was found that the colour values for freeze-dried (FD) inflorescences closely resembled those of fresh samples, indicating that FD effectively preserved the colour during the drying process. Specifically, the redness values for fresh inflorescences were recorded at 16.33, while those for FD, CD, and IMCD were 7.07 ± 0.12, 4.77 ± 0.06, and 2.83 ± 0.06, respectively. These findings suggest that FD resulted in the strongest red colouration, aligning with the existing literature on banana flour [38]. Regarding lightness values, fresh inflorescences had a value of 33.77 ± 0.15, whereas FD, CD, and IMCD recorded 28.43 ± 0.06, 15.43 ± 0.15, and 11.8 ± 0.10, respectively. This indicates that IMCD resulted in the darkest colours, possibly due to enzymatic and non-enzymatic browning caused by exposure to heat. Furthermore, a comparison of lightness and redness values showed consistent results for Jujube [18], indicating the significance of these findings across different products. Additionally, analysing chroma values ranked the drying methods from highest to lowest as FD > CD > IMCD, with freeze-drying resulting in higher chroma values due to the preservation of natural colour resulting from minimised heat application.

Table 1. Colour characteristics of banana inflorescence at different drying methods.

Colour	Fresh	CD	FD	IMCD
Physic				
a* Redness	16.30 ± 0.10 ^{a}	4.77 ± 0.06 ^{c}	7.07 ± 0.12 ^{b}	2.83 ± 0.06 ^{d}
b* Yellowness	13.23 ± 0.12 ^{b}	9.60 ± 0.10 ^{c}	15.30 ± 0.10 ^{a}	7.40 ± 0.14 ^{d}
L* Lightness	33.77 ± 0.15 ^{a}	15.43 ± 0.15 ^{c}	28.43 ± 0.06 ^{b}	11.8 ± 0.10 ^{d}
C* Chroma	20.99 ± 0.15 ^{a}	10.72 ± 0.12 ^{c}	16.85 ± 0.13 ^{b}	7.92 ± 0.02 ^{d}
h* Hue	0.68 ± 0.01 ^{d}	1.11 ^{c}	1.14 ^{b}	1.21 ± 0.01 ^{a}

Values are the mean ± standard deviation, and those with different letters in the same row are significantly different ($p < 0.05$).

In conclusion, the study suggests that freeze-drying is the most effective method for preserving colour in banana inflorescences, making it a recommended choice for product development to ensure consumer acceptance and maintain quality.

3.1.2. Microstructure

The microstructure of banana inflorescence samples under different drying methods is shown in Figure 4. Based on the images, it can be concluded that drying significantly changes the cell structure. The fresh banana inflorescence cells have a spherical-shaped honeycomb structure. During the drying process, the removal of water can cause cell shrinkage, loss of cell turgor, and structural collapse at different rates.

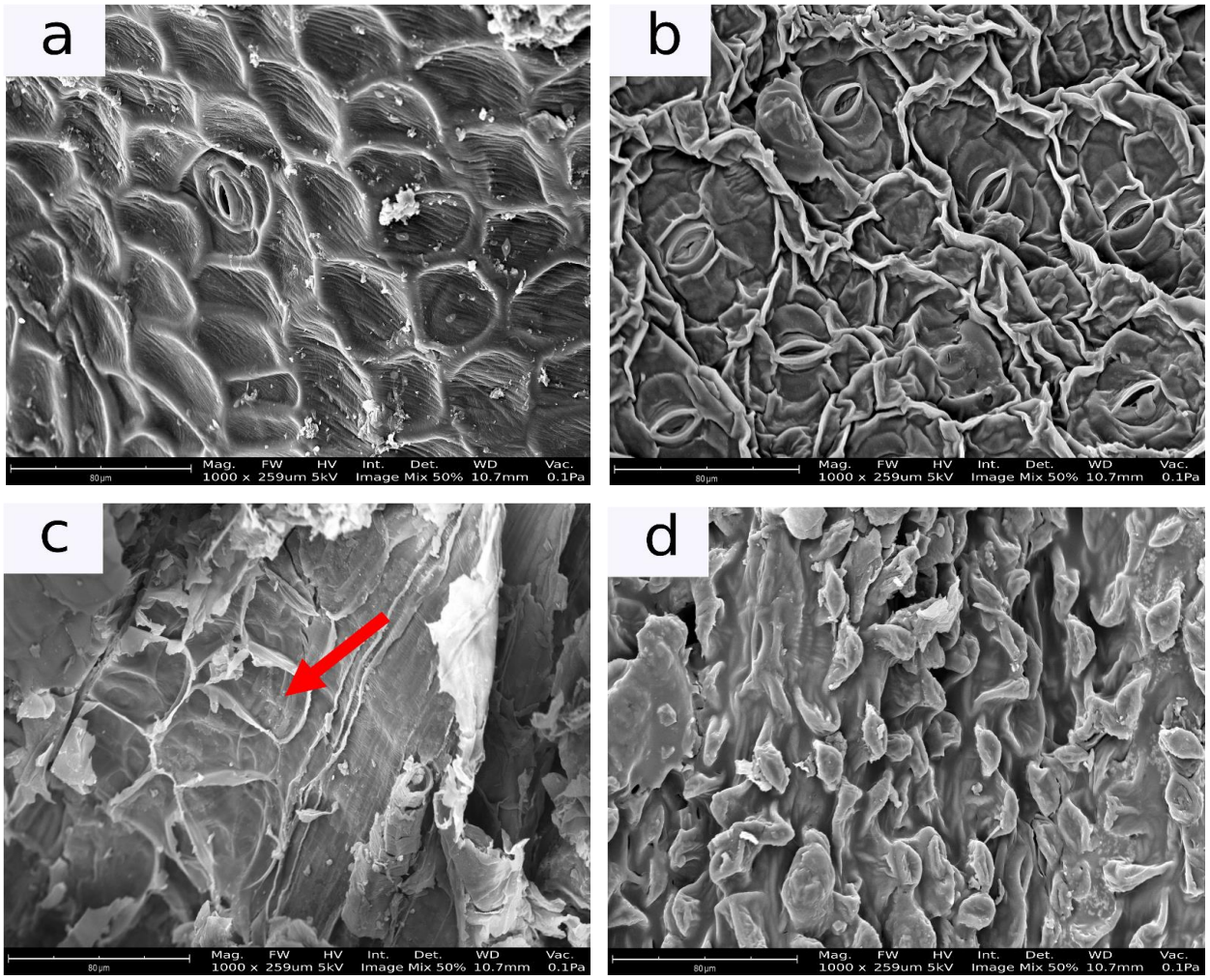


Figure 4. Microstructure of banana inflorescence: (**a**) fresh; (**b**) CD; (**c**) FD; (**d**) IMCD; (c arrow) porous cell matrix.

During the process of CD (convective drying), an even distribution of cells can be observed. However, there is severe shrinkage, damage to cell walls, cell rupturing, and increased cell density. Though cell rupturing enhances the extractable compounds, the prolonged application of heat during convective drying can lead to significant degradation of these compounds. Bioactive compounds are often sensitive to heat, and their stability can be compromised under high temperatures or extended drying times. The degradation mechanisms include oxidation, hydrolysis, and thermal decomposition. Furthermore, prolonged drying can lead to Maillard reactions. It can also reduce the bioactive value by degrading essential compounds. The even distribution of cells observed in CD could be attributed to the use of constant low heat, which results in a uniform distribution of pores, intracellular spaces, and eventually, a uniform structure. A similar structure was reported for Maqui berries [44]. In the FD process (freeze-drying), the shape of the banana inflorescence cells remained with minimal shrinkage, but the cell matrix was open, spongy, and exhibited a more porous structure. These pores were caused by the sublimation of ice crystals during the freeze-drying process. Less cell density was observed in FD, with collapsed tissues being prominent. The microstructures of CD and FD are similar to that of Jujube, according to the literature [18]. In the IMCD method, the cells showed significant shrinkage, and their shapes were uneven. This may be due to the fluctuation of temperature during the on–off time of the microwave. The analysis of the microstructure from three different drying methods highlights the significant impact of drying on the cell structure, which consequently affects the extraction of bioactive compounds. Our findings indicate

that freeze-drying results in an open porous structure, leading to efficient extraction and a higher bioactive yield. The highly porous microstructure created by freeze-drying is particularly favourable for the extraction of bioactive compounds, as it facilitates better solvent penetration and compound release.

3.1.3. Moisture Content

Table 2 reports the moisture content of dried banana powder processed using CD, FD, and IMCD. The moisture content of all drying methods significantly decreased in comparison to the fresh sample, ranging between 7.40 ± 0.33 and 8.22 ± 0.51. Our results are slightly below the previously reported moisture content of culinary banana bracts at 8.44–8.47 [45]. The difference could be due to the use of only bracts for the study conducted by Begum and Deka [45] and the dried condition was 40 °C tray drying.

Table 2. Physicochemical properties of banana inflorescence for different drying methods.

Drying Method	Moisture %	Ash %	pH	TSS (Brix)	Drying Yield
CD	7.89 ± 0.51 ^{b}	14.71 ± 0.58	5.20 ± 0.10 ^{b}	18.53 ± 0.42 ^{c}	8.28 ± 0.22 ^{b}
FD	8.22 ± 0.51 ^{b}	15.50 ± 0.22	5.40 ± 0.20 ^{b}	20.23 ± 0.15 ^{a}	9.73 ± 0.21 ^{a}
IMCD	7.40 ± 0.33 ^{b}	14.81 ± 0.05	5.17 ± 0.12 ^{b}	19.33 ± 0.12 ^{b}	9.60 ± 0.46 ^{a}
Fresh (control) *	92.33 ± 0.58 ^{a}	-	5.83 ± 0.12 ^{a}	17.30 ± 0.10 ^{d}	-
p-value **	0.000	0.069	0.001	0.000	0.003

* Values for the control are on a fresh basis, whereas those for other samples are on a dry weight basis. ** Values are the mean ± standard deviation, and those with different letters in each column are significantly different ($p < 0.05$).

The results revealed that the moisture content at different drying methods was not significantly different. It is reported that the moisture content of bamboo shoots at different drying methods also did not differ significantly [46]. However, it is noticeable that the drying method has an impact on the moisture content, with the descending order of moisture variation being FD > CD > IMCD. This aligns with similar findings for dried ginger, where the moisture content was reported by Ghafoor et al. [47] as 8.34% (FD), 6.84% (CD), and 5.85% (MD—microwave drying). Similar results were reported for Hibiscus cannabinus leaves, which concluded that the moisture content at different drying methods was in the order of FD > CD > MD. The low moisture content in the CD and IMCD samples may be attributed to the rapid removal of water. Moisture content in dried powder is a vital indicator for determining the shelf life, potential microbial spoilage, and stability against physical and chemical changes. All dried samples resulted in a moisture content below 10%, demonstrating the suitability of the dried powder for product development [38].

3.1.4. Ash Content

Table 2 lists the ash content of dried banana inflorescence. There was no significant difference in ash content observed. All the dried samples had ash contents ranging from 14.71 ± 0.58% to 15.50 ± 0.22%. This range of ash % is in accordance with the ash % of culinary banana bracts, which is 10.1–14.00 [45]. However, our study found a slightly different ash content for the FD and IMCD samples. While there was no significant difference among the drying treatments, FD showed a slightly higher ash percentage than CD and IMCD. A higher ash content indicates a concentration of minerals that are not susceptible to volatilisation, which is beneficial for preserving minerals. However, it could also result in the concentration of toxic elements. Therefore, analysis of toxic minerals needs to be conducted for dried products before they are utilised for commercial product development for consumers.

3.1.5. pH

pH is an important indicator of the acid concentration of a food ingredient, which determines its susceptibility to microorganisms. The pH of dried samples ranges between 5.17 ± 0.12 and 5.40 ± 0.20, as summarised in Table 2. All the dried samples showed lower pH compared to the fresh samples. This could be due to the removal of moisture that concentrates the acid molecules, subsequently increasing the acidity. Our results show that the FD samples have a slightly higher pH, which could be due to the higher moisture content. The IMCD samples exhibited the lowest pH (highly acidic). This further validates its low moisture concentration. According to the results, we can conclude that the drying process increases the acidity of a product. The acidity level is determined by its moisture content.

3.1.6. Total Soluble Solids (TSS)

Total soluble solids (TSS) refer to the sugars, organic acids, vitamins, and minerals that remain after the water is removed during the drying process. The study showed that the TSS concentrations significantly increased during the drying process. The fresh samples had 17.30 ± 0.10 TSS, while the dried samples ranged from 19.33 ± 0.12 to 20.23 ± 0.15 TSS. The higher TSS in the dried samples is due to the concentration of total soluble solids during drying. Different drying methods resulted in varying TSS levels, with the CD samples showing the lowest TSS and FD samples showing the highest. Higher TSS is associated with stronger aroma and flavour. These findings suggest that FD results in a higher aroma and flavour compared to IMCD and CD.

3.1.7. Drying Yield

The drying yield is an important measurement of predicting the quantitative value of a final product for commercial product estimation. The results conclude that banana inflorescence yields only <10% of raw materials once it is processed using drying methods, as shown in Table 2. This reflects its higher moisture content as a raw material as a highly perishable by-product with a high moisture content of 92.33%. Once it is processed using drying methods, it yields only 8.28% to 9.60% of the final product. Our findings indicate that the choice of drying method significantly affects the yield, with the order of the yield being 9.60% > 9.73% > 8.23% for IMCD > FD > CD, respectively. The higher yield from IMCD may be attributed to its rapid moisture removal compared to CD and FD. CD resulted in a significantly lower yield, likely due to prolonged exposure to heat leading to increased water removal and cell mass degradation.

3.1.8. EDS Spectrum

The EDS analysis revealed that banana inflorescence is a rich source of minerals. The percentage of minerals at different drying methods is shown in Figure 5. The results indicated that all three drying methods preserved potassium (K) within the range of 32–50%. Additionally, significant concentrations of calcium (Ca), sodium (Na), magnesium (Mg), and phosphorus (P) were found in banana inflorescence. These macro elements are beneficial for muscle and bone strength (Mg), healthy teeth (Ca), healthy joints (P), protein synthesis (S), and nerve signalling (Na). Furthermore, the analysis identified the presence of trace elements such as iron (Fe), copper (Cu), zinc (Zn), selenium (Se), iodine (I), manganese (Mn), and molybdenum (Mo) in banana inflorescence. These minerals serve various functions in the human body, including the formation of haemoglobin (Fe), support of fertility (Zn), protection of the vascular system (Cu), lipid metabolism (Mn), and contribution to enzymes and protein synthesis (Mo). Notably, freeze-dried (FD) banana inflorescence consists of 6% Se, which acts as an antioxidant. Furthermore, FD resulted in higher concentrations of essential elements such as 15.98% Ca, 5.99% Fe, and 8.19% Zn. These findings of the concentrations of minerals demonstrate that banana inflorescence dried powder is suitable for food fortification, as it is beneficial for human health. Our results align with the previous literature on banana inflorescence, highlighting the presence

of essential minerals in different species such as *Musa acuminata* Colla [48], M. *paradisiaca* L. [49], and *Musa balbisiana* Colla [50]. This mineral analysis confirms the suitability of Cavendish banana inflorescence for consumption and its potential for future food or pharmaceutical ingredients.

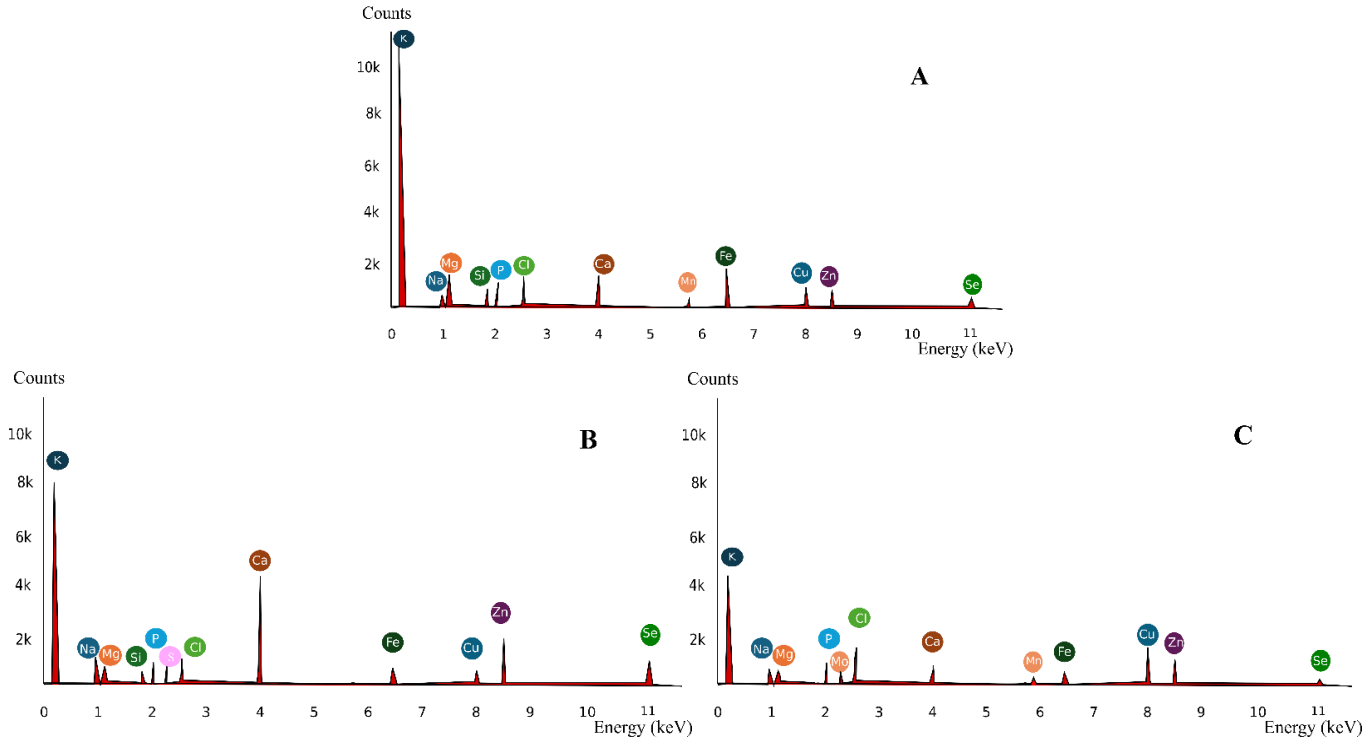


Figure 5. EDS analysis for (**A**) CD, (**B**) FD, and (**C**) IMCD.

3.2. Functional Properties

The functional properties are crucial characteristics for determining the quality and compatibility of food and pharmaceutical ingredients in new product development. The functional properties of extracts obtained through CD, FD, and IMCD are summarised in Table 3.

Table 3. Functional properties of dried banana inflorescence.

Drying Method	Swelling Capacity	Bulk Density (g/mL)	Tapped Density	Water-Holding Capacity (g/g)	Oil-Holding Capacity (g/g)	C %	H %	N %
CD	7.29 ± 0.17 ^{b}	0.46 ± 0.04 ^{b}	0.63 ± 0.02 ^{b}	6.29 ± 0.17 ^{b}	2.52 ± 0.10 ^{b}	42.66 ± 0.74	5.07 ± 0.13	2.58 ± 0.07 ^{a,b}
FD	10.35 ± 0.44 ^{a}	0.13 ± 0.03 ^{c}	0.28 ± 0.02 ^{c}	9.35 ± 0.44 ^{a}	6.01 ± 0.41 ^{a}	41.59 ± 0.24	5.08 ± 0.10	2.48 ± 0.15 ^{b}
IMCD	6.92 ± 0.03 ^{b}	0.58 ± 0.01 ^{a}	0.68 ± 0.01 ^{a}	5.96 ± 0.03 ^{b}	2.23 ± 0.06 ^{b}	42.66 ± 0.74	5.03 ± 0.17	2.78 ± 0.03 ^{a}
p-value *	0.000	0.000	0.000	0.000	0.000	0.126	0.919	0.027

* Values are the mean ± standard deviation, and those with different letters in each column are significantly different ($p < 0.05$).

3.2.1. Swelling Power

The swelling capacity of the dried powder is the measure of its ability to swell by absorbing water from the soluble solids. In Table 3, the swelling capacity of dried banana inflorescence is summarised. Swelling power is a critical parameter in determining the suitability of a powdered material as a food ingredient. The results demonstrated a significant difference among drying methods. The swelling capacity is varied from 6.92 ± 0.03 to 10.35 ± 0.44. The ability of powder to absorb water and expand is influenced by the

size of the particles and the method used to dry it. The results demonstrated the highest swelling capacity from FD samples, which is 10.35 ± 0.44. CD and IMCD reported 7.29 and 6.92, respectively. The increased swelling capacity of freeze-dried (FD) powder can be attributed to its physical and chemical characteristics. FD particles that are small and uniform, with a higher concentration of carbohydrates and protein, have demonstrated the ability to absorb more water and expand more in water compared to powder with larger, coarser particles. Water is able to be trapped more effectively within the capillary structures of fibres in FD. A high swelling capacity is indicative of high-quality powder, as it forms a strong gel structure due to its superior water retention capabilities, leading to improved texture when utilised as a food ingredient. The cohesiveness and consistency of evenly distributed microstructural powders demonstrate their ability to increase in volume through water absorption.

3.2.2. Bulk Density

The mass of particles per unit volume, also known as the bulk density, was investigated and is summarised in Table 3. The findings revealed that the bulk density of dried powders ranges from 0.13 ± 0.03 to 0.58 ± 0.01. The highest bulk density was reported from IMCD, while the lowest was from FD. The high bulk density at IMCD may be attributed to several factors. When heat is applied to a product, moisture evaporation causes cell shrinkage, leading to volume reduction and compaction of cell particles. The arrangement of cells at IMCD is highly dense with low porous structures, which increases the bulk density. The bulk density of CD is in agreement with the bulk density of the outer bracts of culinary banana Musa ABB. However, the results for FD and IMCD cannot be compared with the literature, as banana inflorescence has not been previously studied.

3.2.3. Tapped Density

Tapped density is an important parameter for formulation development in the food industry and pharmaceuticals. Tapped density measures the density of dried powder after compaction. The tapped density of dried powders is summarised in Table 3. The findings concluded that tapped density is highly significant in different drying methods. The tapped density resulted in a higher value of 0.68 ± 0.01 for IMCD. CD resulted in 0.63 ± 0.02 for tapped density, which was the second highest. These higher values could be due to the high intracellular spaces in drying treatments with elevated temperatures. Comparatively, FD resulted in 0.28 ± 0.02, which was very low. FD samples are very compact due to the arrangement of fine fibres. Therefore, our results highlighted that IMCD had higher compressibility and FD had the lowest.

3.2.4. Water-Holding Capacity (WHC)

Water absorption characteristics represent the ability of a product to retain water and reach its correct consistency. According to the results summarised in Table 3, the WHC is highly influenced by the drying method. The WHC of dried powders varied between 5.96 ± 0.03 and 9.35 ± 0.44. The highest WHC is reported for freeze-dried (FD) powders, which can be attributed to the higher swelling of the fibre, carbohydrate, and protein content. The small granular structure of starch polymers in FD enhances the surface for hydration and the WHC. Additionally, the higher swelling capacity of FD facilitates more trapped water. When comparing the WHC of FD, convection-dried (CD), and microwave-dried (MD) banana flour, FD shows the highest WHC [38]. This finding aligns with our results, confirming that FD provides a superior WHC compared to other drying methods. Higher WHC indicates FD as a promising functional ingredient that can be used in food manufacturing industries to improve their texture. Additionally, it makes them suitable for anticaking and anti-sticking agents.

3.2.5. Oil-Holding Capacity

The oil-holding capacity of banana inflorescence indicates its ability to trap oils. The results shown in Table 3 highlighted that the drying method significantly influenced the oil-holding capacity. The variance of oil-holding capacity is due to the physical structure of dried powders. The results demonstrated that the oil-holding capacities of CD and IMCD are 2.52 and 2.23. This result is in agreement with a previous oil absorption capacity reported for microwave-dried banana blossoms [51]. The low oil absorption capacity of CD and IMCD could be due to the superiority of hydrophilic compounds in its proteins resulting in low oil absorbance. However, FD shows a significantly higher oil-holding capacity of 6.01, which could be due to the large pores and loose fibrous physical structure of the FD samples. The oil absorption ability is increased by the surface polarity of dried powder through the lyophilic process. The oil absorption capacity of freeze-dried banana flour is significantly enhanced by the hydrophilic chains present in the amino acid molecules [52]. This enhancement could be attributed to the conditions of the freeze-drying process. The low temperatures and high vacuum conditions likely prevented the collapse of protein molecules and retained their emulsifying capacity. The oil-holding capacity is an important attribute for a food ingredient, as it indicates the ability to mix with fats, which are a key component in the food industry. Moreover, a higher OHC indicates the suitability of dried banana inflorescence as an emulsification agent.

3.2.6. C, H, and N Analysis

The composition of carbon (C), hydrogen (H), and nitrogen (N) in dried banana inflorescence is summarised in Table 2. The analysis indicates that the drying method had no significant impact on the C and H elements. However, a significant difference in the N percentage was observed across different drying methods. The results revealed that all dried powders consisted of 41–43% C, 5–6% H, and 2–3% N. The higher concentration of C suggests a substantial presence of carbohydrates and fibres, which are primary constituents in plant materials and contribute to their caloric content and dietary fibre. The presence of H draws attention to the composition of various organic compounds, including carbohydrates, lipids, and proteins, as hydrogen is a key component of these molecules. The N content represents amino acids and proteins, essential for nutritional value and indicating the presence of nitrogenous compounds such as proteins and amino acids in the banana inflorescence

3.2.7. FTIR

FTIR spectra ranging from 400 to 4000 cm^{-1} obtained from banana inflorescence dried at three different drying methods CD, FD, and IMCD are illustrated in Figure 6. The FTIR spectra demonstrated the presence of lignocellulose materials and functional biomolecules such as phenolics, alkanes, ethers, amines, and organic acids, as explained in Table 4.

The present study showed the absorbance peaks at wavelength (cm^{-1}) regions at 3292, 2924, 2854, 1734, 1638, 1440, 1380, 1310, 1260, 1231, 1151, 1066, 1021, and 915. Similar peaks were identified for banana inflorescences of *Musa acuminata* cv. Nendran [53], *Musa* sp.cv. Kluai Namwa Mali-Ong [39], and *Musa* sp.—cv. not given [54]. The spectral analysis reveals distinct absorption bands indicative of various functional groups present within the examined banana inflorescence samples. The absorption band spanning 3700–2800 cm^{-1} is attributed to the symmetric and asymmetric O–H stretching vibrations associated with both carbohydrates and water constituents [55]. Additionally, evidence of phenolic compounds within this spectral region is noticeable [56]. The peak observed at 3292 cm^{-1} corresponds to the water solubility characteristics of the dried banana inflorescence. Furthermore, the peaks at 2924 cm^{-1} and 2854 cm^{-1} signify C-H stretching vibrations originating from the CH and CH2 groups [39]. The presence of absorbed water is reflected by the peak at 1638 cm^{-1}, denoting bending modes [54]. Moreover, weaker peaks observed at 1440 cm^{-1}, 1380 cm^{-1}, and 1310 cm^{-1} are attributed to CH2, C-O-C bending, and C-O stretching motions, indicative of cellulose and hemicellulose constituents. Additionally, the peak at

1231 cm^{-1} signifies C-O stretching, characteristic of lignin [57]. Vibrations at 1066 cm^{-1}, 1021 cm^{-1}, and 915 cm^{-1} may arise from either amide or aromatic ring vibrations [53]. Notably, the prominent peak at 1066 cm^{-1} corresponds to CO-C pyranose ring vibrations.

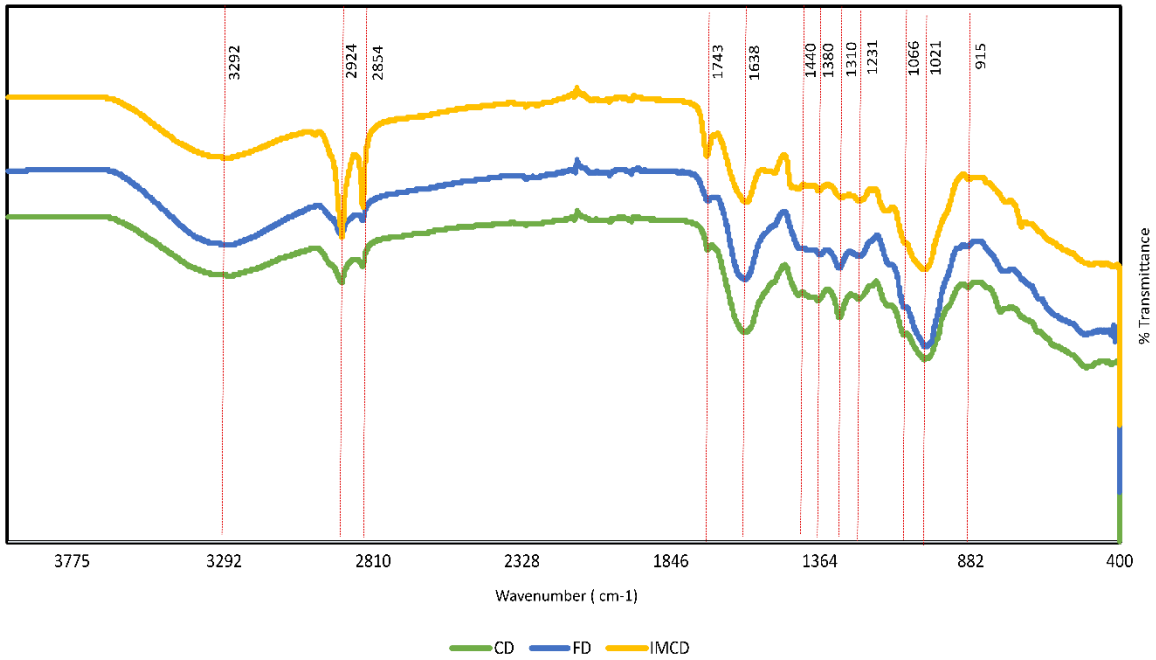


Figure 6. FTIR spectrum of banana inflorescence.

Table 4. The FTIR peaks identified in banana inflorescence.

Wavenumber (cm^{-1})	Band Assignment	Contributing Biomolecules	Reference
3292	=C-H, OH	Unsaturated lipids	[57]
2924, 2854	C-H, OH, CH_2	Alkane	[56]
1743	Amide 1	Aldehyde, Ketone	[57]
1638	COO-	Absorbed water	[54]
1440, 1380, 1310	C-O-H	Starch	[58]
1231	C-O	Lignin	[54]
1066, 1021, 915	C-O-C, C-O, C-C,C-O-P, P—O-P	Aromatic, Phenolics, carbohydrate	[39,59]

The presence of these characteristic peaks across all three drying methodologies suggests their efficacy for the preservation of relevant bioactive compounds within the banana inflorescence, thus rendering them suitable for potential applications in functional food development. FTIR spectroscopy emerges as a reliable tool for fingerprinting the phytochemical compositions within plant materials. Accordingly, the findings underscore the presence of bioactive compounds and functional groups within the banana inflorescence, advocating for further exploration and extraction of these constituents to use their potential for functional food production.

3.3. Bioactive Properties of Banana Inflorescence

Figure 7 presents the banana inflorescence extracts using methanol as a solvent and the Dionex Accelerated Solvent Extractor (ASE). The extract exhibits significantly different colours, depending on the drying method employed, suggesting variations in the composition of bioactive compounds. This difference in colour may be attributed to the varying

stability and concentration of these compounds under different drying conditions. The fresh extract shows a lighter colour than all other extracts from dried banana inflorescence. CD and IMCD extracts show dark colour, similar to its dried powdered sample. However, the extract of FD was the darkest extract, though it was light in colour in its dried form. This is due to the impact of freezing. During freezing, the colour change was minimal. The visual observation of dried powder mainly shows the well-preserved light colour of the fibrous structure. However, when it is extracted, it extracts different bioactive compounds such as polyphenols, which come out of the cell matrix. The freeze-dried extract exhibited a higher concentration of phenols according to our results. These polyphenol extracts are usually yellow to dark brown. Furthermore, the synergetic effects of extracted phenolic compounds may also cause different colour reactions, such as dark brown colour, as shown in Figure 7.

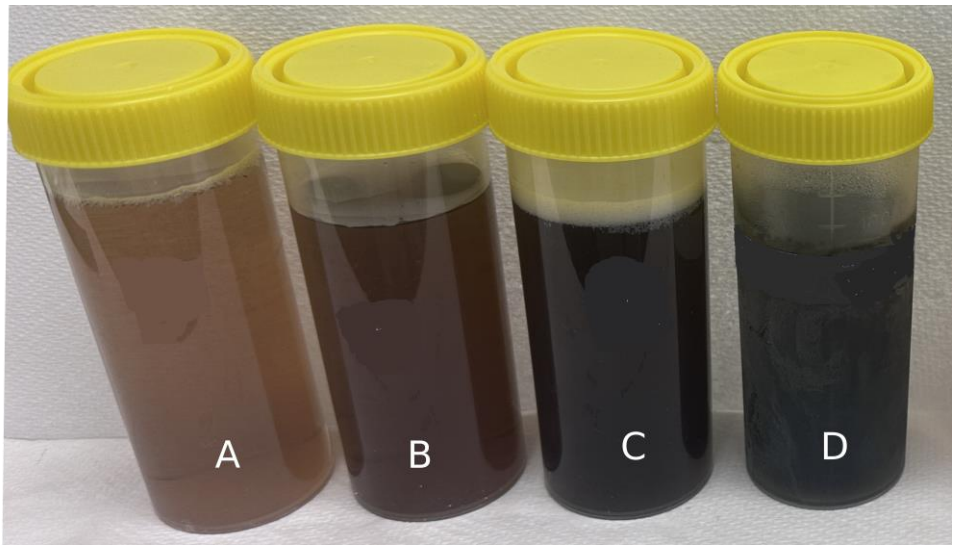


Figure 7. Banana inflorescence extracts from different drying methods at 100 °C: (**A**) fresh, (**B**) CD, (**C**) FD, and (**D**) IMCD.

To assess the bioactivity of the extracts, the samples were analysed for their total phenolic content (TPC) and total antioxidant activity (TAO). These analyses provide insight into the variance in bioactivity, as TPC and TAO are key indicators of the presence and effectiveness of phenolic compounds, which are known for their antioxidant properties.

3.3.1. Total Phenolic Content (TPC)

Figure 8 illustrates the total phenolic concentration of banana inflorescence at three different drying methods. The results show that drying has a significant impact on the total phenolic concentration. All the drying treatments enhanced the total phenolic concentration of banana inflorescence. Fresh samples, which were not subjected to any drying process, exhibited the lowest TPC values, underscoring the importance of drying in enhancing the extractability of phenolic compounds. The lowest phenolic concentration in fresh samples is due to the absence of cell rupturing compared to other drying methods.

FD demonstrated the highest TPC for all extraction conditions, making it the most effective method for preserving phenolic compounds in banana inflorescence. Similarly, FD is reported as the best drying method for TPC in pink lotus flowers [29]. The TPC for FD using 75% methanol was 2906.3 mg/100 g GAE, significantly higher than both CD and IMCD. In contrast, CD showed the lowest TPC values, with 2378.5 mg/100 g GAE in the same solvent, indicating the degradation of phenolic compounds at prolonged drying. However, IMCD exhibited a TPC of 2496.5 ± 24.06 mg/100 g, while CD retained only 2378.5 ± 24.06 mg/100 g with 75% methanol. These findings demonstrated that IMCD has better retention of bioactive compounds than CD. A similar order was observed for

other solvent mixtures as well. Therefore, our study concluded that the total phenolic concentration varies in different drying methods in the order of FD > IMCD > CD.

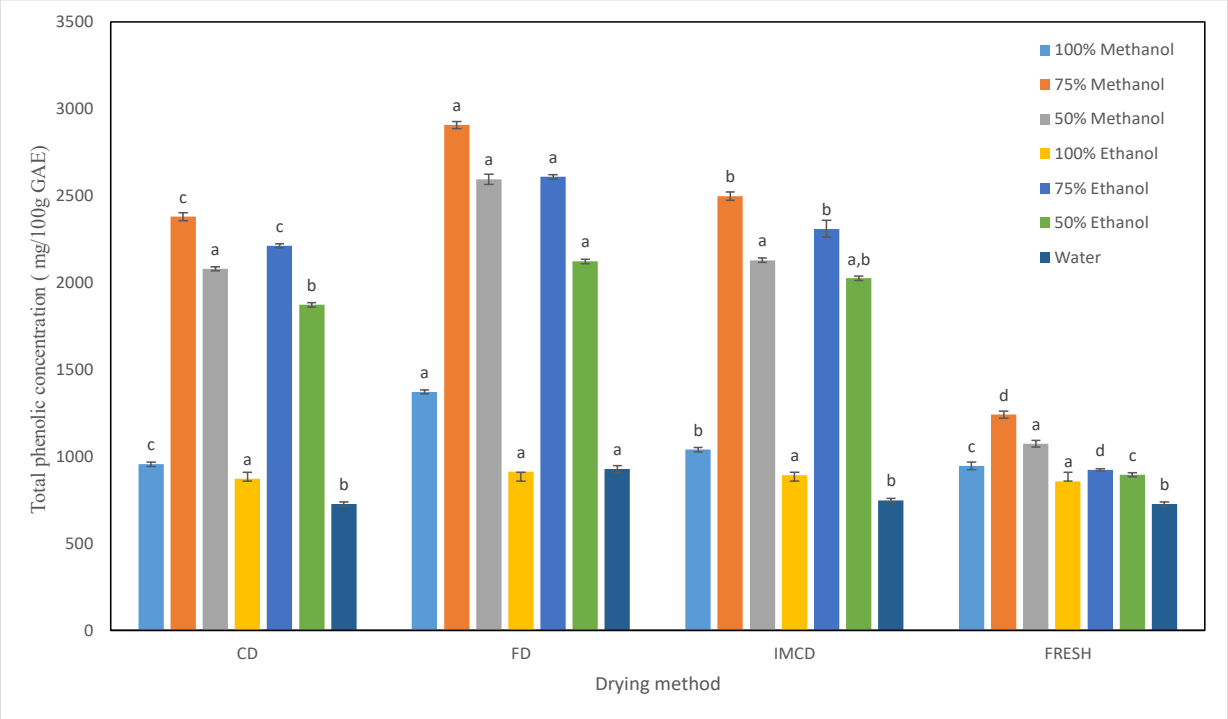


Figure 8. Total phenolic content of extracts obtained from samples dried using different drying methods using different solvents. The total phenolic contents of extracts obtained using different solvents among different drying methods with different letters are significantly different.

The cell structure of FD could be the main reason for this superiority in preserving phenolic compounds, as it shows open pores, which cause the opening of cell vacuoles and make for better extraction. The lowest TPC resulting from CD could be due to the degradation of phenolic compounds during the exposure of banana inflorescence for heat for prolonged conditions. However, IMCD could be a more sustainable option, as it resulted in considerably higher concentrations of phenolics within a noticeably short period of time, which led to energy and time conservation [30]. FD consumed 7 days for drying, which costs high energy [31]. Moreover, large FD instruments are needed to process one batch of samples, which is also expensive. Therefore, on a commercial scale, IMCD would be a more sustainable option than FD.

The extraction conditions also showed a significant impact on the TPC of banana inflorescence extract. The fresh sample (control) exhibited significantly low concentrations for most of the solvents. However, the total phenolic concentration at water and 75% ethanol extractions showed very similar concentrations for both dried and fresh extraction, with slightly higher concentrations found in the dried samples. Water and 75% ethanol resulted in the minimum total phenolic concentration compared to the other solvents, indicating their poor extraction capacity. Our results highlight that water is the least suitable solvent for the total phenolic concentration compared to ethanol and methanol.

Methanol resulted in a higher concentration of the total phenolic concentration compared to ethanol. The total phenolic concentration of 100% methanol ranged between 945.6 and 1371.5 mg/100 g, while 100% ethanol resulted in only 855.3 to 913.2 mg/100 g. Similarly, 50% methanol resulted in a higher total phenolic concentration in the range of 2079.9 to 2593.8 mg/100 g, while a lower total phenolic concentration resulted in 50% ethanol in the range of 1871.5 to 2121.5 mg/100 g. Moreover, 75% methanol extract for all dried samples exhibited its superiority for the total phenolic concentration over 75%

ethanol. Methanol exhibited its superior extraction capacity due to its properties. The existing literature regarding the extraction of phenolic compounds has consistently emphasised the superiority of methanol as a solvent [60]. This aligns with the findings of our study, which also supports the effectiveness of methanol for phenolic extractions. The high extraction efficiency of methanol can be attributed to its specific properties. When dissolving phenolic compounds, methanol's OH bonds form strong hydrogen bonds with the phenol compounds, which is more effective compared to ethanol and water. Additionally, methanol's ability to extract a wide range of compounds with varying polarities further supports its superiority [61]. Our research confirmed that methanol outperformed water and ethanol as solvents. Notably, methanol's capacity to remain in liquid form at elevated temperatures, even above its boiling point, enhances the mass transfer and dissolution rates during extraction processes.

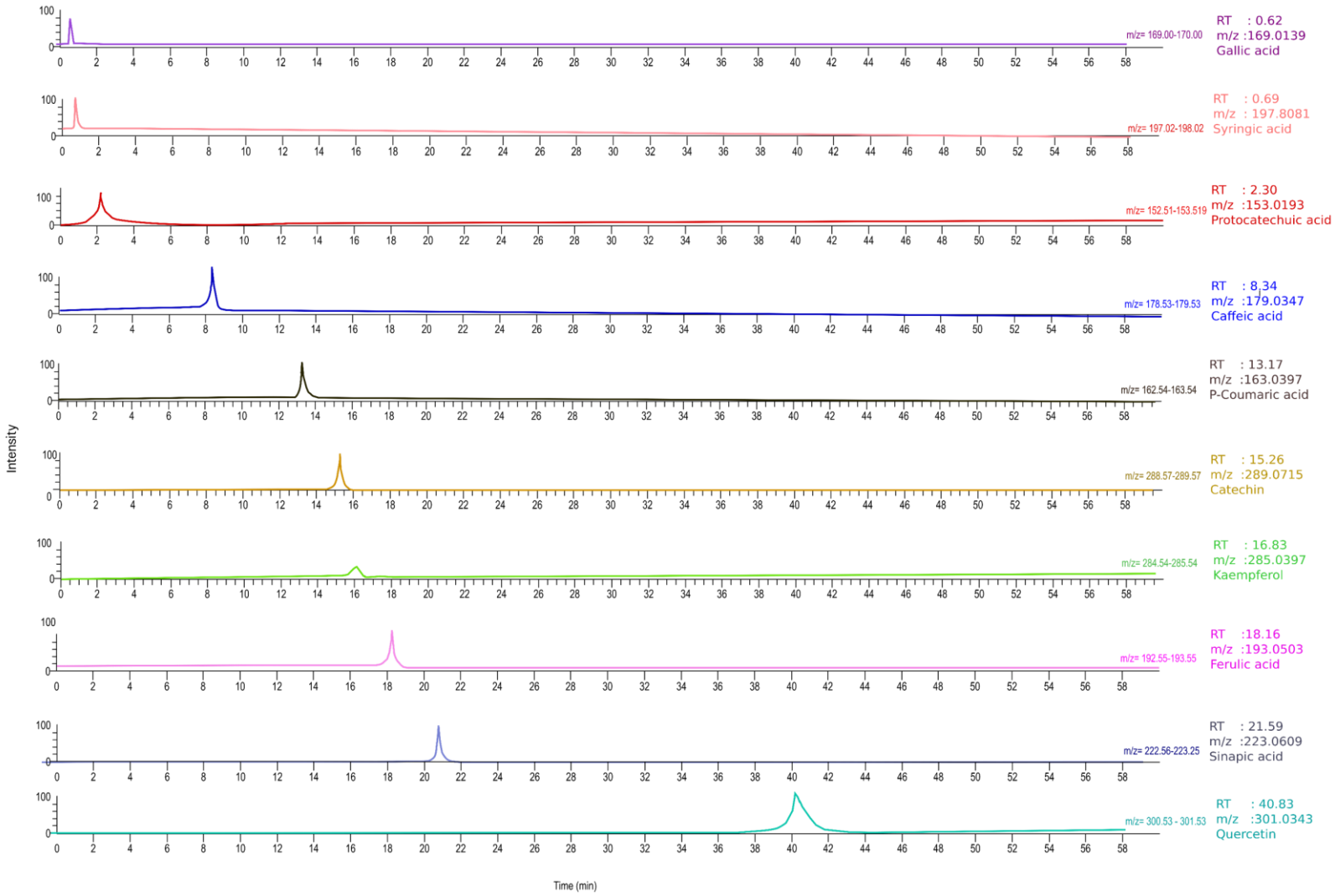
Our results showed that both the drying method and extraction conditions significantly affected the TPC. Comparing the drying treatments and extracted solvents, the highest total phenolic concentration is recorded from 75% methanol as a solvent and FD as the best drying method, followed by IMCD and the lowest CD.

3.3.2. DPPH Scavenging Activity

The DPPH scavenging activity of the CD, FD, and IMCD results were analysed to determine the suitable drying method in terms of antioxidant activity. The results exhibited significant differences among the drying treatments. The antioxidant activity ranged between 25.66 $\pm$ 0.44% and 63.12 $\pm$ 0.25%. Variance of the scavenging activity is observed among the treatments due to the drying method and solvent used for extraction. The results demonstrated that FD extracted with 75% methanol resulted in the highest scavenging activity. In line with our findings reported for TPC, DPPH also exhibited higher concentrations for methanolic extracts than ethanol and water, proving the superiority of methanol in antioxidant activity. These results demonstrated a linear relationship with the total phenolic content. The antioxidant content was in the order of FD > IMCD > CD, according to our analysis. Our results are in agreement with the highest antioxidant concentration reported for FD banana pulp [62,63], ginger [47], and bamboo shoots [46]. However, FD consumes a lot of time and energy. Therefore, IMCD could be a good drying method for future product development. The results from the scavenging activity of banana inflorescence showed the oxidation prevention mechanisms of the bioactive compounds present in banana inflorescence. This finding can be further utilised in developing food enriched with antioxidants.

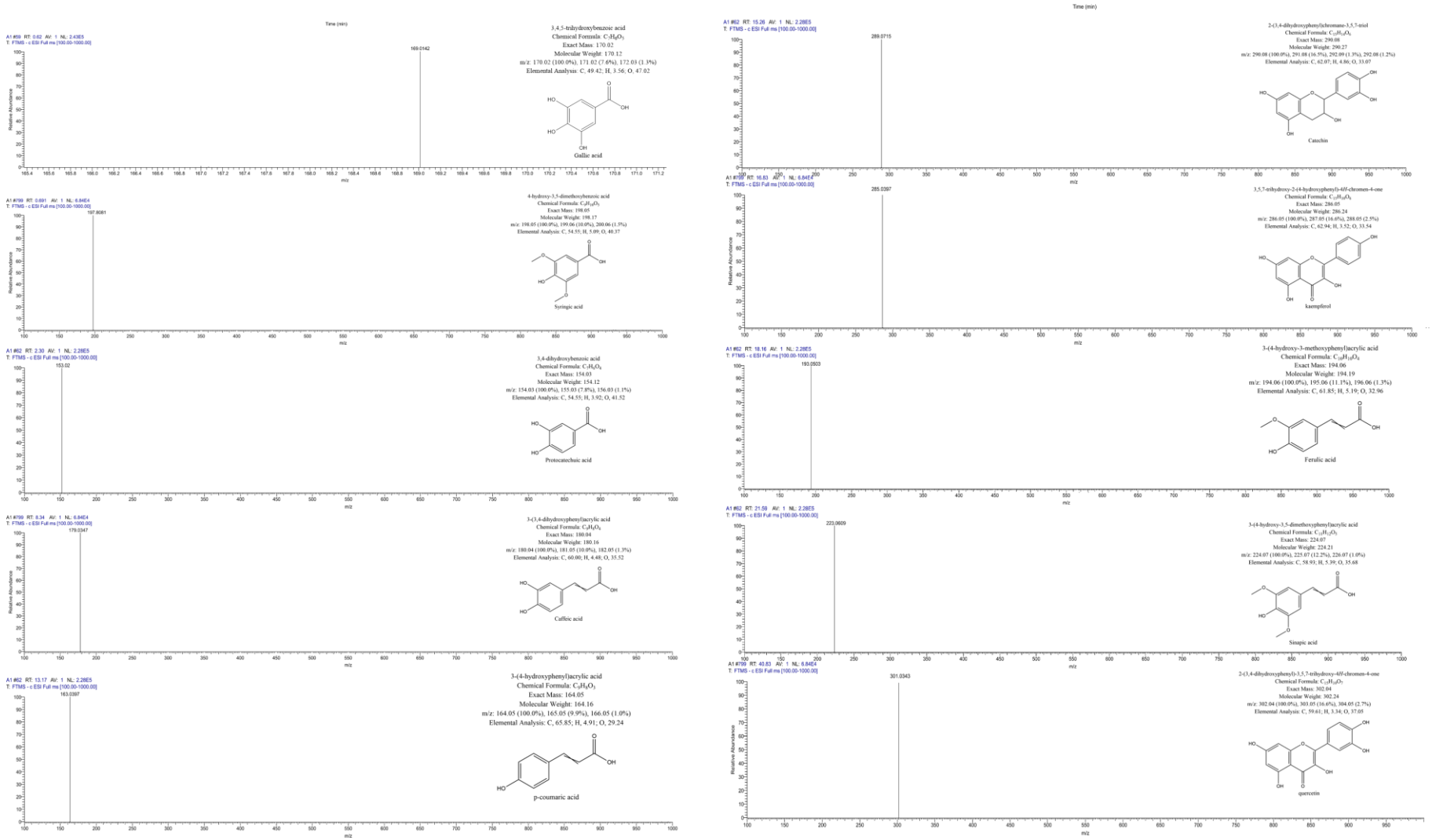
3.3.3. Characterisation of Polyphenols Using LC-MS

Liquid chromatography-mass spectrometry (LC-MS) is a widely used method for identifying and characterising bioactive compounds and functional groups in food and medicinal plants. In this study, LC-MS in negative mode is used to analyse phenolics in fresh, oven-dried (OD), freeze-dried (FD), and microwave-dried (IMCD) banana inflorescence. The qualitative analysis was performed using Xcalibur 3.0.63 software (Thermofisher Scientific, Inc.). Phenolics in banana inflorescence samples were identified based on their *m/z* values and mass spectra in M-H negative ionization mode. The spectra and retention times of the standards were compared with samples to further verify the compounds. Quantification was conducted using calibration curves prepared for the standards. The identified 10 phenolic compounds are listed in Table 5. The results revealed that banana inflorescence is a rich source of phenolic compounds, demonstrating the presence of phenolic compounds such as gallic acid, syringic acid, protocatechuic acid, caffeic acid, coumaric acid, catechin, ferulic acid, sinapic acid, kaempferol, and quercetin. LC-MS graphs related to different phenolic compounds are illustrated in Figure 9A. The mass spectrum of the phenolic compounds is illustrated in Figure 9B.



(**A**)

Figure 9. *Cont.*



(**B**)

Figure 9. (**A**) Extracted LCMS ion chromatograms. (**B**) The mass spectrum for the identified 10 main phenolic compounds in the banana inflorescence extract.

Table 5. Identification of targeted phenolic compounds by LC-MS.

Compound	Molecular Formula	RT (min)	Ionization (ESI^+/ESI^-)	Molecular Weight	Theoretical (*m*/*z*)	Observed (*m*/*z*)	Fresh (mg/100 g)	CD (mg/100 g)	FD (mg/100 g)	IMCD (mg/100 g)
Gallic acid	$C_7H_6O_5$	0.62	[M–H]-	170.0215	169.0142	169.0139	0.074 ± 0.02	0.063 ± 0.00	4.21 ± 0.10	0.05 ± 0.00
Syringic acid	$C_9H_{10}O_5$	0.691	[M–H]-	198.1700	198.0528	197.8081	0.27 ± 0.02	0.09 ± 0.01	20.32 ± 1.59	0.114 ± 0.02
Protocatechuic acid	$C_{13}H_{16}O_9$	2.3	[M–H]-	154.0266	153.0193	153.019	0.02 ± 0.00	0.125 ± 0.04	5.268 ± 0.30	0.222 ± 0.03
Caffeic acid	$C_9H_8O_4$	8.34	[M–H]-	180.0423	179.035	179.0347	0.107 ± 0.03	0.746 ± 0.17	18.035 ± 0.31	1.338 ± 0.11
p-coumaric acid	$C_9H_8O_3$	13.17	[M–H]-	164.0473	163.04	163.0397	0.041 ± 0.01	0.252 ± 0.04	5.724 ± 0.34	0.44 ± 0.04
Catechin	$C_{15}H_{14}O_6$	15.26	[M–H]-	290.079	289.0717	289.0715	0.023 ± 0.00	0.149 ± 0.03	2.966 ± 0.15	0.26 ± 0.03
Ferulic acid	$C_{10}H_{10}O_4$	18.16	[M–H]-	194.0579	193.0506	193.0503	0.08 ± 0.01	0.404 ± 0.10	7.763 ± 0.27	0.687 ± 0.05
Sinapic acid	$C_{11}H_{12}O_5$	21.59	[M–H]-	224.0685	223.0612	223.0609	0.049 ± 0.00	0.279 ± 0.06	4.659 ± 0.16	0.46 ± 0.05
Kaempferol	$C_{13}H_{16}O_9$	16.83	[M–H]-	286.0477	285.0404	285.0397	0.244 ± 0.05	1.45 ± 0.23	28.302 ± 1.60	2.485 ± 0.25
Quercetin	$C_{15}H_{10}O_7$	40.83	[M–H]-	302.0427	301.0354	301.0343	0.254 ± 0.01	0.906 ± 0.16	10.317 ± 0.32	1.397 ± 0.08

Our results align with the findings of Ramírez-Bolaños et al. [43], where they reported the phenolic compounds such as caffeic acid, coumaric acid, ferulic acid, protocatechuic acid, and quercetin compounds in Cavendish banana inflorescence. However, due to the different extraction methods and solvents, these results show different concentrations of phenolic compounds. In another study, ferulic and caffeic acids were identified in Australian-grown Cavendish bananas [64], which also supports our findings about phenolic compounds in the same cultivar. According to the findings, the concentration of gallic acid (4.21 mg/100 g), syringic acid (20.32 mg/100 g), caffeic acid (18.035 mg/100 g), kaempferol (28.302 mg/100 g), ferulic acid (7.763 mg/100 g), p-coumaric acid (5.724 mg/100 g), and quercetin (10.317 mg/100 g) in FD is significantly higher than CD and IMCD. This is due to the favourable microstructure of FD samples, which leads to a higher extraction efficiency and improved bioactive compound preservation, as explained in Section 3.1.2. CD results in lower concentrations of these bioactive compounds, potentially due to higher degradation during the drying process. However, it preserved the essential bioactive compounds such as caffeic acid (0.746 mg/100 g) and ferulic acid (0.404 mg/100 g) in considerable concentrations. The other phenolic compounds such as catechin and kaempferol were also determined in the CD sample in minor quantities. IMCD yields intermediate concentrations, higher than CD but lower than FD, indicating that it preserves phenolic compounds more effectively than CD but not as superior as FD. IMCD resulted in nearly doubled the concentration of kaempferol (2.485 mg/100 g), caffeic acid (1.338 mg/100 g), protocatechuic acid (0.222 mg/100 g), and p-coumaric acid (0.44 mg/100 g).

For further investigation of the LC-MS data for the identified 10 phenolic compounds against the different drying methods, a heat map was created. The heat map in Figure 10 shows the main clusters of phenolic concentration distribution. The colour change shows the concentration change of different phenolic acids. The highest phenolic concentrations were identified in dark red and the lowest in green.

It is highlighted that the dried samples demonstrated higher phenolic concentrations than fresh samples. This could be due to enhancing the extraction with the application of heat/pressure during the drying process. Moreover, our findings showed that the drying method significantly influences the concentration of phenolic compounds. The results concluded that freeze-drying was superior in extracting all the phenolic compounds, resulting in yellow-to-green colour distribution for all phenolic compounds. Kaempferol, quercetin, caffeic acid, and syringic acid demonstrated a higher abundance in the FD samples. Caffeic acid was reported as a predominant phenolic compound for *Palayankodan*, *Nendran*, and *Njalipoovan* cultivars dried under tray drying conditions [65] and for *Cavendish* [43], which is in agreement with our findings. However, our results reported low concentrations of catechin, gallic acid, and protocatechuic acid demonstrated in all drying methods except freeze-drying. Oven drying, the most common drying method, exhibited the potential to preserve all the phenolic compounds. However, the concentration of phenolic compounds resulting from CD was lower than FD and IMCD. Lower concentrations of these bioactive compounds in CD are potentially due to higher degradation during the drying process. This is in agreement with lower temperatures and less exposure to air, as demonstrated in FD, helping in preserving sensitive phenolic compounds. We noticed that IMCD resulted in higher concentrations of phenolic compounds than oven drying. Therefore, we can conclude that oven drying is the least suitable drying method and freeze-drying is the most suitable drying method for phenolic compound preservations.

Our findings confirmed that banana inflorescence consists of phenolic compounds in higher percentages. These compounds have different therapeutic values, which could be further enhanced and utilised for future food and pharmaceutical product development.

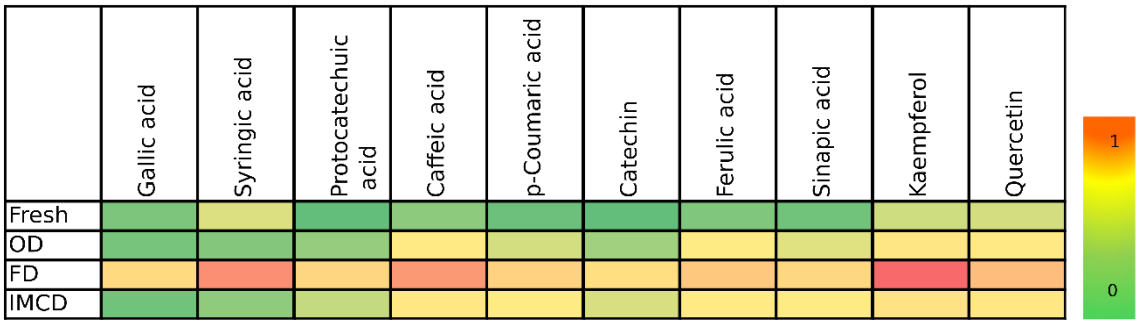


Figure 10. Heat map showing the concentration of phenolic compounds identified in banana inflorescence. Red boxes indicate higher concentrations, and green boxes indicate lower concentrations.

We further explored the medicinal and functional values of the identified phenolic compounds in banana inflorescence using the Phenol Explorer database, version 3.6. According to the database, caffeic acid is a phenolic compound categorised under hydroxycinnamic acids, which have therapeutic values such as antioxidant, anti-inflammatory, antidiabetic and antitoxic [66]. It is available in cranberries, olives, and coffee. Kaempferol is a flavanol compound found in almonds, cloves, cumin, and berries. Kaempferol is an antioxidant compound with anticancer and neuroprotective functions [67]. Another flavanol identified in the banana inflorescence is quercetin. Quercetin holds promising effects on anti-inflammatory and neuroprotective activities [68]. Quercetin was detected in coffee, cocoa, black tea, oregano, tomatoes, and black elderberries in higher concentrations. A quantitative assessment of the phenolic compounds in the Cavendish banana inflorescence cultivar using LC-MS suggests a broader application of phenolics due to their structure and antioxidant activities. Furthermore, our findings could potentially serve as a foundation for informing future decisions regarding which drying method to employ in order to effectively preserve targeted phenolic compounds in various food applications. This knowledge of the impact of different drying methods on specific phenolic compounds is essential for ensuring the maintenance of both the quality and nutritional value of food products.

4. Conclusions

Qualitative and quantitative analysis of bioactive compounds revealed high concentrations of caffeic acid, kaempferol, quercetin, and syringic acid in banana inflorescence, all of which have demonstrated various health benefits, including anticancer effects. The findings of this study suggest that thermal treatment using different drying methods has a significant impact on the preservation and extraction of bioactive compounds from banana inflorescence. The study highlights that FD is the most effective method for retaining high concentrations of the total phenolic content and antioxidant activity. These findings are consistent with previous research on various crops, demonstrating that FD consistently shows superior retention of bioactive compounds compared to other drying methods. However, the high operational costs and time consumption associated with FD may limit its practicality for commercial applications. Conversely, CD shows lower concentrations of phenolic compounds and antioxidant activity compared to FD and IMCD. Despite this, CD is widely used in industrial applications due to its low operational costs, as well as the potential for applications on a large scale. IMCD presents itself as a promising method due to its favourable functional properties and potential for commercial scalability, although it is not yet available for industrial-scale applications. Further research should explore the potential of IMCD on an industrial scale to facilitate the commercial production of high-value extracts from food crops.

Currently, no study has reported the impact of drying on phenolic compounds and the antioxidant activity of banana inflorescence extract. Therefore, this study contributes valuable knowledge on the quantification of these bioactive compounds using different drying methods, which can be useful for food and pharmaceutical applications. Moreover,

this study developed process variables for IMCD for banana inflorescence. In this study, the extraction of bioactive compounds was carried out using Accelerated Solvent Extraction (ASE), which is a green extraction method. This method demonstrates significant energy, solvent, and time savings, which are linked with sustainability and energy conservation. ASE uses high pressure and temperature conditions to expedite the extraction process, significantly lowering energy requirements compared to traditional methods. This enhanced efficiency translates into substantial energy savings, making ASE a more sustainable and cost-effective solution for industries. By optimising the solvent use and enhancing recovery processes, ASE supports the creation of closed-loop systems where materials are continually recycled and reused, thereby reducing the environmental footprint of industrial activities. These scientific methods play a vital role in promoting circular economy principles and are crucial for achieving overall environmental and economic sustainability.

In summary, this study highlights the functional properties of banana inflorescence dried using various methods, with a particular focus on the cost-effective and energy-efficient IMCD technique. Additionally, the research introduces a novel protocol for the extraction and preservation of bioactive compounds from banana inflorescence, employing ASE. Furthermore, it quantifies the different phenolic compounds preserved across the drying methods. These findings significantly contribute to the growing body of knowledge on banana inflorescence, paving the way for future applications of bioactive compounds in the food industry, particularly in the development of functional food ingredients. The development of functional food ingredients from banana inflorescence using energy-saving drying methods and Accelerated Solvent Extraction not only enhances the efficiency of bioactive compound recovery but also significantly contributes to energy conservation and the circular economy. Embracing such innovative technologies is essential for transitioning towards a more sustainable and resilient future. These findings support the potential utilisation of banana inflorescence in functional food and medicinal product development, aligning with Sustainable Development Goals 3 (Good Health and Wellbeing) and 12 (Responsible Consumption and Production).

Author Contributions: N.S.—Conceptualisation, methodology, software analysis, formal analysis, writing—original draft presentation, visualisation, and investigation. I.O.—Supervision, resources, and writing—review and editing. M.H.—Supervision and methodology. A.K.—Conceptualisation, supervision, resources, writing—review and editing, and project administration. All authors have read and agreed to the published version of the manuscript.

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