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FEASIBILITY OF CO-ENCAPSULATING *MOMORDICA CHARANTIA* AND *MORINGA OLEIFERA* EXTRACTS VIA SPRAY DRYING: PRELIMINARY INSIGHTS INTO PHYSICOCHEMICAL PROPERTIES

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Abstract:

The lack of stability and rapid degradation of bioactive components from plants is one of the problems encountered during the preparation of nutraceutical and pharmaceutical formulations. The plants *Momordica charantia* and *Moringa oleifera* demonstrate well-known antioxidative, antidiabetic, and anti-inflammatory activities; however, they are commonly characterized by a low level of stability and solubility. This research evaluates the possibility of co-encapsulation of extracts of *M. charantia* and *M. oleifera* via spray drying in order to increase stability, solubility, and controllable release of the bioactive compounds. The powders obtained were characterized by means of physicochemical characteristics and structural stability in order to evaluate the possibility of obtaining the stable product with a high content of bioactive compounds. In addition, this research evaluates the influence of various carrier materials on powder formation, encapsulation efficiency, and material properties. Preliminary results have shown that co-encapsulation was possible and resulted in the improvement of powder behavior, storability, and activity of bioactive compounds. The obtained data provide valuable information on the applicability of dual-extracts spray drying for co-encapsulation of extracts of plants and can serve as the basis for future research in order to optimize the process.

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Keyword:

Bioactive Compounds, Co-Encapsulation, *Momordica Charantia, Moringa Oleifera,* Physicochemical Properties, Spray Drying.

Introduction

The rise in the interest towards natural remedies and functional foods has led to a demand for acquisition of the bioactive components of plants with antioxidant, anti-inflammatory, and antidiabetic properties. In this regard, *Momordica charantia* and Moringa oleifera can be considered as promising sources owing to their rich phytochemical profile and pharmacological properties. *M. charantia* is widely recognized for its antidiabetic and antioxidant actions attributed to the presence of the following bioactive compounds: charantin, polypeptide-p, and cucurbitane-type triterpenoids (Joseph & Jini, 2013). *M. oleifera* is often called the "miracle tree" owing to the vast biological activity, including anti-inflammatory, cardioprotective, and antidiabetic actions, due to the presence of flavonoids, glucosinolates, phenolic acids, and vitamins (Gopalakrishnan et al., 2016; Mbikay, 2012).

However, the usage of these plant extracts in food products is limited by their chemical instability and insufficient solubility. Phytochemicals are unstable and lose their biological activity when exposed to environmental factors like heat, light, oxygen, and moisture (Shahidi & Ambigaipalan, 2015). Moreover, the poor solubility and low absorbability of these compounds reduce their bioavailability (McClements, 2018). Consequently, it becomes essential to design a certain technique to achieve encapsulation and stabilization of these substances.

Spray drying method, which is a convenient technique for encapsulation, can be used to solve the above-mentioned issues. It allows converting the liquid extracts into the dried powders via solvent evaporation at the low temperature, which prevents destruction of thermolabile substances. In combination with the appropriate wall material, the spray drying technique facilitates stability, solubility, and dispersability of the bioactive compounds. In the current experiment, the cheap and readily available polysaccharide – maltodextrin with good film-forming properties – will be used as the only encapsulating agent since the stabilizing properties of this substance were proved (Gharsallaoui et al., 2007; Augustin & Sanguansri, 2015). Despite the large number of studies that deal with the spray drying of a single plant extract, there are not many data regarding the co-encapsulation of several botanical extracts in one particle. However, the co-encapsulation provides an opportunity to deliver bioactive components simultaneously and achieve synergetic effects. Nonetheless, the complexity of formulations can be explained by different physical and chemical properties of the extracts, which influence the process of spraying and the quality of the end product (Tonon et al., 2008). In the current case, the co-encapsulation of *M. charantia* and *M. oleifera* has not been sufficiently studied and has great potential.

The current experiment aims to investigate the possibility of co-encapsulation of the aqueous extracts of *M. charantia* and *M. oleifera* by using the spray drying method and the maltodextrin as the only wall material. The obtained powders will be evaluated in terms of their physicochemical properties (moisture content, solubility, water activity, bulk density, and encapsulation yield). Besides, the surface morphology and microstructure of the samples will be examined via field emission scanning electron microscopy (FESEM). By analyzing the influence of a single encapsulating agent, it will be possible to estimate the efficiency of maltodextrin in the preparation of the dual extract formulations. Although there is a constant increase in the number of scientific papers on the encapsulation of different botanical substances, there are not so many of them dedicated to the co-delivery of several plant extracts and the impact of such formulations on physicochemical properties. This paper is aimed at addressing this issue and provides some preliminary data on the behavior and stability of the co-spray-dried powders of *M. charantia* and *M.* oleifera.

Literature Review

There are four points will be discussed in this section which are the bioactive properties of two main materials, *M. charantia* and *Moringa oleifera*, introduced the uniqueness and specialties of the compounds. Other than the focus on the components, the literature review reveals the method of encapsulation by spray drying, and an overview of co-encapsulation in terms of the opportunities and challenges.

Bioactive Properties of Momordica Charantia

Momordica charantia is a medicinal plant that is popular under the name of bitter melon or bitter gourd. This plant belongs to the Cucurbitaceae family and has been widely used in traditional medicine for the treatment of diabetes, inflammation, and metabolic disorders (Joseph & Jini, 2013). The antidiabetic properties of *M. charantia* are explained by the bioactive compounds like charantin, vicine, polypeptide-p, and cucurbitane-type triterpenoids. The last group of compounds has been proved to stimulate glucose uptake, enhance insulin secretion and inhibit gluconeogenesis.

Along with antidiabetic effects, *M. charantia* also has potent antioxidant effects due to the high content of phenolics, flavonoids, and ascorbic acid. Antioxidants act as scavengers of free radicals and provide cell protection against oxidative stress. Additionally, the fruit possesses antimicrobial, anticancer, and immunomodulatory activities and is, therefore, a multifunctional ingredient of functional products (Shahidi & Ambigaipalan, 2015). However, bioactive substances of *M. charantia* are unstable in the presence of heat, light, and oxygen and, therefore, need protection through encapsulation.

Bioactive Properties of Moringa Oleifera

Moringa oleifera is a medical plant of Moringaceae family found in sub-Himalayan regions of India, Pakistan, and Nepal and currently grown in tropical and subtropical regions. It is known as "miracle tree" and "drumstick tree" and is characterized by a wide range of vitamins, minerals, amino acids, and phytochemicals. Specifically, leaves, seeds, and pods of *M. oleifera* contain vitamins (A, C, E), minerals (calcium, potassium, iron), amino acids, and flavonoids, glucosinolates, and phenolic acids (Gopalakrishnan et al., 2016).

Antioxidant effects of *M. oleifera* have been proven in multiple researches showing free radical scavenging and lipid peroxidation reduction. Furthermore, *M. oleifera* has significant anti-inflammatory effects thanks to isothiocyanates and flavonoids that inhibit pro-inflammatory cytokines and enzymes. Finally, *M. oleifera* shows potential in the treatment of hyperglycemia, hyperlipidemia, and cardiovascular risk factors and is a promising ingredient of functional foods (Mbikay, 2012). Like *M. charantia,* bioactives of *M. oleifera* are unstable under environmental conditions and need to be protected through encapsulation.

Spray Drying as an Encapsulation Technology

Spray drying is a common method of encapsulation because of its simplicity, low cost, and ability to be scaled up to an industrial level. In the course of the process, liquid substrate is atomized and dried in the flow of heated air resulting in formation of dry particles. Short drying time and fast heat transfer allow protecting heat-sensitive substances from thermal degradation and make spray drying suitable for encapsulating botanical extracts (Gharsallaoui et al., 2007).

Selection of proper wall material is important in spray-drying encapsulation. Maltodextrin, a polysaccharide obtained by partial hydrolysis of starch, is a popular wall material due to its low viscosity at high solid concentration and film-forming and tasteless properties. Maltodextrin provides encapsulation of bioactive substances and their protection against oxidation, moisture, and light. Studies have shown the effectiveness of maltodextrin encapsulation in increasing the stability, solubility, and bioavailability of plant extracts (Augustin & Sanguansri, 2012; Fang & Bhandari, 2010).

There are numerous studies about spray drying of individual plant extracts like beetroot juice (Koc et al., 2026), açai pulp (Tonon et al., 2008) and bitter gourd extract (Raj & Masood, 2016). They have proved the importance of process parameters' optimization (inlet temperature, feed flow rate, feed composition) for efficient encapsulation and desirable powder properties. Still, there is very little research on co-encapsulation of multiple plant extracts and possible interactions of different bioactives during spray drying.

Co-Encapsulation: Opportunities and Challenges

Co-encapsulation is a term used to describe simultaneous encapsulation of two or more bioactive substances or extracts in one carrier matrix. It brings opportunities like simplification of the formulation process, synergic effects and savings. Combining different bioactive components will produce a synergic effect, which will contribute to higher functional efficacy of the final product. For instance, antidiabetic and antioxidant properties of *M. charantia* and *M. oleifera* could work synergistically together, providing health effects better than separate formulations.

However, co-encapsulation involves some formulation difficulties, related to different physicochemical properties of various extracts (viscosity, solubility, thermal stability), which could influence atomization, drying kinetics and characteristics of the final powder. Incompatibility between bioactives may cause chemical interactions leading to decomposition and reduction of efficacy. Therefore, proper optimization of feed composition, proportion of the carrier and parameters of spray-drying process is necessary for successful co-encapsulation (McClements, 2018). To the best of authors' knowledge, the co-encapsulation of *M. charantia* and *M. oleifera* extracts by spray drying has never been studied before. The current study aims to close the gap and assess the feasibility of the proposed technology along with preliminary physicochemical properties of co-encapsulated powders.

Materials and Methods

In this section of description justifies the materials to be experimented, and the methodology of spray drying and co-encapsulation by preparation of feed solution process, spray drying and physicochemical characterization.

Plant Material and Extract Preparation

Fresh fruits of *Momordica charantia* and leaves of *Moringa oleifera* were purchased from the local markets in Pulau Pinang, Malaysia. Plant materials were washed with distilled water, dried at room temperature (25 ± 2°C) for 48 hours, and afterwards were ground to fine powder using a laboratory mill. Aqueous extracts were prepared by incubating 50 g of each powdered plant material with 500 mL of distilled water at room temperature for 24 hours with periodic stirring. The solutions were filtered through Whatman No. 1 filter paper and kept at 4°C for further use.

Preparation of Feed Solution for Spray Drying

The feed solution for spray drying was prepared by mixing equal amounts of *M. charantia* and *M. oleifera* aqueous extracts. Maltodextrin (dextrose equivalent 16–19; provided by Hong Aun, Penang) was dissolved in the mixture at 20% (w/v) concentration. Then the mixture was stirred continuously with the help of a magnetic stirrer at room temperature till complete dissolution. After that, the feed solution was filtered through 100-mesh sieve.

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Spray Drying Process

Spray drying was carried out by using laboratory scale spray dryer (SD-2L Spray dryer, Zhengzhou Keda Machinery & Instrument, China) fitted with two-fluid atomizer nozzle. The operation parameters were optimized and established as: inlet temperature 150 °C, outlet temperature 80-85 °C, feed flow rate 5 mL/min with compressed air flow rate 0.2MPa and aspirator rate 100%. The dried powder was obtained through the cyclone separator, transferred into airtight amber bottles and kept in desiccators at ambient temperature for further analysis.

Physicochemical Characterization

Encapsulation Yield

Encapsulation efficiency was defined as the ratio between the weight of spray-dried powder collected to the total weight of solids contained in the feed solution. The weight of total solids in the feed solution was determined by drying a known volume of feed solution in oven at 105 °C until constant weight is achieved. The formula is as follows:

$$\text{Encapsulation Yield (\%)} = \left(\frac{W_p}{W_s}\right) \times 100\%$$

W_p = Total weight of the spray-dried powder collected (g)
W_s = Total weight of dry solids presents in the initial feed solution (g)

Moisture Content

Moisture content was measured gravimetrically by oven drying of about 1 g of the powder at 105 °C until constant weight. The moisture content was determined as percentage of weight loss in relation to the initial sample weight. Gravimetric and soluble solid determination was done as follows,

$$\text{Moisture Content (\%)} = \left(\frac{W_i - W_f}{W_i}\right) \times 100\%$$

W_i = Initial weight
W_f = Final weight

Water Activity

The water activity (aw) of the spray-dried powders was determined at 25°C using a water activity meter (AquaLab Series 4TE, Meter Group, USA). Triplicate samples were analyzed, and the averages were recorded.

Solubility

The solubility of the powders was tested based on the procedure outlined by Koc et al., (2026). About 1 g of the powder was dissolved in 100 mL of distilled water and mixed for 5 minutes. Centrifugation of the mixture was done at 3000 rpm for 5 minutes. Subsequently, drying of the supernatant was done at 105°C until constant weight was obtained. Solubility of the powders was expressed as the percentage of soluble solids in relation to the initial powder weight.

$$\text{Solubility (\%)} = \left(\frac{W_{ss}}{W_{sample}}\right) \times 100\%$$

W_{ss} = Weight of the dried supernatant residue
W_{sample} = Initial weight of the powder (1g)

Bulk Density

The bulk density was determined by measuring the weight of a fixed amount of powder in a graduated cylinder without tapping the powder in the cylinder. The bulk density is determined as the ratio of the powder weight and volume.

Morphological Analysis

Surface morphological analyses of the spray-dried powders were conducted through field emission scanning electron microscopy (FESEM, Zeiss Supra 35VP, Germany). Powder samples were attached to aluminum stubs through double adhesive tape and then coated with gold for prevention of charging. The images were obtained at different magnifications (500x, 1000x, and 5000x) with accelerating voltage of 10kV.

Phytochemical Screening

Qualitative phytochemical analysis was carried out to assess the bioactive class present in the spray-dried powders. Colorimetric and precipitation reactions were utilized for detection of flavonoids, saponins, tannins, alkaloids, and glycosides as per the prescribed methods (Das & Kaistha, 2006; Kancherla et al., 2019).

Antioxidant Activity Assay

Antioxidant activities of co-encapsulated powders were measured using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical scavenging ability method according to Brand-Williams et al. (1995). DPPH radical scavenging activities of the powder samples were measured by dissolving the powder samples in methanol at varying concentrations (0.01 - 0.05 g/mL). Thereafter, 1 mL of each concentration of the sample was mixed with 1mL of DPPH solution (0.1mM in methanol). The mixtures were incubated in darkness at room temperature for 30 minutes and their absorbance were measured at 517nm using UV-vis spectrophotometer. DPPH radical scavenging % activity was determined and the IC_{50} values (concentrations required to scavenge 50% of DPPH radicals) were calculated using dose-response curve.

$$\text{DPPH Scavenging Activity (\%)} = \left(\frac{A_{control} - A_{Sample}}{A_{control}}\right) \times 100\%$$

$A_{control}$ = Absorbance of the DPPH solution without sample
A_{sample} = Absorbance of the sample reaction mixture at 517nm

Statistical Analysis

All experiments were conducted in triplicate, and results were presented as mean ± standard deviation. Data were statistically analyzed by one-way analysis of variance (ANOVA). Significant differences were determined by Tukey's post hoc test at 95% confidence level ($p < 0.05$).

Results and Discussion

Physicochemical Properties of Co-Encapsulated Powder

Physicochemical characteristics of co-encapsulated powder are the key markers of quality and functional features of the product. The key parameters analyzed in this study include encapsulation efficiency, solubility, moisture content, water activity, and bulk density (Table 1). These properties are critical for determination of application possibilities of the powder in food and pharmaceutical industries and assessment of the effectiveness of the spray drying method.

Table 1: Physicochemical Properties of Co-Encapsulated Powder

Property	Value
Encapsulation Yield (%)	60.0 ± 2.5
Solubility (%)	100.0
Moisture Content (%)	4.2 ± 0.3
Water Activity (aw)	0.28 ± 0.02
Bulk Density (g/mL)	0.42 ± 0.03

Encapsulation Yield and Process Efficiency

According to the experiment, the spray drying process resulted in 60.0 ± 2.5% encapsulation efficiency. This result corresponds to the acceptable yield for laboratory-scale spray drying process and is similar to the data on encapsulation efficiency achieved when maltodextrin is used as the carrier substance in encapsulation of botanical extracts (Gharsallaoui et al., 2007; Tonon et al., 2008). It is known that such low yield is associated with the characteristic problems of spray drying process (such as adhesion of particles to the drying chamber walls, separation inefficiency in the cyclone collector, etc.). Relatively high standard deviation (±2.5%) indicates some variability of the process, which is typical of small-scale operations and depends on such factors as fluctuations in feed flow rate, atomization pressure, and others. It should be noted that maltodextrin usage at 20% (w/v) concentration ensured sufficient stability of carrier matrix and proper separation of discrete particles. Low viscosity of the solution at high solid concentration contributed to good atomization properties, while excellent film-forming properties led to quick surface drying of particles, reducing their stickiness, which is typical for sugar-rich botanical extracts encapsulation (Augustin & Sanguansri, 2015). Absence of wall fouling and nozzle clogging is additional confirmation of the compatibility of maltodextrin with co-extract mixture of M. charantia and M. oleifera.

Although yield of 60% is acceptable for initial feasibility studies, optimization of process parameters may result in improvement of the process efficiency in the future. For example, changing of the inlet and outlet temperature may change the drying rate. Optimizing the feed solid concentration may balance the viscosity and drying efficiency. Usage of other carrier substances (maltodextrin + gum arabic, etc.) may improve the wall material properties and facilitate the process. Also, changes in the cyclone separator design or installation of additional collectors may increase powder yield.

Solubility and Reconstitution Behavior

Complete solubility of 100% was demonstrated by the co-encapsulated powder in water. Such reconstitution properties are highly valuable for functional food and beverage applications because instant dissolvability is a prerequisite for the acceptability and efficacy of products (Fang & Bhandari, 2010). Thus, the complete solubility implies the incorporation of the bioactive substances from both *M. charantia* and *M. oleifera* extracts into the maltodextrin matrix.

The reason for complete solubility of the powder can be explained by several aspects. In particular, maltodextrin is highly hydrophilic polysaccharide that dissolves easily in aqueous systems, providing excellent water dispersibility of the encapsulated powder. Another reason for complete solubility is associated with the spray-drying procedure applied in this research: fast evaporation of water and controlled drying temperature resulted in the formation of fine, non-agglomerated particles with high specific surface area and, thus, high water dispersibility and dissolvability. Besides, lack of indentations on the surface of powder particles, revealed by FESEM (see below), implies low level of structural defects that can hamper water dissolvability.

The nutritional and pharmaceutical value of such a characteristic is obvious. After ingestion, powder will be dissolved in gastrointestinal fluid, allowing the delivery of phytochemicals into the organism. In case of antioxidant substances, such as flavonoids and phenolic acids, whose effects depend on their release and interactions with biologically active sites, this property will provide an advantage in terms of higher bioavailability.

Moisture Content and Water Activity: Implications for Stability

The moisture content of the powder was found to be 4.2 ± 0.3%, which is within the appropriate range for spray-dried powders (from 2% to 5%). Low moisture content is important from the viewpoint of stabilization: excess moisture can lead to development of microbiological spoilage, degradation of phytochemicals due to enzymes activity and Maillard browning and lipid oxidation. Consistency of the drying procedure is proven by low standard deviation (±0.3%).

Complementary information concerning the stability of powder is provided by water activity (aw) of 0.28 ± 0.02. The value is below the threshold of aw=0.60 that corresponds to inhibition of microorganisms' proliferation. Water activity, not moisture content, should be considered while evaluating the stability of food products because it characterizes not the total amount of water but its availability for microbes (Augustin & Sanguansri, 2015). Water activity below 0.30 prevents the growth of bacteria, yeasts, and molds.

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In addition, the low level of water activity reduces the risk of moisture-related structural modifications, such as particle agglomeration and caking that adversely affect flowability of powders. The described property is especially important for industrial production of encapsulates since the flowability of powders is critical for their correct dosing and proper mixing into food formulations. The high degree of dryness combined with low water activity provides sufficient support for long-term stability of co-encapsulated powder in terms of its storage in moisture impermeable packaging at room conditions.

Bulk Density and Handling Properties

The bulk density of the co-encapsulated powder is equal to 0.42 ± 0.03 g/mL. The value is typical for spray-dried powders obtained through maltodextrin wall material. The bulk density is one of the key physical parameters that affects packaging efficiency, cost of transportation, and precision of dosing in food and pharmaceutical applications. Usually, lower bulk densities indicate presence of pores in the structure of particles and, therefore, more air inside, which leads to higher flowability but reduced compactness of powders (Gharsallaoui et al., 2007).

In particular, low bulk density of the co-encapsulated powder can be attributed to the hollow and porous nature of particles formed during fast drying and associated with formation of pores during evaporation of water. While this feature is advantageous in terms of development of controlled release systems, it can create certain difficulties for volumetric dosing systems that require precise density of powders. At the same time, narrow standard deviation (±0.03 g/mL) indicates good batch-to-batch reproducibility that is important for industrial scale production of powders. Future research will examine the effect of different spray-drying conditions (feed solid concentration, inlet temperature, etc.) on bulk density of the product.

Morphological Characterization via Field Emission Scanning Electron Microscopy (FESEM)

Field emission scanning electron microscopy (FESEM) was used to analyze surface morphology and microstructure of co-encapsulated powder. As it can be seen from micrographs shown in Figure 1 and Figure 2, the powder consists of predominantly spherical particles with smooth to slightly wrinkled surfaces, which is a common feature for maltodextrin-based encapsulated systems and associated with fast surface drying of particles (Tonon et al., 2008; Koc et al., 2026).

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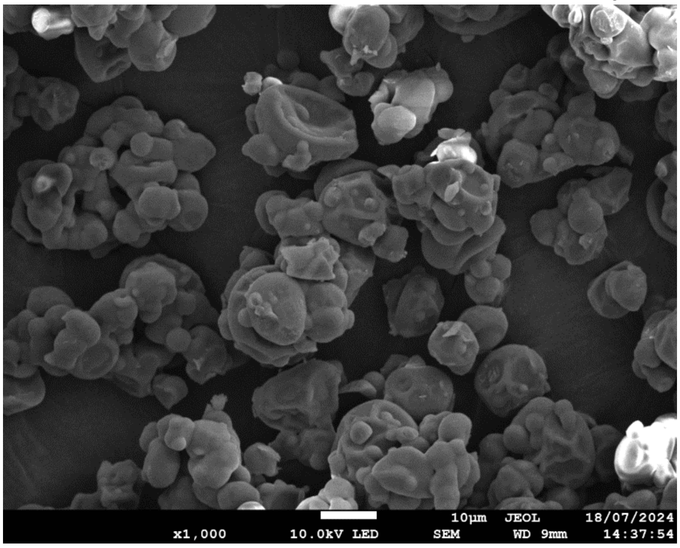

Figure 1: FESEM Micrograph of Spray-Dried Co-Encapsulated Powder at 1000× Magnification (Sample: S12-1)

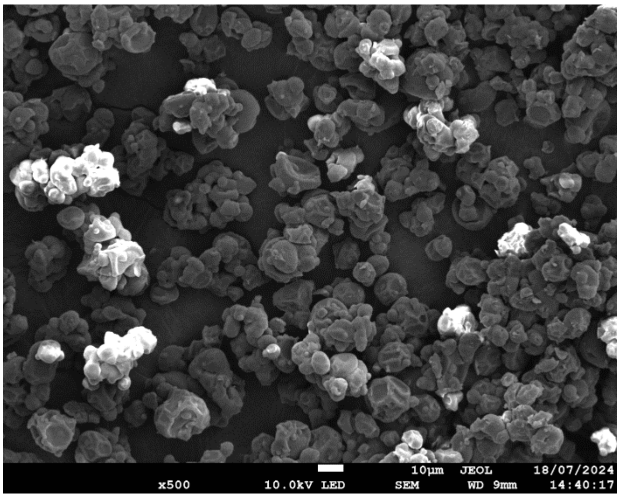

Figure 2: FESEM Micrograph of Spray-Dried Co-Encapsulated Powder at 500× Magnification (Sample: S12-2)

The formation of spherical morphology results from atomization process, which involves formation of liquid droplets in spherical form due to surface tension effects prior to their drying. The smooth morphology indicates uniform and fast formation of maltodextrin film, which successfully encapsulates bioactive core materials. The smooth surface morphology is advantageous for the following reasons. First, it minimizes the contact of encapsulated bioactives with environment (oxygen, moisture, and light), which provides for high oxidative stability and prolonged shelf life of powders. Second, spherical particles possess excellent flowability compared to irregular or angular particles.

The slight wrinkling on the surface of some of the particles is common in spray dried powders and is caused by differential shrinkage during the later stages of drying. This occurs due to the hardening of the outer layer of the droplet while the inner part of the particle is still drying up, thus causing some pressure differentials within the particles (Janiszewska, 2014). However, there was no sign of cracking, rupturing or collapse of hollow shells within the sample particles. Such problems would be indicative of early removal of the core substance and loss of encapsulation integrity. Hence, this indicates that the spray drying parameters have been set at an optimal level.

There was little or no sign of particle agglomeration. This is another factor that confirms the positive properties of reconstitution and solubility of the powder as indicated in the physicochemical analysis. This shows the efficiency of using maltodextrin in preventing surface stickiness and inter-particle agglomeration during drying. Thus, the results obtained through FESEM reveal successful microencapsulation and the appropriateness of the powder in terms of its application requirements.

Qualitative Phytochemical Screening and Bioactive Retention

Phytochemical screening of the co-encapsulated powder was done to test the presence of the various types of bioactive compounds in the powder and to evaluate the level of retention of these bioactives in the process of spray drying. The results of the qualitative tests have been summarized in Table 2 and show that flavonoids, tannins, saponins, and reducing sugars are present in the powder. This indicates successful preservation of the majority of heat-stable bioactives in the process of spray drying since these bioactives are characteristic of *M. charantia* and *M.* oleifera.

Table 2: Qualitative Phytochemical Screening of Co-Encapsulated Powder

Phytochemical Class	Result
Flavonoids	Present
Tannins	Present
Saponins	Present
Reducing Sugars	Present
Carotenoids	Absent
Terpenoids	Absent

Flavonoids, which are a group of polyphenolic compounds, have high antioxidant, anti-inflammatory and vasodilatory properties. Hence, their presence is very important in the powder because these compounds contribute to the effectiveness of the two plants as medicines. Tannins are astringent substances that possess antimicrobial and antidiabetic properties, and their detection indicates the retention of the bioactive compounds. Saponins, which are glycosides with cholesterol-lowering and immunomodulatory properties have also been detected in the powder. The presence of reducing sugars indicates the presence of carbohydrate bioactives in the powder. This is not surprising since carbohydrates have no medicinal value but add energy and taste to the powder.

However, it should be noted that there are no carotenoids and terpenoids in the powder even though they are present in the fresh plant materials. Carotenoids like β-carotene and lutein are extremely heat-labile and get oxidized and degraded when exposed to high temperatures (Shahidi & Ambigaipalan, 2015). Similarly, terpenoids such as volatile monoterpenes and

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sesquiterpenes get evaporated and decomposed at the inlet temperatures (140–160°C) used in spray drying.

Future research could examine the possible addition of antioxidant agents (such as ascorbic acid or tocopherols) to the feed mixture for protection against oxidative destruction of the bioactive compounds during the drying process. Another possibility to consider would be the use of protective carrier systems consisting of maltodextrin mixed with gum arabic and modified starch. Besides, lower inlet temperatures could be tested despite possible lower efficiency since they allow minimizing the thermal destruction. Although carotenoids and terpenoids are absent in the powder, the presence of flavonoids, tannins, and saponins proves that the co-encapsulated powder has potent biological activity and can be used for development of products for antioxidant, anti-inflammatory and metabolic health.

Fourier Transform Infrared Spectroscopy (FTIR) Analysis

In order to identify the chemical composition and the nature of the interactions between the compounds from the plant extracts and the encapsulating carrier material in the dried product, Fourier transform infrared spectroscopy (FTIR) was conducted. The FTIR spectra, shown in Figure 3, have some characteristic absorption bands indicating the presence of bioactive compounds in the powder.

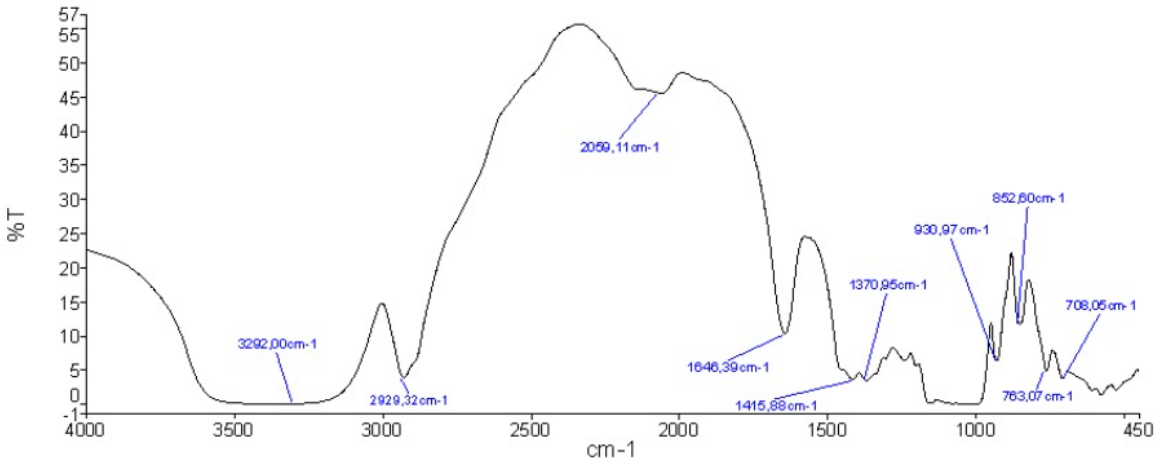

Figure 3: FTIR Spectrum of Co-Encapsulated Spray-Dried Powder Showing Functional Group Vibrations

The broad band observed at approximately 3300 cm-1 is caused by O-H stretching vibrations and is typical for hydroxyl functional groups of the organic compounds. Since there are many hydroxyl-containing molecules, such as polyphenols (flavonoids, phenolic acids) and polysaccharides (maltodextrin), this band proves the presence of these compounds in the powder. The broadness of the band indicates a lot of hydrogen bonds in the system and can explain its structural stability and cohesiveness (Bharudin et al., 2013).

The clear absorption peak in the range of 2900 cm-1 belongs to C-H stretching vibrations and is caused by the aliphatic chains. These vibrations are specific for both maltodextrin molecules and lipophilic compounds of the plant extracts. This band is associated with methyl ($-CH_3$) and methylene ($-CH_2-$) groups and confirms the integrity of the organic framework of the bioactive compounds after the spray drying process.

The sharp absorption band in the region of 1700 cm-1 is related to C=O stretching vibrations and shows the presence of carbonyl functional groups, such as carboxylic acids, esters and ketones. It can be associated with flavonoids, phenolic acids and other aromatic bioactives because of the presence of carbonyl groups in their structures. This band confirms the integrity of the organic molecules after encapsulation with no signs of chemical transformation or oxidation (Shahidi & Ambigaipalan, 2015).

Moreover, there is another set of absorption bands observed in the fingerprint region (bands below 1500 cm^{-1}), indicating the C-O stretching vibrations and C-C vibrations typical of carbohydrates. As the co-encapsulation was performed using maltodextrin powder, the existence of such absorptions is typical for the used material. The fingerprint region is known to be complicated as it includes absorption bands caused by different molecular fragments and can be used for characterizing more complex substances.

More importantly, the FTIR spectrum does not indicate any additional absorption bands or peak shifts related to the presence of the encapsulated bioactive molecules. It should be noted that the absence of new bands and peaks means that no chemical bonds were formed between the bioactives and the carrier. Consequently, the interaction between the components was performed physically, i.e. via weak van der Waals and hydrogen bonds. Physical encapsulation mechanism is common for systems developed based on maltodextrin carrier as they provide a protective matrix for the bioactives without forming any covalent bonds. Such physical interactions ensure the controlled release of the bioactive compounds upon the dissolution of the powder, thus making it applicable for functional food and drug development.

DPPH Radical Scavenging Activity and Antioxidant Potential

The antioxidant activity of the co-encapsulated powder was measured using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity test – one of the most popular colorimetric tests that is applied for estimation of free radicals scavenging activity of plant extracts and formulations (Brand-Williams et al., 1995). The principle of the DPPH test is based on the reduction of the stable DPPH radical, which has a typical purple color with a maximum absorbance at 517 nm. Upon the reaction with antioxidant compounds, the color changes that are determined spectrophotometrically.

Three concentrations of the powder – 0.003 g/mL, 0.006 g/mL, and 0.010 g/mL – were used to investigate the dose-response effect. As a control, the absorbance of the solution of DPPH radicals dissolved in methanol was measured and equals 1.187. The absorbance values and percentages of inhibition are presented in Table 3 and Figure 4.

Table 3: DPPH Radical Scavenging Activity of Co-Encapsulated Powder

Concentration (g/mL)	Absorbance (A_s)	% Inhibition
0.003	0.803	32.35
0.006	0.773	34.88
0.010	0.733	38.25

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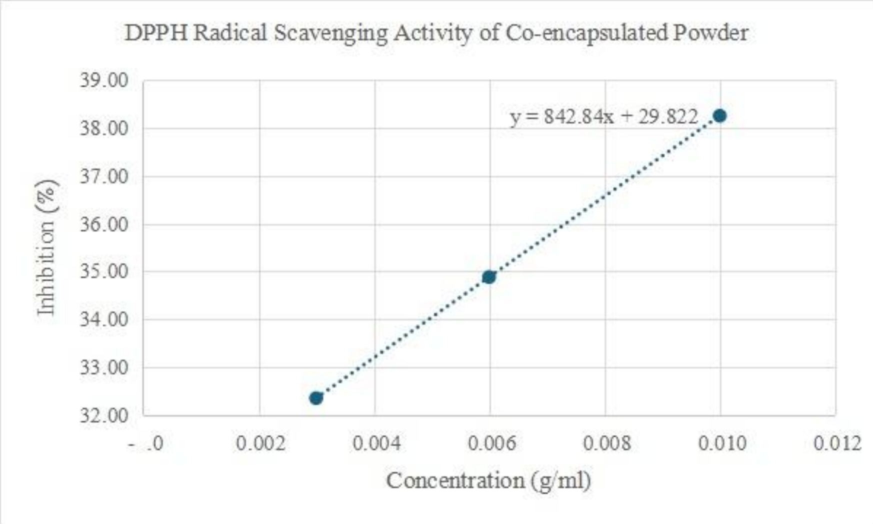

Figure 4: DPPH Radical Scavenging Activity of Co-Encapsulated Powder Showing Dose-Response Relationship

As can be seen from the results obtained, there is a clear dependence of the radical scavenging activity on the powder concentration – with the increase of the powder concentration from 0.003 g/mL to 0.010 g/mL, the percentage of inhibition increases from 32.35% to 38.25%. Such dose-dependent effect is typical for antioxidant systems and proves that the encapsulated bioactive compounds possess the ability to donate hydrogen atoms or electrons to neutralize the radicals.

The result of linear regression analysis of the inhibition was described by the equation y = 842.84x + 29.822. From the coefficient of determination (R^2), it is clear that the data fitted in a good linear way. According to the regression model, the IC_{50} was estimated to be about 0.0239 g/mL (23.9 mg/mL). Although it is greater than IC_{50} values for pure antioxidants standards like ascorbic acid (0.002 – 0.005 g/mL) or quercetin (0.001-0.003 g/mL), the obtained result can be compared to the data for other plant-based spray dried powders or natural extracts (Rodrigues et al., 2014; Tonon et al., 2008).

A number of reasons can explain the moderate antioxidant activity found in this work. First of all, the co-encapsulated powder contains maltodextrin as the carrier and is represented by a large part of this substance, which makes a dilution of the active phytochemicals in this product. In contrast to pure antioxidant standards, which consist of bioactives only, the co-encapsulated formulation is a complex substance, where bioactives make up only a part of its mass. The second reason is that the plant extracts used in this research are crude aqueous extracts without any purification procedure, thus containing lower concentrations of specific antioxidant compounds than the pure isolates (Osman et. al., 2017). And finally, there is a possibility of degradation of thermolabile antioxidants like carotenoids and some terpenoids in the process of spray drying, as shown by the phytochemical screening data (Table 2).

The obtained IC_{50}, despite being higher than the IC_{50} values of the pure standards, still indicates significant antioxidant activity, which is valuable for the application of the co-encapsulated powder as a functional food or nutraceutical. Free-radical scavenging activity of the powder was found to depend on the concentration and was caused by the presence of phenolic compounds like flavonoids, tannins, and phenolic acids, known for their ability to donate electrons or hydrogen atoms to the ROS and stop the process of the chain reaction.

Moreover, co-encapsulation of *M. charantia* and *M. oleifera* extracts can cause synergistic antioxidant effect, as the result of which the combined phytochemical composition of both plants provides enhanced free-radical scavenging activity comparing to the single-extract formulations. The hypothesis of the synergy is supported by the presence of complement bioactive compounds of the extracts, including flavonoids from both sources, glucosinolates from *M.* oleifera, and cucurbitane triterpenoids from *M. Charantia*, although it requires further evaluation with quantitative methods of investigation.

At last, it must be mentioned that the DPPH method gives only the preliminary information about the antioxidant potential of the substance, as it does not consider the whole variety of antioxidant mechanisms taking place in the biological environment (Fadil et. al., 2025). For the complete estimation of the antioxidant capacity of the co-encapsulated powder, additional tests, including FRAP, ORAC, and SOD-like activity assays, should be performed.

Conclusion Overall, the DPPH radical scavenging assay indicates that the co-encapsulation of the spray dried powder exhibits moderate antioxidant activity, which shows a concentration-dependent effect. The obtained value of IC_{50} = 0.0239 g/mL, although higher compared to those of the standard antioxidants, lies within the acceptable limit for natural product formulations. This IC_{50} value is consistent with the functionality of the powder to be used as an effective means of managing oxidative stress, metabolic conditions, and preventing diseases. The persistence of the antioxidant activity in the encapsulated and spray dried powder justifies the efficiency of the method and the appropriateness of the co-encapsulation system.

Conclusion

This research study was able to prove that it is possible to co-encapsulate the extracts from *Momordica charantia* and *Moringa oleifera* using spray drying as a technique. This has opened up new possibilities for the creation of bioactive rich botanical powders for use in food and pharmaceutical products. The research process resulted in an encapsulation yield of 60%, and the powders created showed high dispersibility in water.

The morphological analysis carried out using FESEM proved that the encapsulation resulted in the formation of spherical microcapsules characterized by smooth surface morphology to ensure proper flowability and easy reconstitution. The existence of phytochemicals such as flavonoids, saponins, and tannins confirms the existence of functional bioactive compounds which are known to possess antioxidant activity. In addition, DPPH radical scavenging analysis was performed to validate the potential of the product as an antioxidant, resulting in concentration-dependent antioxidant activity and IC_{50} value of 0.0239 g/mL. Even though the antioxidant activity was lower compared to pure phytochemicals, the results are quite impressive for a natural, co-encapsulation product.

With the presence of antioxidant capacity and the stability of the powder in terms of structure and composition, the powder can be considered as a multifunctional plant-based ingredient with health benefits. It is worth mentioning that the research helps to fill the existing literature gap by showing the possibility of dual extraction encapsulation in one spray drying process. In addition, spray drying is proved to be an effective technology for stabilizing biologically active ingredients obtained from plants.

Further research could address optimal design of carrier matrices, increased retention of heat-sensitive bioactive compounds like carotenoids and terpenoids, and testing of the stability and bioavailability of the formulation in artificial gastrointestinal environments. Moreover, in vivo tests, shelf-life analysis, and controlled release profile evaluation would be necessary to thoroughly understand the clinical significance and commercial prospects of this novel co-encapsulation system. This way, a more scientifically sound and plant-derived formulation can be developed, which can find application in the nutraceutical, pharmaceutical, and functional foods industries.

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Author Contribution Statement:	All authors contributed significantly to the development of this manuscript. Shafifah Hanim Shaykany Hazim: Investigation, Data curation, Formal analysis, Visualization, Writing – Original Draft. Nurul 'Adilatil Hakimah Nur Azli: Investigation, Data curation, Formal analysis, Writing – Original Draft. Vicinisvarri Inderan: Methodology, Validation, Formal analysis, Writing – Review & Editing. Mohamad Syafiq Abdul Wahab: Methodology, Resources, Validation, Writing – Review & Editing. Siti Hawa Mat Yaman: Investigation, Resources, Data curation, Writing – Review & Editing. Mohd Othman Halim: Resources, Project administration, Writing – Review & Editing. Mohamed Syazwan Osman: Conceptualization, Methodology, Supervision, Project administration, Validation, Writing – Review & Editing. All authors read and approved the final version of the manuscript prior to submission.

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