Food Production, Processing and Nutrition

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Physical, functional and bioactive properties of microencapsulated powders from banana pseudostem and inflorescence extracts

K. S. Gayathry[1*] and Jenny Ann John[1]

Abstract

Application of agricultural by-products in the functional food and beverage industry is currently gaining prominence. Banana (*Musa* spp) is a popular tropical fruit with global production of 124.97 million tonnes. The banana production industry contributes to large amount of solid waste/ banana by-products, such as, pseudostem and inflorescence. *Palayankodan (Musa × paradisiaca Mysore AAB group), Nendran (Musa × paradisiaca AAB group) and Njalipoovan (Musa × paradisiaca AB group)* are three popular and common cultivars in Kerala, a state in South India. The present study was aimed to extract the potential bioactive compounds from the pseudostem and inflorescence of the above-mentioned cultivars and to standardise the process of microencapsulation using spray drying. Ultrasonication assisted extraction using ethanol as solvent was carried out. The extract and wall material parameters were standardised for microencapsulation. The encapsulated powders were analysed for encapsulation yield, retention efficiency, physical properties, phytochemical composition, antioxidant potential and anti-diabetic activity. The encapsulation yields and retention efficiencies of the encapsulated powders were found to be approximately 75 and 70.51%, respectively. Results revealed that the powders exhibited lower bulk density, good solubility and reconstitutability. Scanning electron microscopy was also conducted to reveal the particle morphology. All the powders exhibited smooth, spherical shape, with no pores. The phenolic and flavonoid contents of the encapsulated pseudostem and inflorescence extract powders ranged from 2.75 to 3.13 mg GAE/ g of powder and 34.83 to 46.67 mg QE/g of powder, respectively. The present study also reported the in vitro bioactive properties, in terms of antioxidant and anti-diabetic activities of the encapsulated powders. The HPLC analysis of the microencapsulated powders revealed the presence of gallic acid, protocatechuic acid, trans cinnamic acid, trans ferulic acid, epicatechin and syringic acid. It is clear from the study that the encapsulated powders from banana by-products have a great potential to be utilised by the functional food industry.

Keywords Banana by-products, Encapsulation, Physical properties, Particle morphology, Antioxidant, Anti-diabetic

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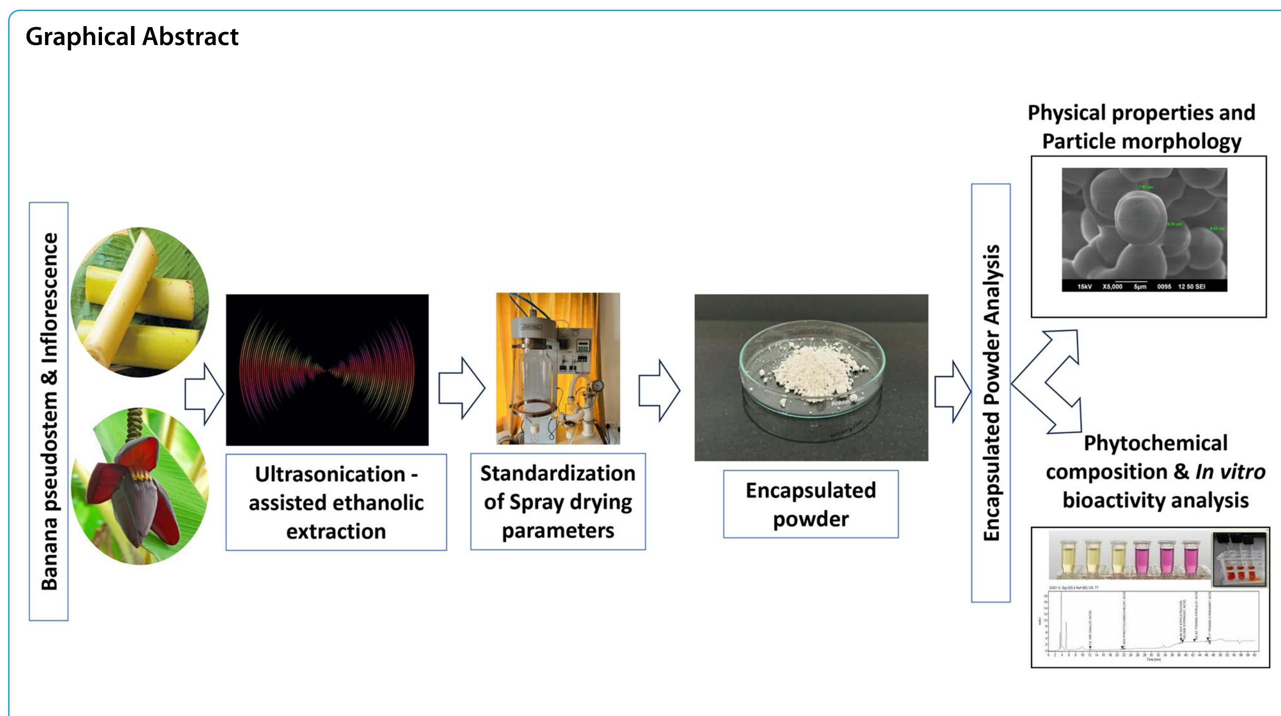

Background

Agricultural waste valourisation is an upcoming strategy in the functional food industry. Banana is a very popular tropical fruit. It is estimated that, banana cultivation creates approximately 4 tonnes of biomass wastes per each tonne of fruit harvested. Several researchers have identified the nutraceutical properties of banana pseudostem and inflorescence. Hence, these banana by-products could be identified as promising sources of bioactive compounds by the functional food industry. However, these bioactive compounds are unstable and may be organoleptically unacceptable. The process of microencapsulation can address this problem. Spray drying is one of the most cost-effective and feasible process for encapsulation. There is also a need to standardise the process of microencapsulation and analyse the bioactive potential of the powders for further food applications.

Introduction

Functional foods and beverages are gaining acceptance and popularity in the recent years. Functional food is a broad term which includes convenient foods, modified foods, dietary supplements and fortified products such as, baked goods, cereals, confectionaries, dairy based products, fruit and vegetable products, meat products and beverages, among others. At present, functional foods are conquering the hearts of the population and thereby, markets. The increased occurrence of diseases due to hectic, demanding life styles; awareness regarding healthy, holistic routines; higher cost of health care and competition among food producers are some of the relevant reasons that supplemented to the growth of functional food industry (Cong et al., 2020; Corbo et al., 2014; Shori et al., 2019). The concept, 'food as medicine' is getting immense recognition, hence contributing to the importance of functional foods in day-to-day life. In addition, researchers are exploring the prospects of utilising agro by-products owing to the considerable presence of bioactive phytochemicals and cost effectiveness. Moreover, a relatively new idea called 'combination therapy' is in focus, in which the utilization of phytonutrients along with commercial drugs are encouraged to address various lifestyle diseases, due to the increased healthcare cost as well as possible side effects of synthetic drugs (Prabhakar et al., 2014). Subsequently, there is a possibility of utilization of potential phytochemicals from agro by-products by the functional food and nutraceutical industry, which in turn will lead to the management of diseases such as diabetes by combination therapy.

Value addition from agricultural by-products is an upcoming strategy and an area where several studies have been reported. Agricultural by-products are considered as a promising raw material for the generation of various value-added products like biogas, bioethanol, enzymes, biofertilizer, animal feed vitamins and antioxidants. (Lim & Matu, 2015; Ravindran et al., 2018; Vodnar et al., 2019). They are also rich in bioactive, components, that can be

used as an alternate nutrient source in functional foods. Furthermore, utilization of these by-products will reduce the cost of raw materials, as well as will aid in the effective management of their disposal.

Banana by-products are excellent sources of phytochemicals, yet underutilized (Reddy & Hemachandran, 2014). Around 60% of banana biomass is left as waste (Alzate et al. 2021) in which a major portion is banana pseudostem and inflorescence (Ramu et al., 2017). Traditionally, pseudostem and inflorescence are used in ethnic cuisines as well as medicines for various ailments. Several researches have also undertaken measures to extract the potential bioactive components from both the pseudostem and inflorescence and to establish their nutraceutical properties (Aiemcharoen et al., 2022; Chiang et al. 2021; Ramu et al., 2022; Muchahary & Deka, 2021; Ravindran et al., 2021). Hence, these valuable bioactive components can be successfully used by the food as well as the nutraceutical industry. However, it is essential to ensure the proper delivery of the components in to the food system without affecting the acceptability and the bioavailability of the matrix. This can be addressed by the technique of encapsulation.

Microencapsulation can be defined as a process of creating a wall around the core material to avoid chemical and physical reactions and to maintain the biological, functional and physicochemical properties of the core materials (Bakry et al., 2016). Presently, the concept of microencapsulation is gaining importance in food industry along with increased relevance of the concept of functional foods. Functional foods contain various bioactive compounds which are either highly susceptible to harsh environment in processing or intestinal conditions or these compounds may impart undesirable flavour/aroma. Bioactive compounds which when released at target site at suitable time can result in surprising health benefits. Encapsulation helps in preservation of components from unwanted exposure inside and outside the body, improves stability of active ingredient or combining two such ingredients in a formulation; masks flavours and odours that are not appealing and results in timely or extended release of functional compounds (Desai & Park 2005). Microencapsulation can be accomplished by different techniques. Among them, spray drying is one of the simplest, fastest, most feasible and cost-effective technique (Delshadi et al., 2020; Piñón-Balderrama et al., 2020; Assadpour & Jafari 2019). Moreover, spray dried products have good quality and stability (Anandharamakrishnan 2014; Gharsallaoui 2007).

There are limited studies reported on the encapsulation of bioactive compounds from the extracts of banana pseudostem and inflorescence as well as physical and functional analysis of the encapsulated powders. *Palayankodan (Musa × paradisiaca Mysore AAB group), Nendran (Musa × paradisiaca AAB group) and Njalipoovan (Musa × paradisiaca AB group)* are three popular and common cultivars in Kerala, a state in South India. The present study was an attempt to extract bioactive components from the pseudostem and inflorescence of above- mentioned native cultivars and to standardise the process to encapsulate the extracts using spray drying. The encapsulated powders were analysed for encapsulation yield and retention efficiency, physicochemical properties, phytochemical composition, antioxidant potential and anti-diabetic activity. Scanning electron microscopy analysis was also carried out to observe the particle morphology of the microencapsulated powders.

Materials and methods

Materials

The pseudostem and inflorescence of *Palayankodan, Nendran and Njalipoovan* cultivars were collected from a local farm in Ernakulam district, Kerala, India. Reagents namely 2,2-Diphenyl-1-picrylhydrazyl (DPPH), 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) ($ABTS^{\cdot}$), α – amylase enzyme from porcine pancreas and α – glucosidase from *Saccaromyces cervisiae* were purchased from Sigma Aldrich, India. All the other chemicals used for different assays, namely, sodium carbonate, aluminium chloride, silver nitrite, sodium hydroxide, gallic acid, quercetin, trolox, potassium ferricyanide, trichloroacetic acid, ferric chloride, dinitrosalicylic acid, acarbose, 3 mM 4-Nitrophenyl-β-D- glucopyranoside, were of analytical grade.

Methods

Preparation of pseudostem and inflorescence

The present study used pseudostem 'tender core' along with two to three immediately surrounding layers. The inflorescence was taken as a whole after removing the outer sheath. The raw materials were cut into small pieces. Browning of the pseudostem and inflorescence pieces were minimized by dipping in 0.2% citric acid for 30 min (Ravindran et al., 2021). The raw materials were tray dried at 45 °C for 24 h (Saravanan & Aradhya, 2011) after removing the citric acid solution. The dried pieces were ground fine in a blender. Six different samples of dried pseudostem and inflorescence from the three different cultivars, namely *Palayankodan*, *Nendran* and *Njalipoovan* were obtained and were stored for extraction.

Extraction with ethanol

Ultrasound assisted extraction was carried out following the method outlined by Albishi et al. (2013). Preliminary trials were conducted to identify the best extraction

solvent for pseudostem and inflorescence. The pseudostem and inflorescence, were extracted with 60% and 80% ethanol, respectively. Briefly, 10 g of samples were extracted with 150 mL suitable extraction solvent at room temperature (27 ± 2 °C) for 20 min in the ultrasonicator bath (50 kHz), filtered and concentrated in a rotary evaporator at a temperature of 40 ± 2 °C under vacuum to obtain 6 different extracts. The phenolic profile, phytochemical composition and bioactive properties of the extracts have been reported previously (Gayathry & John, 2023). In the present study these extracts were further encapsulated by spray drying and were analysed.

Microencapsulation of the extracts

Spray drying was the technique employed for microencapsulation. A combination of maltodextrin (DE 18) and gum arabic was used as the wall material.

Spray drying conditions The process was carried out in a lab scale mini spray dryer (Techno Search Process and Systems, Mumbai, India) following the method outlined by Tan et al., (2015a, 2015b) with slight modifications. The inlet temperature and outlet temperature were kept constant and maintained at 150 ± 2 °C and 90 ± 2 °C. The atomisation pressure of 1 bar and the feed flow rate of 4 mL/min were also maintained. The outlet temperature was controlled by the feed flow rate. The spray drying conditions were kept constant for all trials conducted.

Standardisation of extract and wall material parameters for encapsulation The ratio of the maltodextrin and gum arabic in the wall material stock solution (MD:GA), the total concentration of maltodextrin and gum arabic in the wall material stock solution (C) and the ratio of extract to wall material in the feed solution (E: W) were the factors which affected the yield, efficiency as well as the quality of the powder. Preliminary trials were conducted for the standardisation of these parameters in order to maximise the encapsulation yield and the retention of bioactive compounds after the process. Table 1 shows the different combinations of MD:GA, C and E: W for the standardisation of each of these parameters.

The feed solutions prepared were spray dried and the powders obtained were analysed for yield and retention of phenolics and flavonoids (TPC Retention and TFC Retention). Initially, trials were conducted to select the suitable ratio of maltodextrin (MD) and gum arabic (GA) in the wall material solution. During these experiments, the other two parameters namely C and E: W were kept constant at 30% and 1:1, respectively (Table 1).

Once the ratio of MD:GA was selected, subsequent trials were conducted with different concentrations of wall material stock solution. During these trials, E: W was kept constant at 1:1. Finally, the suitable ratio of extract to wall material was also determined. Previously optimised combination of MD: GA and C were used during these trials.

The three parameters namely ratio of the maltodextrin and gum arabic in the wall material stock solution (MD:GA), the total concentration of maltodextrin and gum arabic in the wall material stock solution (C) and the ratio of extract to wall material in the feed solution (E: W) were standardised from the above-mentioned trials and this resulted combination was further used for the preparation of feed solution for microencapsulation of extracts.

Preparation of feed solution Suitable amount of the extracts was mixed well with the coating material as per the ratio obtained after standardisation. The solution was then thoroughly dispersed using a Probe Ultrasonicator (50 kHz) for 20 min at room temperature to obtain the feed solution for spray drying. Each time, the prepared feed solution was analysed for the total solids content by gravimetric method (AOAC 2005). The microencapsulation process was carried out by spray drying to obtain six different encapsulated powders of pseudostem and inflorescence extracts from three cultivars. The powders were collected and kept in previously weighed sealed containers at room temperature for further analysis. All experimental trials for the preparation of encapsulated powders were conducted in duplicate.

Table 1 Combinations of MD:GA, C and E: W for standardisation of each parameter

Parameters	Standardisation of MD:GA					Standardisation of C			Standardisation of E: W	
Trials	I	II	III	IV	V	VI	VII	VIII	IX	X
MD:GA	1:0	1:1	2:1	3:1	4:1	1:1	1:1	1:1	1:1	1:1
C	30	30	30	30	30	20	30	40	30	30
E: W	1:1	1:1	1:1	1:1	1:1	1:1	1:1	1:1	1:1	1.5:1

MD GA—Ratio of maltodextrin and gum arabic, C—Total concentration of wall material solution, *E* W—Ratio of extract to wall material solution

Encapsulation yield and retention efficiency

Encapsulation yield was calculated as the ratio of the dry weight of the powder collected to the dry weight of the feed solution (total solid content of the feed solution) and expressed as percentage (Maia et al., 2019).

$$Encapsulation\ yield\ (\%) = \frac{Dry\ weight\ of\ the\ powder}{TS\ of\ feed} \times 100$$

Retention efficiency was calculated according to Piacentini (2016) with slight modification.

$$Retention\ efficiency\ (\%) = \frac{Wp}{Wf} \times 100$$

Where, Wp and Wf is the phenolic content in the encapsulated powder and feed, expressed as mg GAE/assay, respectively.

Physical properties of the encapsulated powder

Water activity Water activity was measured using *Lab*Swift- aw, Novasina AG, Switzerland at ambient temperature.

Bulk density, tapped density and particle density Bulk and tapped densities were measured by following the standard procedures. A known amount of encapsulated powder was taken in a 10 mL graduated measuring cylinder and the volume occupied by the powder was noted. Bulk density was calculated as

$$\rho B = \frac{W}{V}$$

Where, ρB = Bulk density, W = weight of the powder, V = volume of the powder

The same sample taken for bulk density was tapped in a constant rate for 5 min (32 taps approximately per minute) and the tapped volume was noted. Tapped density was calculated as

$$\rho T = \frac{W}{V}$$

Where, ρT = Tapped density, W = weight of the powder, V = volume of the powder

Particle density was calculated according the method outlined by Seth et al. (2017). Briefly, 1 g of the encapsulated powder was taken in a 10 mL graduated measuring cylinder. 5 mL of petroleum ether was added carefully to the cylinder and shaken well to ensure that the particles are suspended. Finally, 1 mL of petroleum ether is added through the sides of the measuring cylinder to wash down the particles attached to the wall. The particle density is expressed in percentage and is calculated by the formula,

$$\rho P = \frac{Weight\ of\ the\ powder}{Total\ volume\ of\ the\ suspended\ particles\ and\ petroleum\ ether\ (mL) - 6} \times 100$$

Flowability and cohesiveness The flowability and cohesiveness for the encapsulated powder were estimated in terms of Carr's Index (CI) and Hausner ratio (HR), respectively. The CI and HR for the powders were calculated from bulk and tapped density by the following formulae (Seth et al. 2017),

$$CI = \frac{\rho T - \rho B}{\rho T} \times 100$$

$$HR = \frac{\rho T}{\rho B}$$

Where, ρB is bulk density and ρT is tapped density.

Solubility, wettability and dispersibility of the encapsulated powders Solubility of the encapsulated powders was calculated according to Seth et al. (2017). Briefly, 1 g of powder was mixed with 100 ml of distilled water and the mixture is thoroughly mixed. 50 ml of the solution is transferred to centrifuge tubes followed by centrifugation for 5 min at 3000 rpm. The system is kept undisturbed for 30 min after which 25 ml of supernatant solution was transferred to previously weighed petriplates. The plates are oven dried at 105 °C for 4 h. Weight difference was noted and solubility was expressed as percentage.

Dispersibility was evaluated based on the formula given by Seth et al. (2017). 1 g of powder sample was thoroughly mixed with 10 ml of distilled water. The reconstituted powder was filtered and the solution was transferred to previously weighted petriplates. The plates were oven dried at 105 °C for 4 h. Dispersibility was calculated according to the formula

$$Dispersibility\ (\%) = \frac{(10 + a)\ X\ \%TS}{aX\,\frac{(100-b)}{100}}$$

Where, 'a' is the amount of the encapsulated powder taken in g, 'b' is the moisture content in the powder and 'TS' is the total solid content in the reconstituted powder.

Wettability is the time required by 1 g of the encapsulated powder, placed on the water surface to penetrate completely into 400 ml of distilled water at room temperature, without stirring. Wettability was measured according to Seth et al. (2017) and was expressed in seconds.

Particle morphology of the encapsulated powders

The particle morphology was analysed through scanning electron microscope, JEOL JSM – 6390LV, Tokyo, Japan. The samples were placed on the sample holder (adhesive carbon tape fixed over brass stub) and over-coated with gold using a JFC 1600 auto fine coater machine. The SEM measurements were performed at 15 and 20 kV accelerating voltage. Different magnifications were used as indicated on the images.

Phytochemical composition of the micro encapsulated powders

Total Phenolic content (TPC) The total phenolic content was evaluated by Folin Ciocalteu method, according to the method outlined by Singleton and Rossi (1965), with slight variation, using gallic acid as standard. 0.5 mL of Folin Ciocalteu's phenol reagent was added to 0.5 mL of standard/the reconstituted powder sample taken in test tubes. Saturated solution of sodium carbonate was added to neutralize the mixture, followed by 10 mL of distilled water. After mixing in a vortex, the contents in the tubes were kept in dark for 45 min and were centrifuged for 5 min at 4000 g. Absorbance of supernatant was taken at 725 nm against a reagent blank. The TPC of each sample was calculated using standard curve and the the results were expressed as mg of gallic acid equivalent per gram of powder (mg GAE/g of powder).

Total Flavonoid Content (TFC) Aluminium chloride colorimetric assay was performed to determine the total flavonoid content by Zhishen et al. (1999). 1 mL of reconstituted powder sample or standard was mixed with 4 mL of distilled water in a test tube to which 0.5 mL of 5% silver nitrite solution was added. The mixture was incubated for 5 min and was added with 0.3 mL 10% aluminum chloride. Further, 2 mL of 1 M sodium hydroxide was added me after incubation for 6 min. The total volume was made up to 10 mL using distilled water. The absorbance was measured against a reagent blank at 510 nm. Quercetin was taken as the standard and the TFC was expressed as mg Quercetin equivalent per gram of powder (mg QE/ g of powder).

Phenolic profile of the encapsulated powders by HPLC analysis

The encapsulated powder samples were prepared in HPLC grade methanol by dissolving suitable concentrations (2000 ppm). HPLC apparatus (Agilent Technologies, 1260 Infinity II) with DAD was used for the separation. The column used was a 110 Å250 mm × 4.6 mm i.d. 5 µm particle size, C18 (Phenomenex Gemini). A binary system consisting of 0.1% aqueous orthophosphoric acid (Solvent A) and 0.1% orthophosphoric acid in methanol (Solvent B) was used for performing gradient elution. The gradient applied were 0 min, B 8%; 6.5 min B 10%; 16 min B 12%; 30 min B 25%; 31 min B 30%; 50 min B 90%; 50.8 min B 100%; 54 min B 8% at a flowrate of 0.8 mL/min. The injection volume was 50 µl and the wavelengths used for detection was 225 nm. Identification and quantification of the phenolic compounds were done by comparison with commercially available standards.

Antioxidant properties of the encapsulated powders

DPPH radical scavenging assay The DPPH free radical scavenging activity of the reconstituted powder samples were measured by using method outlined by Feng et al. (1998). 2 mL of the sample was mixed with equal amount of ethanol followed by 250 µl of 1 mM DPPH solution. The contents were incubated in dark for 30 min. Absorbance was measured at 514 nm. A control blank was also maintained without extract. The percentage inhibition was calculated according to the equation given below: -

$$\%Inhibition = \frac{A_0 - A_1}{A_0} \times 100$$

Where, A_0 = Absorbance of the control

A_1 = Absorbance of the extract/standard

The result is expressed as half maximal effective concentration (EC_{50}) value which is the effective concentration to obtain a 50% antioxidant effect. Gallic acid was used as the standard.

ABTS free radical scavenging activity assay ABTS assay was estimated by the procedure given by Van den Berg et al. (1999), slightly modified by John & Shahidi (2010). 2.0 mM ABTS and 2.5 mM AAPH stock solutions were prepared in 0.1 M phosphate buffer saline (pH 7.4, 0.15 M NaCl). The stock solutions were mixed in equal volumes to prepare $ABTS^{\cdot+\cdot}$ The radical solution was heated for 12 min at 60 °C and stored at dark conditions away from sunlight. The solution was used within 3 h as the absorbance of the radical solution reduces with time. The powder samples and suitable dilutions of standard (Trolox) were prepared in PBS. 1.96 mL of the $ABTS^{\cdot+}$ solution was added to 40 µl of sample/standard. The absorbance of the positive blank without extract/sample was measured at 734 nm at 0 min as well as 6 min after the addition of test compound to obtain the corrected blank. The absorbance of the samples was measured after 6 min. The ABTS scavenging activity was calculated using a

standard curve and the results were expressed as microgram Trolox equivalent per mg of powder (µg TE/ mg of powder).

Ferric Reducing Antioxidant Power (FRAP) assay The method followed by Yen and Chen. (1995) was used to determine the Ferric Reducing Antioxidant Power (FRAP). 2.5 mL of 0.2 M Phosphate buffer and 2.5 mL of 1% (w/v) potassium ferricyanide mixed with 1.0 mL of sample/standard. The mixture was incubated for 20 min at 50 °C, followed by addition of 2.5 mL 10% (w/v) trichloroacetic acid (TCA). The mixture was then centrifuged for 10 min at 2000 g. 1.0 mL of supernatant was added with 2.5 mL distilled water and 0.5 mL 0.1% ferric chloride (w/v) and the absorbance was measured at 700 nm. The results were expressed in terms of microgram Trolox equivalent per g of powder (µg TE/ mg of powder).

Anti-diabetic properties of the encapsulated powders

Alpha amylase inhibition assay The in vitro α-amylase inhibition assay for the extracts was performed using the slightly modified method published by Ali et al. (2006). An enzyme preparation of 0.5 unit/mL was made by dissolving porcine pancreatic α amylase in phosphate buffer (0.02 M, pH 6.9 6.7 Mm NaCl). The substrate was starch solution (1% w/v) in buffer. 100 µl of enzyme preparation was mixed with 100 µl of sample or standard. Incubation of the solution mix was done at room temperature for 10 min followed by addition of 100 µl of the substrate. The mixture was incubated for another 10 min at room temperature. DNSA solution was prepared as described. 1 g DNSA was dissolved in 60 mL distilled water and mixed with 30 g sodium potassium tartarate. 20 mL of 2 N NaOH was added and heated at 70 °C and final volume was made up to 100 mL. The prepared DNSA solution was added to this and the reaction was stopped by boiling for 5 min. 3 mL distilled water was added once the solution was cooled. The absorbance was measured at 540 nm. The solution without sample and the solution without enzyme were kept as control blank and sample blank respectively. Acarbose was kept as the standard for the assay. Percentage inhibition at each concentration was calculated as follows.

$$\%Inhibition = \frac{[C_{blank-}\langle S - |S_{blank}\rangle] \times 100}{C_{blank}}$$

Where, C_{blank} = Absorbance of Control blank
S = Absorbance of sample or standard
S_{blank} = Absorbance of the sample blank
The results were expressed as IC_{50} value which represents the concentration at which the sample or standard exerts half of its maximal inhibitory effect.

Alpha glucosidase inhibition assay In vitro α-glucosidase inhibition assay was performed following the method outlined by Kim et al. (2011). 100 µl of yeast alpha glucosidase enzyme (0.5 unit/mL) was mixed with 100 µl phosphate buffer (pH 6.8, 0.2 M) and then, added with 100 µl test sample. The system was incubated for 15 min at 37 °C. 200 µl of 3 mM 4-Nitrophenyl-β-D- glucopyranoside (pNPG) was added. The mixture was allowed to stand for 10 min at 37 °C. The reaction was stopped by the addition of 1.5 mL 0.1 N sodium carbonate and the absorbance was measured at 405 nm. Solution without sample was used as control blank and the solution without enzyme was used sample blank. The percentage inhibition was calculated as follows;

$$\%Inhibition = \frac{[C_{blank-}\langle S - |S_{blank}\rangle] \times 100}{C_{blank}}$$

Where, C_{blank} = Absorbance of Control blank
S = Absorbance of sample or standard
S_{blank} = Absorbance of the sample blank
The results were expressed as IC_{50} value against acarbose standard.

Statistical analysis

All data were represented as mean ± standard deviation ($n = 3$). The results were determined using one-way analysis of variance (ANOVA). The statistical analysis of the data was conducted using statistical package $GRAPES_{1.0.0}$ developed by Kerala Agricultural University. The results were considered statistically significant if the $p \leq 0.05$.

Results and discussion

The results of the present study are compiled and discussed in the subsequent sections.

Standardisation of extract and wall material parameters for encapsulation

The selection of appropriate wall material, the concentration of wall material in the stock solution and the extract to wall material ratio are crucial factors which affect the functional as well as bioactive properties of the encapsulated polyphenol rich extract microcapsules (Lu et al. 2021). Trials were conducted to standardise these parameters for the encapsulation of the pseudostem and inflorescence extracts of the three cultivars of interest. For the standardisation trials, pseudostem extract of *Palayankodan* cultivar was used.

Standardisation of the ratio of maltodextrin and gum Arabic in the wall material

Several studies reported the advantages of using maltodextrin and gum arabic in combination for spray drying. These include, low viscosity, high solubility and stability

Table 2 Effect of different ratios of maltodextrin and gum arabic on yield, TPC and TFC retentions

MD: GA	Yield (%)	TPC retention (%)	TFC retention (%)
1:0	66.77^{c}	65.16^{c}	42.65^{d}
1:1	75.83^{a}	72.2^{a}	58.97^{a}
2:1	71.22^{bc}	54.5^{e}	53.38^{b}
3:1	73.41^{ab}	61.6^{d}	35.93^{e}
4:1	76.7^{a}	66.56^{b}	48.78^{c}

Values in the same column with the same superscript letter are not statistically significant from each other ($p < 0.05$)

(Gaona et al. 2022; Labuschagne 2018; Tan et al. 2015a, 2015b; Carneiro et al. 2013; Pegg & Shahidi 2007). Moreover, both the compounds complement each other well. Table 2 shows the yield, TPC and TFC retentions of the powder obtained with different ratios of MD and GA. The powder obtained with the ratio 1:1, showed the highest TPC and TFC retentions when compared with the other combinations (1:0, 2:1, 3:1 and 4:1). The ratio 4:1 gave the highest yield among the obtained powders, though statistically insignificant ($p \geq 0.5$). However, the TPC and TFC retentions were found to be significantly higher in the 1:1 than in the 4:1 ratio ($p \leq 0.5$). Hence, for the subsequent trials, the ratio of maltodextrin and gum arabic was standardised as 1:1.

Similar results were reported by Tan et al., (2015a, 2015b) while optimising encapsulation process for aqueous bitter gourd extract. The highest retention of TPC (57.85%) and TFC (50.79%) was observed for the ratio 1:1 of MD and GA. Asik et al (2021) also reported a minimum loss of phenolics and maximum process yield while using a combination of MD and GA. Ga´cina et al. (2022) also reported highest concentration and retention of phenolics and flavonoids while using MD and GA in combination, without significantly affecting the process yield.

Standardisation of the total concentration of maltodextrin and gum Arabic in the wall material

The optimum concentration of wall material in the stock solution is important to ensure the efficient encapsulation of the core along with maximum process yield. The carrier concentration has a significant effect on the process yield (Kalajahi & Ghantiha 2022). However, high carrier concentration might not necessarily result in highest retention of bioactives. Hence, in the present study, three different concentrations of wall material (20, 30 and 40%) were used for the preparation of the feed. The ratio of MD: GA was 1:1 and for the present experiment the extract to wall material ratio was kept as 1:1. Figure 1 represents the effect of wall material concentration on the yield, TPC and TFC retention.

The highest powder yield (82.38%) was obtained when wall material concentration of 40% was used in the stock solution. On the contrary, TPC and TFC retentions were significantly higher in the 30% concentration. The lowest concentration *i.e.*, 20% resulted in the lowest yield as well as lower retentions, as showed in Fig. 1.

It has been established that sufficient amount of coating material is required to encapsulate the core material to the maximum, in order to ensure the efficiency of the process. An increased amount of coating material in the present study resulted in highest process yield. Various researchers are in accordance with this report (Navidad-Murrieta 2020; Maia et al. 2019; Kalal et al.

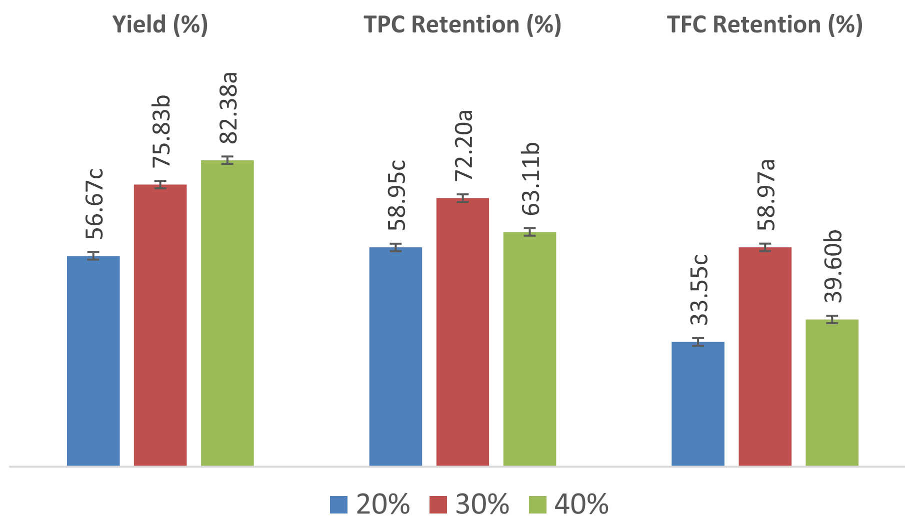

Fig. 1 Effect of wall material concentration on the yield, TPC retention and TFC retention

2016). However, an increased concentration may not result in higher retention of bioactives, which is evident from the results of the present study. Kha et al. (2014) and Mishra et al. (2014) also observed a similar trend, where lower retention of core material was reported at a higher concentration of wall material. This could be due to the possible dilution effect caused by the increased encapsulation agent concentration (Boyano-Orozco et al. 2020). Hence, the concentration of 30% was selected in the present study for subsequent experiments, owing to the better retention of bioactive compounds.

Standardisation of ratio of extract to wall material (E:W)

The effect of E: W on the yield as well as the TPC and TFC retentions during encapsulation was also investigated in the study. Two different ratios, 1.5:1 and 1:1, were considered for the trials. The total concentration of wall material solution and the ratio of MD:GA in the wall material solution were previously standardised.

The process yield, TPC and TFC retentions were 75.83%, 72.7% and 63.11%, respectively, for E: W, 1:1. However, the higher amount of extract to wall material (1.5:1), resulted in lower process yield of 74%. Similarly, lesser TPC and TFC retentions of 58.97% and 47.41%, respectively, were observed in the present study for E: W. Inadequate amounts of encapsulating agent or wall material in the feed solution could be the reason for less efficient encapsulation (Kha et al. 2014).

According to the results, MD: GA, C and E: W were standardised as 1:1, 30% and 1:1, respectively. These standardised parameters were used while preparing the feed solution for subsequent encapsulation trials.

Encapsulation yield and retention efficiency

Encapsulation yield of the standardised powders is given in Table 3. The process yields of encapsulated pseudostem and inflorescence extracts of *Palayamkodan*, *Nendran* and *Njalipoovan* cultivars were found to be approximately 75%, in the lab scale spray dryer. No significant difference ($p \geq 0.5$) in the process yield was observed among the three banana cultivars, nor between the source (inflorescence and pseudostem). This might be because the spray drying and powder recovery conditions were the same for all processes.

Encapsulation yield is a significant factor to be considered, as the yield of the powder determine the cost and effectiveness of the process. A process yield of 76.16% was reported while encapsulating banana peel extract, which is in accordance with the present study (Vu et al. 2020). However, a less process yield of 67% was also reported while encapsulating polyphenol extract of black thorn flower (Ga´cina et al. 2022). The encapsulation yield depends on the several factors, such as, spray drying conditions, physicochemical properties of wall material as well as core, ratio of core to wall material and efficacy of recovery of the powder. Interestingly, the process yield of the spray dried powder from lab scale spray dryer is not considered optimal, as the losses are more when compared to large scale spray dryers (Sosnik et al. 2015). Hence, the yield in the present study was considered as satisfactory, since a better yield can be expected in the industrial scale.

Retention efficiency was calculated as the retention of bioactive compounds in the encapsulated powders after spray drying, in comparison with the amount present in the infeed solution.

The powders showed an average retention of 69.97 ± 1.82% of total phenolic content (Table 4). The spray drying conditions and wall material parameters were same throughout all the trials. Hence, no significant difference was observed in the retention ($p \geq 0.5$). The results obtained in the present study were in accordance with Robert et al. (2010). However, Tan et al. (2015a, 2015b) reported that the retention efficiency was 95%, when bitter gourd extract was microencapsulated with the combination of 1:1 of maltodextrin and gum arabic. Vu et al. (2020) also obtained a retention efficiency of 98% for *Musa cavendish* peel extract with maltodextrin as wall material. The present study showed a lower efficiency, which could be attributed to spray drying conditions, particle

Table 3 Process yield of encapsulated pseudostem and inflorescence extracts of *Palayamkodan*, *Nendran* and *Njalipoovan* cultivars

Variety	Encapsulation Yield (%)	
	Pseudostem Extract Powder	Inflorescence Extract Powder
Palayamkodan	74.9 + 1.31	75.55 + 1.53
Nendran	75.56 + 1.44	76.58 + 3.07
Njalipoovan	75.27 + 1.49	75.80 + 1.97

Table 4 Retention efficiency of encapsulated pseudostem and inflorescence extracts of *Palayamkodan*, *Nendran* and *Njalipoovan* cultivars

Variety	Retention Efficiency (%)	
	Pseudostem Extract Powder	Inflorescence Extract Powder
Palayamkodan	70.02 ± 1.67	69.14 ± 1.68
Nendran	68.55 ± 2.22	70.31 ± 1.69
Njalipoovan	71.51 ± 1.41	70.33 ± 2.29

Table 5 Physical properties of microencapsulated banana pseudostem and inflorescence extract powders

Variety	Powder	aW at 31.3 °C	Bulk density (g/cm^3)	Tapped density (g/cm^3)	Particle density (g/cm^3)	Flowability CI	Cohesiveness HR	Solubility (%)	Dispersibility (%)	Wettability (s)
Palayamkodan	Pseudostem	0.534 ± 0.010	0.25 ± 0.01	0.49 ± 0.03	0.85 ± 0.01	48.86	1.96	93.79 ± 0.02	86.33 ± 0.02	278 ± 1.52
	Inflorescence	0.533 ± 0.008	0.26 ± 0.01	0.51 ± 0.03	0.85 ± 0.01	48.87	1.96	93.79 ± 0.03	84.23 ± 0.03	279 ± 2.51
Nendran	Pseudostem	0.538 ± 0.005	0.25 ± 0.01	0.48 ± 0.03	0.85 ± 0.01	47.84	1.92	93.79 ± 0.06	88.37 ± 0.06	273 ± 5.50
	Inflorescence	0.537 ± 0.015	0.24 ± 0.01	0.48 ± 0.02	0.85 ± 0.01	50.10	2.00	93.87 ± 0.10	86.61 ± 0.10	277 ± 2.51
Njalipoovan	Pseudostem	0.537 ± 0.003	0.25 ± 0.01	0.49 ± 0.02	0.84 ± 0.01	49.05	1.96	93.77 ± 0.01	88.05 ± 0.01	273 ± 7.50
	Inflorescence	0.533 ± 0.010	0.24 ± 0.01	0.51 ± 0.02	0.84 ± 0.01	52.35	2.10	93.78 ± 0.01	87.84 ± 0.01	274 ± 3.50

size and particle distribution. Besides, the phytochemical as well as physicochemical composition of the crude extracts in the study could also be another reason for lower retention efficiency when compared with other reported studies.

The physical properties of the microencapsulated pseudostem and inflorescence extract powders were analysed and tabulated as shown in Table 5. The measurement of physical properties of encapsulated powders was essential, owing to the fact that these properties affect and influence the behaviour of the powders during storage, handling and further processing (Fitzpatrick et al. 2004). All powder samples exhibited similar results for physical properties and were statistically insignificant ($p \geq 0.5$).

Water activity

Water activity is an important physical property which affect the food quality and shelf-life stability of the powders. The average water activity of the powder samples was 0.535 ± 0.009 at 31.3 °C. Damián et al. (2022) reported a water activity of 0.33 for gum arabic microcapsules of red banana peel extract. Vu et al. (2020) also stated a water activity of 0.3 for the microencapsulated phenolic rich extract of *Musa cavendish* peel. Similarly, another study also reported water activity of 0.328 for encapsulated blue berry waste extract, using sodium alginate as wall material (Waterhouse et al. 2017). The microcapsules in the present study showed a slightly higher water activity in comparison with the above studies. However, studies have been reported that dried powders with water activity less than 0.6 is stable, as well as microbiologically safe for storage; since the amount of free water present for biochemical reactions and microbial proliferation is less (Coronel-Aguilera et al. 2015 & Eroğlu et al. 2018). The slightly higher wateractivity for the encapsulated powders could be attributed to the inlet temperature and feed flow rate.

Bulk, tapped and particle densities

Bulk, tapped and particle denisties are physical properties, which are imperative for economical as well as functional reasons. These properties are important to establish the optimum package size to regulate transportation costs and have a profound influence on the subsequent processing of the powders (Rupp et al. 2023). They also reflect the instantisation and flowability characters of food powders. The encapsulated pseudostem and inflorescence extract powders showed an average bulk, tapped and particle densities of 0.25 ± 0.01 g/cm^3, 0.49 ± 0.03 g/cm^3 and 0.85 ± 0.01 g/cm^3, respectively.

Bulk density of non fat dry milk has a wide range, from 0.18 to 1.25 g/mL (Kalyankar et al. 2016). The bulk density obtained for the encapsulated powders in this study is well within this range. Similarly, Vonghirundecha et al. (2022), who reported the spray drying of polyphenol-rich extract from *Moringa oleifera* leaf, were also in accordance with the obtained results. However, a lower bulk, tapped and particle densities were observed in the present study when compared to another reported study on sweetened yoghurt powder (Seth et al. 2017). The bulk, tapped and particle densities of a powder changes tremendously depending on the way particles are packed, the compaction, consolidation etc. (Abdullah & Geldart 1999). Hence, no unique value can be specified for a given food powder.

Flowability and cohesiveness

Flowability of a powder indicates the ease with which the powder moves (Sharma et al. 2012). Carr's Index (CI) was calculated to express the flowability and the encapsulated powders showed a CI ratio of 48 – 52. Cohesiveness specifies the resistance to flow of the powders and is calculated as Husner's ratio (HR). The powders exhibited an HR around 2. The results revealed that all the encapsulated powders had low flowability and cohesiveness since the CI and HR were greater than 38 and 1.6, respectively (Lebrun et al. 2012).

Solubility, wettability and dispersibility

Properties of encapsulated powders, such as. solubility, wettability and dispersibility reflects the efficient reconstitution of the powders. The banana pseudostem and inflorescence extract encapsulated powders exhibited a solubility above 90%, dispersibility above 80% and an average wettability of 275 s. The results established the fact that the powders had good reconstitution properties.

Particle morphology of the encapsulated powders

The particle morphology of the encapsulated pseudostem and inflorescence powders were obtained using scanning electron microscopy (Fig. 2). The size of the powder particles was found to be less than 10 µm. The particles exhibited a smooth spherical shape, as well as wrinkled and shrunken surface, along with some concavities. Moreover, agglomeration could also be observed (Figs. 3 and 4) in all the encapsulated powders. However, pores were not observed, which ensures the prevention of degradation of the encapsulated components during processing and storage.

The wrinkles and shrunk surfaces on the particle could be due to the heat induced expansion during spray drying process and rapid cooling. Waterhouse et al. (2017) also drew a similar conclusion. The agglomeration observed might be due to factors such as, glass transition

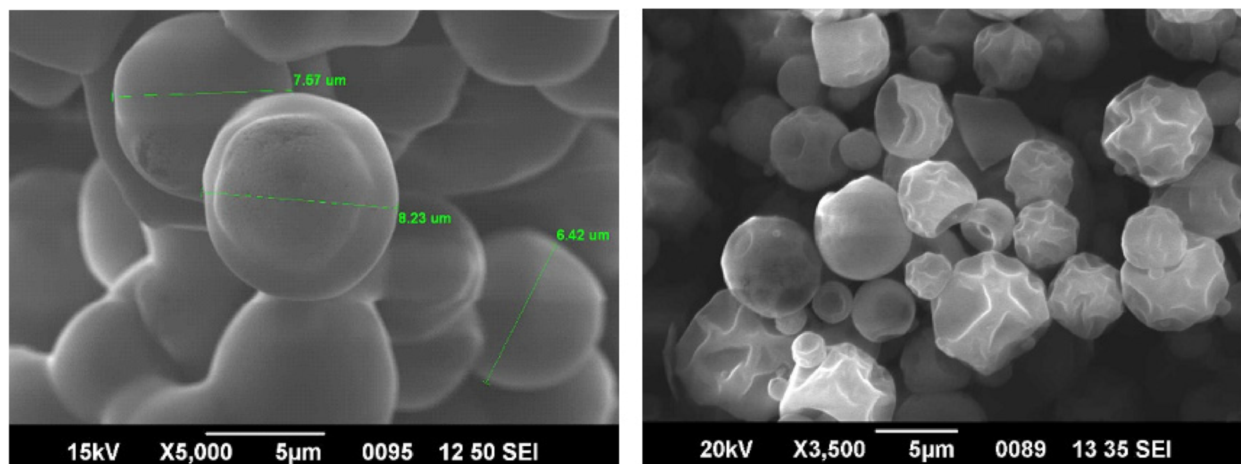

Fig. 2 SEM micrograph of encapsulated powder showing the size and shape of the microcapsules

temperature and viscoelasticity, which could be attributed to the wall materials used for encapsulation. Nevertheless, the morphology analysis of all the powders showed a spherical presentation, devoid of holes or pores. This indicates the stability of the powders during further processing and storage. It was also ensured that the bioactives are intact in the microcapsules.

Phytochemical composition of encapsulated powders

The phytochemical composition in terms of total phenolic content (TPC) and total flavonoid content (TFC) of the microencapsulated powders of pseudostem and inflorescence extracts are compiled in Table 6.

TPC of the encapsulated pseudostem and inflorescence extract powders of three cultivars ranged from 2.75 to 3.13 mg GAE/ g of powder. Statistically significant difference ($p \le 0.5$) in the values were observed among different cultivars. *Njalipoovan* cultivar showed the highest TPC in both the pseudostem and inflorescence extract microcapsules. TFC of the encapsulated pseudostem and inflorescence extract powders were found to range between 34.83 and 46.67 mg QE/g of powder. Among the powders, the *Palayamkodan* inflorescence extract encapsulated powder showed the highest value. However, among the stem extract powders, *Njalipoovan* cultivar exhibited the highest value.

The study shows that both TPC and TFC were higher in the encapsulated inflorescence extract powders than the encapsulated pseudostem extract powders, in all the three cultivars. A few recent studies on banana peel, another banana by-product, have shown higher values for TPC than in the present study. TPC content of 4.92 ± 0.3 mg GAE/g and 6 mg GAE/g DM was reported by Damián et al. (2022) and Vu et al. (2020), respectively, in the microencapsulated powders of banana peel extract. The present results also revealed that the microcapsules of banana pseudostem and inflorescence extracts showed an average retention of 70% of TPC for all the powders. This clearly indicates that the microencapsulation of pseudostem and inflorescence extracts, using a combination of maltodextrin and gum arabic, could preserve and retain these bioactive components in the powder.

Phenolic profile of encapsulated powders by HPLC analysis

Detailed HPLC analysis was performed to identify and quantify the phenolic compounds present in the microencapsulated pseudostem and inflorescence extracts of the mentioned cultivars. The phenolic compounds quantified in the encapsulated powders are listed in Table 7. Six phenolic compounds, namely, gallic acid, protocatechuic acid, trans cinnamic acid, trans ferulic acid, epicatechin and syringic acids were identified in different samples. Gallic acid was present in all samples. Protocatechuic acid was identified in all samples, except *Palayankodan* pseudostem microcapsules. Similarly, trans cinnamic acid was found in all the powders, except *Nendran* pseudostem microcapsules. Epicatechin was the major phenolic compound present in the *Njalipoovan* inflorescence microcapsules. Trans ferulic acid was only identified in the microencapsulated *Njalipoovan* inflorescence extract. Syringic acid was detected in all samples except *Palayankodan* and *Njalipoovan* pseudostem extracts.

The qualitative phenolic profile of the powders was similar to that of the extracts, which was previously investigated and reported (Gayathry & John 2023). Hence, it is clear that the microencapsulation process helps to retain the bioactive compounds in the extracts. This was confirmed by the positive results of the antioxidant and

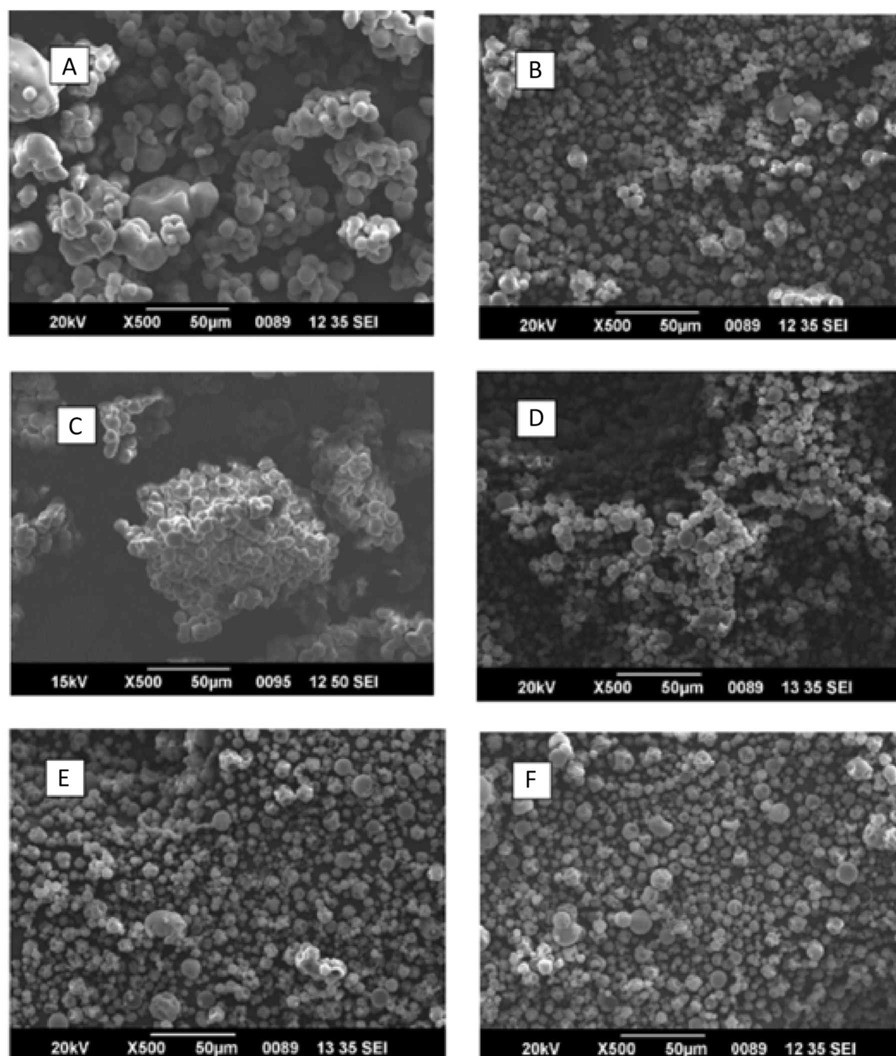

Fig. 3 SEM micrographs of encapsulated pseudostem and inflorescence powders of different cultivars. **A** *Palayamkodan* pseudostem extract encapsulated powder; **B** *Palayamkodan* inflorescence extract encapsulated powder; **C** *Nendran* pseudostem extract encapsulated powder; **D** *Nendran* inflorescence extract encapsulated powder; **E** *Njalipoovan* pseudostem extract encapsulated powder; **F** *Njalipoovan* inflorescence extract encapsulated powder

anti-diabetic properties of the encapsulated powder samples (Sect. 3.7 and 3.8). However, some degradation of the phenolic compounds was expected after spray drying, since there was no complete retention of phenolic compounds in our study (approximately 70% of phenolic retention for all the powders). Júnior et al. (2023) also reported a similar finding in the case of *ciriguela* peel microcapsules. Their report also emphasised that the liquid *ciriguela* peel extract showed the presence of some phenolic compounds which could not be detected in the microencapsulated extract powder. They opinionated that the processing conditions, such as, microencapsulation could result in some possible degradation of bioactive compounds.

Antioxidant properties of encapsulated powders

The antioxidant properties of encapsulated powders were analysed by different assays namely 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical scavenging assay, 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) free radical scavenging assay and ferric reducing antioxidant power (FRAP).

Table 8 shows the antioxidant activities of the microencapsulated powders. The results revealed that the pseudostem extract microcapsules showed better scavenging activity in DPPH and $ABTS^{\cdot}$ scavenging assays. Interestingly, inflorescence extract microcapsules exhibited better reducing activity. This pattern was evident in the microcapsules of all the different

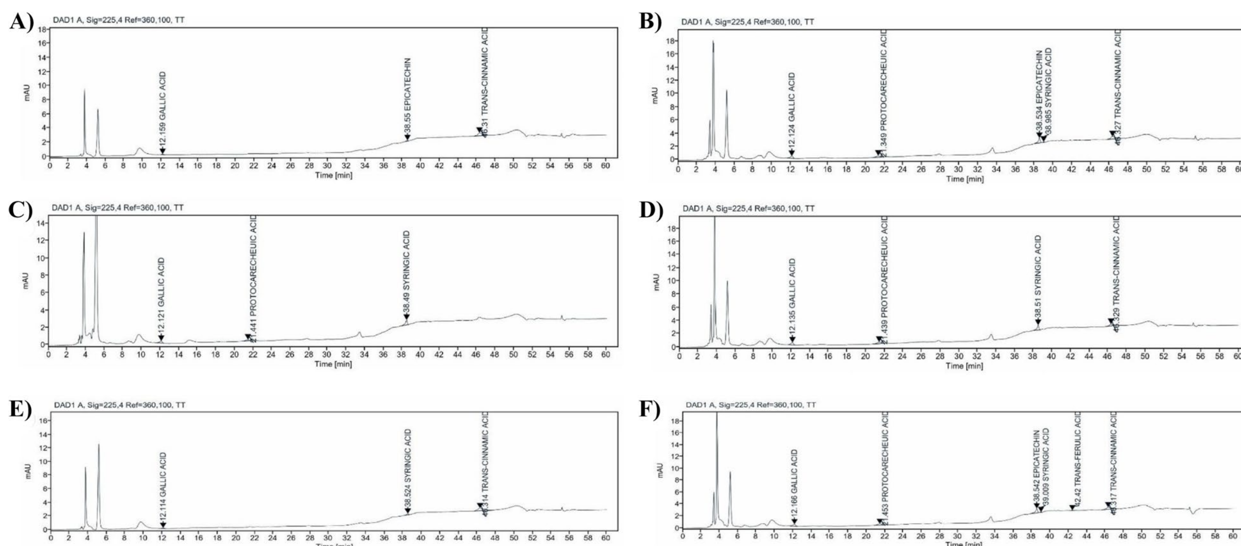

Fig. 4 Chromatograms of encapsulated pseudostem and inflorescence powders of *Palayankodan*, *Nendran* and *Njalipoovan* cultivars. **A** *Palayamkodan* pseudostem extract encapsulated powder; **B** *Palayamkodan* inflorescence extract encapsulated powder; **C** *Nendran* pseudostem extract encapsulated powder; **D** *Nendran* inflorescence extract encapsulated powder; **E** *Njalipoovan* pseudostem extract encapsulated powder; **F** *Njalipoovan* inflorescence extract encapsulated powder

Table 6 Phytochemical composition of microencapsulated powders of pseudostem and inflorescence

Variety	Pseudostem powder		Inflorescence powder	
	TPC[1]	TFC[2]	TPC[1]	TFC[2]
Palayankodan	2.72 ± 0.08^{c}	34.83 ± 0.58^{c}	3.08 ± 0.02^{b}	46.67 ± 0.71^{a}
Nendran	2.75 ± 0.02^{b}	34.96 ± 0.58^{b}	2.94 ± 0.01^{c}	35.55 ± 0.53^{c}
Njalipoovan	2.95 ± 0.01^{a}	35.78 ± 0.53^{a}	3.13 ± 0.02^{a}	41.20 ± 0.19^{b}

Values in the same column with the same superscript letter are not statistically significant from each other ($p > 0.05$)

TPC Total Phenolic Content, *TFC* Total Flavonoid content, *GAE* Gallic acid equivalent, *QE* Quercetin equivalent

[1] mg GAE/g of powder; [2]mg QE/g of powder

cultivars. Amongst the microcapsules from different cultivars, the encapsulated pseudostem and inflorescence extract powders of *Njalipoovan* cultivar exhibited better antioxidant activity in all the assays when compared to *Palayamkodan* and *Nendran* cultivars. The EC_{50} values for the DPPH radical scavenging assay of the encapsulated powders ranged from 0.62 to 0.92 mg/mL as compared to gallic acid standard (0.67 μg/mL). The pseudostem and inflorescence extract microcapsules from *Njalipoovan* variety showed an EC_{50} value of 0.62 and 0.79 mg/mL, respectively. Likewise, $ABTS^{\cdot}$ radical scavenging assay also revealed the better antioxidant potential for powders from *Njalipoovan* pseudostem and inflorescence extracts. A similar result was observed in the FRAP assay, where *Njalipoovan* pseudostem and inflorescence microcapsules showed the

Table 7 Phenolic profile of microencapsulated pseudostem and inflorescence extract powders of *Palayankodan*, *Nendran* and *Njalipoovan* cultivars

Compounds	Concentration (μg/ml)					
	Palayankodan		***Nendran***		***Njalipoovan***	
	Pseudostem	Inflorescence	Pseudostem	Inflorescence	Pseudostem	Inflorescence
Gallic acid	0.009	0.077	0.053	0.075	0.019	0.08
Protocatechuic acid	-	0.085	0.041	0.09	0.058	0.091
Syringic acid	-	0.017	0.191	0.234	-	0.016
Trans cinnamic acid	0.093	0.081	-	0.033	0.117	0.068
Epicatechin	0.055	0.462	-	-	-	0.512
Trans ferulic acid	-	-	-	-	-	0.011

Table 8 Antioxidant activities of pseudostem and inflorescence encapsulated powders of *Palayankodan, Nendran and Njalipoovan* cultivars

Variety	DPPH (EC_{50}—mg/mL)		ABTS (μg TE/mg of powder)		FRAP (μg TE/mg of powder)	
	Pseudostem	Inflorescence	Pseudostem	Inflorescence	Pseudostem	Inflorescence
Palayankodan	0.86 ± 0.48^a	0.92 ± 0.26^a	14.06 ± 0.07^b	11.46 ± 0.31^b	0.09 ± 0.01^b	0.10 ± 0.03^b
Nendran	0.72 ± 0.06^b	0.84 ± 0.16^b	13.26 ± 0.10^c	10.07 ± 0.85^c	0.06 ± 0.05^c	0.09 ± 0.03^c
Njalipoovan	0.62 ± 0.28^c	0.79 ± 0.24^c	20.48 ± 0.8^a	15.20 ± 0.8^a	0.13 ± 0.03^a	0.15 ± 0.02^a

Values in the same column with the same superscript letter are not statistically significant from each other ($p \geq 0.05$)

DPPH 2,2-diphenyl-1-picrylhydrazyl, *ABTS* 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid), *FRAP* Ferric Reducing Antioxidant Power, *TE* Trolox equivalent

best activity. As mentioned in the preceding Sect. (3.5), the phytochemical composition of the powders also revealed higher TPC and TFC content in the *Njalipoovan* cultivar (Table 6), in comparison with other cultivars. Hence, the better antioxidant potential could be correlated.

The present study reported a higher antioxidant potential in terms of DPPH scavenging and FRAP assays, for both pseudostem and inflorescence encapsulated powders in comparison with microencapsulated *Musa cavendish* peel extract (Vu et al. 2020). Lourenço et al. (2020) reported similar results for DPPH and FRAP assays for pineapple peel extract encapsulated powder. Similarly, the ABTS radical scavenging activity of the encapsulated powders in the present study was comparable with that of microencapsulated *Moringa oleifera* leaf polyphenol-rich extract (Vonghirundecha et al. 2022). The present study confirmed that the encapsulated banana pseudostem and inflorescence powders have antioxidant properties comparable to other agricultural by-products.

Anti-diabetic properties of encapsulated powders

Diabetes is a condition that is prevailing among population and is considered as a life style disease by World Health Organization (WHO 2023). Phenolics and flavonoids have been established as hypoglycaemic agents (Bacanli et al. 2019; Sun et al. 2020). TPC and TFC in the microencapsulated pseudostem and inflorescence extract powders were analysed in the present study. Antioxidant property analysis also revealed good results. Hence, the study also aimed to evaluate the anti-diabetic activities of the powders by α-amylase and α-glucosidase inhibition assays.

Table 9 shows the half minimal inhibitory concentration of the encapsulated powders for the α-amylase and α-glucosidase inhibition assays. Acarbose was used as standard. The results of the present study revealed that the powders of the three cultivars had promising hypoglycaemic potential, when compared to acarbose standard ($IC_{50} = 81.04 \pm 20.12$ μg/mL and 90.38 ± 38.17 μg/mL for α-amylase and α-glucosidase inhibition assays, respectively). The IC_{50} values of the encapsulated powders ranged from 149.88 ± 22.03 μg/mL to 212.23 ± 18.74 μg/mL for α-amylase inhibition assay; and from 773.89 ± 9.28 μg/mL to 1074.21 ± 143.65 μg/mL for α- glucosidase inhibition assay. Interestingly, the pseudostem microcapsules of all the cultivars showed a better α-amylase inhibition than the inflorescence microcapsules. On the other hand, in the α- glucosidase inhibition assay, the inflorescence extract powders showed the better anti-diabetic potential in comparison with pseudostem encapsulated powders. In both the assays, the microencapsulated powders of pseudostem and inflorescence extract of *Njalipoovan* cultivar showed better anti-diabetic activity in comparison with the other two cultivars.

Sylla et al. (2021) reported an IC_{50} value for anti-diabetic assays ranging from 72.28 ± 0.16 μg/mL to

Table 9 Half minimal inhibitory concentration (IC_{50} μg/mL) for α-amylase and α-glucosidase inhibition assays of micro encapsulated pseudostem and inflorescence powders of *Palayamkodan, Nendran* and *Njalipoovan* cultivars

Variety	IC_{50} (μg/ml) α-amylase inhibition assay		IC_{50} (μg/ml) α-glucosidase inhibition assay	
	Pseudostem	Inflorescence	Pseudostem	Inflorescence
Palayamkodan	156.90 ± 55.77^b	212.23 ± 18.74^c	1074.21 ± 143.65^a	801.54 ± 77.18^b
Nendran	196.55 ± 12.11^a	195.17 ± 7.12^a	1044.23 ± 13.31^b	939.44 ± 8.31^a
Njalipoovan	149.88 ± 22.03^c	195.57 ± 29.44^b	1027.07 ± 48.03^c	773.89 ± 9.28^c

Values in the same column with the same superscript letter are not statistically significant from each other ($p \geq 0.05$)

Table 10 Phytochemical composition and bioactive properties of banana by-products' extracts before and after encapsulation

Variety	*Palayankodan*				*Nendran*				*Njalipoovan*			
	Pseudostem		Inflorescence		Pseudostem		Inflorescence		Pseudostem		Inflorescence	
	Extract	Powder	Extract	Powder	Extract	Powder	Extract	Powder	Extract	Powder	Extract	Powder
TPC (mg GAE/g)	10.62 ± 0.21	2.72 ± 0.08	15.34 ± 0.02	3.08 ± 0.02	7.26 ± 0.04	2.75 ± 0.02	7.84 ± 0.2	2.94 ± 0.01	12.16 ± 0.12	2.95 ± 0.01	14.89 ± 0.23	3.13 ± 0.02
TFC (mg QE/g)	238.51 ± 0.35	34.83 ± 0.58	180.71 ± 0.17	46.67 ± 0.71	511.37 ± 0.12	34.96 ± 0.58	428.16 ± 0.08	35.55 ± 0.53	618.96 ± 0.1	35.78 ± 0.5	565.79 ± 0.1	41.20 ± 0.2
DPPH assay EC50 (mg/ml)	0.85 ± 0.11	0.86 ± 0.48	0.92 ± 0.05	0.92 ± 0.26	0.57 ± 0.25	0.72 ± 0.06	0.64 ± 0.18	0.84 ± 0.16	0.48 ± 0.15	0.62 ± 0.28	0.6 ± 0.05	0.79 ± 0.24
ABTS assay (mg TE/g)	4.61 ± 0.28	0.14 ± 0.07	2.85 ± 0.21	0.12 ± 0.31	3.53 ± 0.31	0.13 ± 0.10	2.33 ± 0.24	0.10 ± 0.85	5.22 ± 0.77	0.20 ± 0.8	1.13 ± 0.05	0.15 ± 0.8
FRAP assay (µg TE/g)	41.36 ± 0.86	9.24 ± 0.01	80.58 ± 0.31	10.12 ± 0.03	24.26 ± 0.62	6.44 ± 0.05	54.21 ± 0.81	9.45 ± 0.03	38.30 ± 0.6	13.4 ± 0.03	62.52 ± 0.3	15.2 ± 0.02
α amylase inhibition assay IC50 (mg/ml)	0.18 ± 0.11	0.16 ± 0.50	0.39 ± 0.42	0.21 ± 0.12	0.21 ± 0.61	0.2 ± 0.02	0.76 ± 0.17	0.2 ± 0.18	0.18 ± 0.22	0.14 ± 0.07	0.22 ± 0.02	0.2 ± 0.39
α glucosidase inhibition assay IC50 (mg/ml)	0.61 ± 0.97	1.074 ± 0.14	0.23 ± 0.38	0.80 ± 0.13	0.2 ± 0.41	1.043 ± 0.48	0.4 ± 0.63	0.93 ± 0.77	0.22 ± 0.83	1.027 ± 0.38	0.31 ± 0.18	0.773 ± 0.99

1g of powder contains 50% of extract

559.57 ± 1.82 µg/mL for encapsulated polyphenols of olive pomace against acarbose standard, which is in accordance with the present study. However, a lower IC_{50} value of 4.96 mg/ml was reported for alpha glucosidase inhibition assay for encapsulated *Moringa peregrina* leaf extract (Nouri et al. 2022). From the results of the present study, it is confirmed that the microencapsulated powders of pseudostem and inflorescence extracts of the three cultivars have hypoglycaemic potential. Further, in vitro cell line studies and in vivo studies have to be undertaken in order to establish it.

Phytochemical composition and bioactive properties of banana by-products' extracts before and after encapsulation

The phenolic profile, antioxidant and hypoglycaemic potential of the extracts from banana pseudostem and inflorescence of different cultivars have been reported earlier (Gayathry & John 2023). The present study further encapsulated these extracts to enhance the shelf-stability, as well as the sensory acceptance of the extracts. The phytochemical composition and associated bioactive properties of the extracts before and after microencapsulation are summarised in Table 10. As anticipated, the phytochemical components and their activities were reduced after encapsulation, primarily due to the conditions of spray drying. Moreover, 1 g of the encapsulated powder contained only 50% of the extract, which is reflected in the results. However, taking into consideration the advantages of encapsulation, it is clear that the microencapsulated powders have a great potential to be utilised by the food industry.

Conclusion

The current study investigated the possibility of utilising the potential bioactives from banana by-products, such as, pseudostem and inflorescence of three banana cultivars, namely *Palayamkodan*, *Nendran* and *Njalipoovan*. It also aimed to microencapsulate the extract, by spray drying, to minimise the negative sensory attributes and maximise the bioavailability of the extracts. The powders showed satisfactory process yield (75%) and retention efficiency (70%) of the bioactive compounds. Scanning electron microscopy revealed that the powders had smooth spherical shape with diameter less than 10 µm. The phenolic and flavonoid contents of the powders ranged from 2.75 to 3.13 mg GAE/ g of powder and 34.83 to 46.67 mg QE/g of powder, respectively. The HPLC analysis of the powders identified and quantified gallic acid, protocatechuic acid, trans cinnamic acid, trans ferulic acid, epicatechin and syringic acid. The DPPH and ABTS scavenging assays and FRAP assay established the antioxidant activity of encapsulated powders. Interestingly, the microencapsulated inflorescence powders had a better reducing activity than the pseudostem powders for all the cultivars. The α-amylase and α-glucosidase inhibition assays confirmed that the powders are good hypoglycaemic agents in comparison with acarbose standard. From the results of the current study, it can be concluded that, microencapsulation of pseudostem and inflorescence extract using spray drying can successfully be applied by the food and nutraceutical industry. The process ensures the utilisation of potential bioactives from the banana by-products, thereby leading to valourisation. However, further in vivo and clinical studies are required to confirm and validate the functional properties of the developed powders and to evaluate their effects on human health.

Abbreviations

TPC	Total phenolic content
TFC	Total Flavonoid Content
MD	Maltodextrin
GA	Gum Arabic
TS	Total solids
SEM	Scanning Electron Microscopy
GAE	Gallic Acid Equivalent
QE	Quercetin Equivalent
DPPH	2,2-Diphenyl-1-picrylhydrazyl
ABTS	2,2′-Azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)
DNSA	Dinitro salicylic acid
pNPG	4-Nitrophenyl-β-D- glucopyranoside
CI	Carr's Index
HR	Husner's ratio
WHO	World Health Organization

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Authors' contributions
GKS prepared the draft of the manuscript. JAJ read and edited the manuscript. All authors read and approved the manuscript.

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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
Both authors declare no competing interests.

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References

Abdullah, E. C., & Geldart, D. (1999). The use of bulk density measurements as flowability indicators. *Powder Technology, 102*(2), 151–165.

Aiemcharoen, P., Wichienchot, S., & Sermwittayawong, D. (2022). Antioxidant and anti-diabetic activities of crude ethanolic extract from the banana inflorescence of musa (ABB group) namwa maliong. *Functional Foods in Health and Disease, 12*(4), 161–174.

Albishi, T., John, J. A., Al-Khalifa, A. S., & Shahidi, F. (2013). Phenolic content and antioxidant activities of selected potato varieties and their processing by-products. *Journal of Functional Foods, 5*(2), 590–600.

Ali, H., Houghton, P. J., & Soumyanath, A. (2006). α-Amylase inhibitory activity of some Malaysian plants used to treat diabetes; with particular reference to Phyllanthus amarus. *Journal of Ethnopharmacology, 107*(3), 449–455.

Alzate Acevedo, S., Díaz Carrillo, Á. J., Flórez-López, E., & Grande-Tovar, C. D. (2021). Recovery of banana waste-loss from production and processing: A contribution to a circulareconomy. *Molecules, 26*(17), 5282. https://doi.org/10.3390/molecules26175282

Anandharamakrishnan, C. (2014). Liquid-Based Nanoencapsulation Techniques. In *Techniques of Nanoencapsultaion of Food Ingredients* (pp. 29 – 41). New York: Springer. https://doi.org/10.1007/978-1-4614-9387-7_4

Asik, S., Atbakan, K. T., & Topuz, A. (2021). Optimization of spray drying condition and wall material composition for myrtle extract powder using response surface methodology. *Drying Technology, 39*(12), 1869–1882.

Assadpour, E., & Mahdi Jafari, S. (2019). A systematic review on nanoencapsulation of food bioactive ingredients and nutraceuticals by various nanocarriers. *Critical Reviews in Food Science and Nutrition., 59*(19), 3129–3151. https://doi.org/10.1080/10408398.2018.1484687

Bacanli, M., Dilsiz, S. A., Başaran, N., & Başaran, A. A. (2019). Effects of phytochemicals against diabetes. *Advances in Food and Nutrition Research, 89*, 209–238. https://doi.org/10.1016/bs.afnr.2019.02.006

Bakry, A. M., Abbas, S., Ali, B., Majeed, H., Abouelwafa, M. Y., Mousa, A., & Liang, L. (2016). Microencapsulation of Oils: A Comprehensive Review of Benefits, Techniques, and Applications. *Comprehensive Reviews in Food Science and Food Safety., 15*(1), 143–182. https://doi.org/10.1111/1541-4337.12179

Boyano-Orozco, L., Gallardo-Velázquez, T., Meza-Márquez, O. G., & Osorio-Revilla, G. (2020). Microencapsulation of rambutan peel extract by spray drying. *Foods, 9*(7), 899.

Carneiro, H. C., Tonon, R. V., Grosso, C. R., & Hubinger, M. D. (2013). Encapsulation efficiency and oxidative stability of flaxseed oil microencapsulated by spray drying using different combinations of wall materials. *Journal of Food Engineering, 115*(4), 443–451.

Chiang, S. H., Yang, K. M., Lai, Y. C., & Chen, C. W. (2021). Evaluation of the in vitro biological activities of Banana flower and bract extracts and their bioactive compounds. *International Journal of Food Properties, 24*(1), 1–16.

Cong, L., Bremer, P., & Mirosa, M. (2020). Functional Beverages in Selected Countries of Asia Pacific Region: A Review. *Beverages, 6*(2), 21. https://doi.org/10.3390/beverages6020021

Corbo, M. R., Bevilacqua, A., Petruzzi, L., Casanova, F. P., & Sinigaglia, M. (2014). Functional beverages: The emerging side of functional foods: Commercial trends, research, and health implications. *Comprehensive Reviews in Food Science and Food Safety., 13*(6), 1192–1206. https://doi.org/10.1111/1541-4337.12109

Coronel-Aguilera, C. P., & San Martín-González, M. F. (2015). Encapsulation of spray dried β-carotene emulsion by fluidized bed coating technology. *LWT-Food Science and Technology, 62*(1), 187–193. https://doi.org/10.1016/j.lwt.2014.12.036

Delshadi, R., Bahrami, A., Tafti, A. G., Barba, F. J., & Williams, L. L. (2020). Micro and nano-encapsulation of vegetable and essential oils to develop functional food products with improved nutritional profiles. *Trends in Food Science and Technology, 104*(6), 72–83. https://doi.org/10.1016/j.tifs.2020.07.004

Eroğlu, E., Tontul, İ, & Topuz, A. (2018). Optimization of aqueous extraction and spray drying conditions for efficient processing of hibiscus blended rosehip tea powder. *Journal of Food Processing and Preservation, 42*(6), e13643.

Feng, N. K., Cheng, Z. J., Lin, C. N., & Teng, C. M. (1998). Scavenger and antioxidant properties of prenylflavones isolated from Artocarpus heterophyllus. *Free Radical Biology and Medicine, 25*(2), 160–168.

Fitzpatrick, J. J., Barringer, S. A., & Iqbal, T. (2004). Flow property measurement of food powders and sensitivity of Jenike's hopper design methodology to the measured values. *Journal of Food Engineering, 61*(3), 399–405.

Gaćina, N., ElezGarofulić, I., Zorić, Z., Pedisić, S., & Dragović-Uzelac, V. (2022). Influence of Encapsulation Parameters on the Retention of Polyphenols in Blackthorn Flower Extract. *Processes, 10*(12), 2517.

Gaona, I. J. A., Fanzone, M. L., Galmarini, M. V., Chirife, J., Ferreras-Charro, R., García-Estévez, I., & Escribano-Bailón, M. T. (2022). Encapsulation of phenolic compounds by spray drying of Ancellotta and Aspirant Bouchet wines to produce powders with potential use as natural food colorants. *Food Bioscience, 50*, 102093.

Gayathry, K. S., & John, J. A. (2023). Phenolic profile, antioxidant, and hypoglycaemic potential of pseudostem and inflorescence extracts of three banana cultivars. *Biomass Conversion and Biorefinery.* 1–9.

Gharsallaoui, A., Roudaut, G., Chambin, O., Voilley, A., & Saurel, R. (2007). Applications of spray-drying in microencapsulation of food ingredients: An overview. *Food Research International, 40*(9), 1107–1121.

Horwitz, W., & Latimer, G. W. (2005). Official methods of analysis of AOAC International (Vol. 1, p. 17). Gaithersburg: AOAC international

John, J. A., & Shahidi, F. (2010). Phenolic compounds and antioxidant activity of Brazil nut (Bertholletia excelsa). *Journal of Functional Foods, 2*(3), 196–209.

Júnior, M. E. S., Araújo, M. V. R. L., Martins, A. C. S., dos Santos Lima, M., da Silva, F. L. H., Converti, A., & Maciel, M. I. S. (2023). Microencapsulation by spray-drying and freeze-drying of extract of phenolic compounds obtained from ciriguela peel. *Scientific Reports, 13*(1), 15222. https://doi.org/10.1038/s41598-023-40390-4

Kalajahi, S. E. M., & Ghandiha, S. (2022). Optimization of spray drying parameters for encapsulation of nettle (Urtica dioica L.) extract. *LWT, 158*, 113149.

Kalal, A. Y., Hiregoudar, S., Nidoni, U., Ramachandra, C., & Naik, N. (2016). Nanoencapsulation of probiotic bitter gourd juice powder. *International Journal of Agricultural Science and Research., 6*(2), 9–20.

Kalyankar, S. D., Deshmukh, M. A., Chopde, S. S., Khedkar, C. D., Lule, V. K., & Deosarkar, S. S. (2016). Milk powder. In *Encyclopedia of Food and Health* (pp. 724 – 728). Academic Press. https://doi.org/10.1016/B978-0-12-819813-1.00003-7

Kha, T. C., Nguyen, M. H., Roach, P. D., & Stathopoulos, C. E. (2014). Microencapsulation of gac oil by spray drying: Optimization of wall material concentration and oil load using response surface methodology. *Drying Technology, 32*(4), 385–397.

Kim, J. S., Hyun, T. K., & Kim, M. J. (2011). The inhibitory effects of ethanol extracts from sorghum, foxtail millet and proso millet on α-glucosidase and α-amylase activities. *Food Chemistry, 124*(4), 1647–1651.

Labuschagne, P. (2018). Impact of wall material physicochemical characteristics on the stability of encapsulated phytochemicals: A review. *Food Research International, 107*, 227–247.

Lebrun, P., Krier, F., Mantanus, J., Grohganz, H., Yang, M., Rozet, E., ... & Hubert, P. (2012). Design space approach in the optimization of the spray-drying process. *European Journal of Pharmaceutics and Biopharmaceutics*. 80(1), 226–234.

Lim, S. F., & Matu, S. U. (2015). Utilization of agro-wastes to produce biofertilizer. *International Journal of Energy and Environmental Engineering, 6*(1), 31–35. https://doi.org/10.1007/s40095-014-0147-8

Lourenço, S. C., Moldão-Martins, M., & Alves, V. D. (2020). Microencapsulation of pineapple peel extract by spray drying using maltodextrin, inulin, and arabic gum as wall matrices. *Foods, 9*(6), 718.

Lu, W., Yang, X., Shen, J., Li, Z., Tan, S., Liu, W., & Cheng, Z. (2021). Choosing the appropriate wall materials for spray-drying microencapsulation of natural bioactive ingredients: Taking phenolic compounds as examples. *Powder Technology, 394*, 562–574. https://doi.org/10.1016/j.powtec.2021.08.082

Maia, P. D., dos Santos Baião, D., da Silva, V. P. F., de AraújoCalado, V. M., Queiroz, C., Pedrosa, C., & Pierucci, A. P. T. (2019). Highly stable microparticles of cashew apple (Anacardium occidentale L.) juice with maltodextrin and chemically modified starch. *Food and Bioprocess Technology, 12*, 2107–2119.

Mishra, P., Mishra, S., & Mahanta, C. L. (2014). Effect of maltodextrin concentration and inlet temperature during spray drying on physicochemical and antioxidant properties of amla (Emblica officinalis) juice powder. *Food and bioproducts processing*, *92*(3), 252–258.

Muchahary, S., & Deka, S. C. (2021). Impact of supercritical fluid extraction, ultrasound-assisted extraction, and conventional method on the phytochemicals and antioxidant activity of bhimkol (Musa balbisiana) banana blossom. *Journal of Food Processing and Preservation, 45*(7), e15639.

Navidad-Murrieta, M. S., Pérez-Larios, A., Sanchéz-Burgos, J. A., Ragazzo-Sánchez, J. A., Luna-Bárcenas, G., & Sáyago-Ayerdi, S. G. (2020). Use of a taguchi design in Hibiscus sabdariffa extracts encapsulated by spray-drying. *Foods, 9*(2), 128.

Nouri, S., Moslehishad, M., Hosseini, S. M., & Etemadi, M. (2022). Comparison of Antioxidant and Alpha-Glucosidase Inhibitory Properties of Moringa peregrina and Ferulago carduchorum Leaf Extracts and Microencapsulation of Superior Plant. *Journal of Food Quality*. 2022. Pages https://doi.org/10.1155/2022/5887180

Pegg, R. B., & Shahidi, F. (2007). Encapsulation, stabilization, and controlled release of food ingredients and bioactives. *Handbook of food preservation* (pp. 527–586). CRC Press.

Piacentini, E. (2016). Encapsulation efficiency. *Encyclopedia of membranes*, 706-707

Piñón-Balderrama, C. I., Leyva-Porras, C., Terán-Figueroa, Y., Espinosa-Solís, V., Álvarez-Salas, C., & Saavedra-Leos, M. Z. (2020). Encapsulation of active ingredients in food industry by spray-drying and nano spray-drying technologies. *Processes, 8*(8), 889. https://doi.org/10.3390/pr8080889

Prabhakar, P. K., Kumar, A., & Doble, M. (2014). Combination therapy: A new strategy to manage diabetes and its complications. *Phytomedicine, 21*(2), 123–130. https://doi.org/10.1016/j.phymed.2013.08.020

RamírezDamián, M., Meza-Márquez, O. G., Osorio-Revilla, G., Gallardo-Velázquez, T., Téllez-Medina, D. I., & Ramos-Monroy, O. A. (2022). Microencapsulation of Red Banana Peel Extract and Bioaccessibility Assessment by In Vitro Digestion. *Processes, 10*(4), 768.

Ramu, R., Shirahatti, P. S., Anilakumar, K. R., Nayakavadi, S., Zameer, F., Dhananjaya, B. L., & Prasad, M. N. (2017). Assessment of nutritional quality and global antioxidant response of banana (Musa sp. CV. Nanjangud Rasa Bale) pseudostem and flower. *Pharmacognosy Research, 9*(Suppl 1), S74.

Ramu, R., Shirahatti, P. S., Deepika, T. H., Bajpe, S. N., Sreepathi, N., Patil, S. M., & Prasad, N. (2022). Investigating Musa paradisiaca (Var. Nanjangud rasa bale) pseudostem in preventing hyperglycemia along with improvement of diabetic complications. *Journal of Applied Biology and Biotechnology, 10*(4), 56–65.

Ravindran, A., John, J. A., & Jacob, S. (2021). Nutritional, functional and shelf-life assessment of processed banana inflorescence (Musa paradisiaca). *Journal of Postharvest Technology, 9*(2), 58–70.

Ravindran, R., Hassan, S. S., Williams, G. A., & Jaiswal, A. K. (2018). A review on bioconversion of agro-industrial wastes to industrially important enzymes. *Bioengineering, 5*(4), 1–20. https://doi.org/10.3390/bioengineering5040093

Reddy, J., & Hemachandran, J. (2014). Comparative evaluation of the anti-diabetic and hypoglycaemic potentials of the parts Musa paradisiaca plant extracts. *International Journal of Scientific and Research Publications, 4*(4), 1–5.

Robert, P., Gorena, T., Romero, N., Sepulveda, E., Chavez, J., & Saenz, C. (2010). Encapsulation of polyphenols and anthocyanins from pomegranate (Punica granatum) by spray drying. *International Journal of Food Science & Technology, 45*(7), 1386–1394.

Rupp, T., Trojosky, M., Wettring, M., Hinderlich, M., & Kohlus, R. (2023). Contact disc dryer. In M. S. Jafari. & N. Malekjani. (Eds.) *Drying Technology in Food Processing* (pp. 175–201). Woodhead Publishing.

Saravanan, K., & Aradhya, S. M. (2011). Potential nutraceutical food beverage with antioxidant properties from banana plant bio-waste (pseudostem and rhizome). *Food and Function, 2*(10), 603–610. https://doi.org/10.1039/c1fo10071h

Seth, D., Mishra, H. N., & Deka, S. C. (2017). Functional and reconstitution properties of spray-dried sweetened yogurt powder as influenced by processing conditions. *International Journal of Food Properties, 20*(7), 1603-1611

Sharma, A., Jana, A. H., & Chavan, R. S. (2012). Functionality of milk powders and milk-based powders for end use applications—a review. *Comprehensive Reviews in Food Science and Food Safety, 11*(5), 518–528.

Shori, A. B., Baba, A. S., & Muniandy, P. (2019). Potential health-promoting effects of probiotics in dairy beverages. *Value-added ingredients and enrichments of beverages*. 173–204. https://doi.org/10.1016/B978-0-12-816687-1.00005-9

Singleton, V. L., & Rossi, J. A. (1965). Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American Journal of Enology and Viticulture, 16*(3), 144–158.

Sosnik, A., & Seremeta, K. P. (2015). Advantages and challenges of the spray-drying technology for the production of pure drug particles and drug-loaded polymeric carriers. *Advances in Colloid and Interface Science, 223*, 40–54.

Sun, C., Zhao, C., Guven, E. C., Paoli, P., Simal-Gandara, J., Ramkumar, K. M., ... & Xiao, J. (2020). Dietary polyphenols as anti-diabetic agents: Advances and opportunities. *Food Frontiers*, 1(1), 18–44. https://doi.org/10.1002/fft2.15

Sylla, N., Bouyahya, A., Taha, D., Dakka, N., & Elhajji, H. (2021). Study of the antioxidant and antidiabetic activity in vitro of free and encapsulated phenolic compounds of olive pomace. *Biocatalysis and Agricultural Biotechnology, 36*, 102126

Tan, S., Kha, T. C., Parks, S., Stathopoulos, C., & Roach, P. (2015a). Optimising the Encapsulation of an Aqueous Bitter Melon Extract by Spray-Drying. *Foods, 3*, 400–419.

Tan, S. P., Tuyen, C. K., Parks, S. E., Stathopoulos, C. E., & Roach, P. D. (2015b). Effects of the spray-drying temperatures on the physiochemical properties of an encapsulated bitter melon aqueous extract powder. *Powder Technology, 281*, 65–75.

Van den Berg, R., Haenen, G. R., van den Berg, H., & Bast, A. A. L. T. (1999). Applicability of an improved Trolox equivalent antioxidant capacity (TEAC) assay for evaluation of antioxidant capacity measurements of mixtures. *Food Chemistry, 66*(4), 511–517.

Vodnar, D.C., Călinoiu, L.F., Mitrea, L., Precup, G., Bindea, M., Păcurar, A.M., & Ştefănescu, B.E. .(2019). A new generation of probiotic functional beverages using bioactive compounds from agro-industrial waste. In A. Grumenzescu & A.M. Holban (Eds.), *Functional and Medicinal Beverages* (pp. 483–528) Academic Press. https://doi.org/10.1016/B978-0-12-816397-9.00015-7

Vonghirundecha, P., Chusri, S., Meunprasertdee, P., & Kaewmanee, T. (2022). Microencapsulated functional ingredients from a Moringa oleifera leaf polyphenol-rich extract: Characterization, antioxidant properties, in vitro simulated digestion, and storage stability. *LWT, 154*, 112820.

Vu, H. T., Scarlett, C. J., & Vuong, Q. V. (2020). Encapsulation of phenolic-rich extract from banana (Musa cavendish) peel. *Journal of food science and technology, 57*, 2089–2098

Waterhouse, G. I., Sun-Waterhouse, D., Su, G., Zhao, H., & Zhao, M. (2017). Spray-drying of antioxidant-rich blueberry waste extracts; interplay between waste pretreatments and spray-drying process. *Food and Bioprocess Technology, 10*, 1074–1092.

World Health organization (2023). https://www.who.int/health-topics/diabetes Accessed on 28 Oct 2023

Yen, G. C., & Chen, H. Y. (1995). Antioxidant activity of various tea extracts in relation to their antimutagenicity. *Journal of Agricultural and Food Chemistry, 43*(1), 27–32.

Zhishen, J., Tang, M., & Wu, M. (1999). The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. *Food Chemistry, 64*(4), 555–559

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