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The impact of different plant-based wall materials on the microencapsulation of Medium Chain Triglycerides (MCTs) via spray drying technique

Hoi Chin Hew [a], Siok Peng Kek [a], Chin Ping Tan [b], Siou Pei Ng [a,*]

[a] Department of Bioscience, Faculty of Applied Sciences, Tunku Abdul Rahman University of Management and Technology, Jalan Genting Kelang, 53300, Setapak, Kuala Lumpur, Malaysia
[b] Department of Food Technology, Faculty of Food Science and Technology, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia

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ABSTRACT

There is a critical need in the market for sustainable, plant-based substitutes to replace conventional animal-derived wall materials for oil encapsulation. This study focused on the potential of a combination of plant-derived wall materials (pea protein isolate, soy protein isolate, modified starch and gum Arabic) and maltodextrin as a wall material for encapsulating medium-chain triglycerides (MCTs) oil using the spray drying technique. The physical characteristics of the spray-dried powders were evaluated including their microstructure morphology, particle size distribution, bulk density, tapped density, microencapsulation efficiency, water activity and moisture content. The emulsifying properties of plant-derived protein were found to be promising when compared to those of sodium caseinate, a commonly used control material in food formulations. The research on MCTs oil retention showed the wall materials to have the highest microencapsulation efficiency (MEE) with low surface oil content by sodium caseinate (90.85 ± 4.11 %) > soy protein isolate (86.14 ± 5.20 %) > modified starch (80.85 ± 4.13 %) > pea protein isolate (80.72 ± 8.32 %) > gum Arabic (75.21 ± 7.86 %). Observation through scanning electron microscopy indicated that the spray dried powders were predominantly spherical in shape with smooth, non-cracked surfaces, which suggests that the drying was effective and successfully retained the 40 % (w/w) MCTs oil within the microcapsules. The soy protein isolate and maltodextrin wall material microcapsules had the highest particle size and a mean diameter of (50.84 ± 5.47 μm). The successful production of these microcapsules demonstrates that the selected plant-derived matrix represents a viable and sustainable alternative to animal-based encapsulating agents in the development of functional lipid-based powder ingredients.

1. Introduction

Medium-chain triglycerides (MCTs) oil is typically extracted from palm kernel oil and coconut oil. Oil palm is Malaysia's vital commodity crop and palm kernel oil is known for its high content of medium chain fatty acids (MCFAs) (Marten et al., 2006). MCFAs are desirable fatty acids as compared to long chain fatty acids because upon digestion of MCTs, MCFAs are not repackaged into chylomicrons due to their length in nature, which allows them to be directly transported into the liver (Myrie & Jones, 2011). MCTs oil enhances energy expenditure and increases satiety, which results in negative energy balance which reduces food consumption and supports body weight management (Myrie & Jones, 2011). However, the incorporation of MCTs oils into various food products remains limited due to its low water solubility (Francisco et al., 2020). Therefore, the conversion of MCTs oil into an encapsulated powder using different plant-derived wall materials is expected to allow versatility in the production of functional lipid-based ingredients in the food, beverages, and nutraceutical products. The high microencapsulation efficiency (MEE) of microcapsules is largely determined by selected composition of wall materials. The microencapsulating wall material plays an important part because they serve as a protective layer and minimize the exposure to external variables in the formation of a stable microcapsule with enhanced microencapsulation efficiency. The encapsulating materials have been employed as encapsulating agents for flavours and oil compounds. These include low molecular weight polysaccharides such as starches, maltodextrins, gum Arabic (GA), and corn

* Corresponding author.
E-mail address: ngsp@tarc.edu.my (S.P. Ng).

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syrups solids, lipids-based carriers such as mono and diglycerides and protein materials including casein, whey protein and gelatin (Augustin & Sanguansri, 2008). Combining mixtures of polysaccharides such as maltodextrin with different dextrose equivalents, and pectin with proteins sources including whey protein concentrate, whey protein isolate, sodium caseinate (SC), skim milk protein, soy protein isolate (SPI) and pea protein isolate (PPI) or with hydrocolloids such as gum Arabic and mesquite gum, has been demonstrated to yield micro-particles with enhanced functional attributes compared to utilizing a single biopolymer component (Akbarbaglu et al., 2021). Proteins exhibit effective emulsifying properties that are responsible for maintaining the stability of oil-in-water emulsion—a critical step in spray drying encapsulation of lipid-based compound. In contrast, polysaccharides possess film-forming properties that contribute to structural stability in encapsulation systems. Several protein-containing isolates have been used as the wall material due to the presence of amphiphilic characteristics, which are caused by the presence of both hydrophilic and hydrophobic functional groups; these, combined with their high diffusivity, facilitate efficient dispersion along the interface of the encapsulated oil surface (Le Priol et al., 2019). Sodium caseinate (control material) is selected over other animal milk-derived proteins due to its high solubility in water, good emulsification properties, rapid formation of interfacial films and excellent surface active activity (Pu et al., 2024). A combination of proteins with various carbohydrates-based as wall materials, particularly the combination of maltodextrin and sodium caseinate has been shown to improve the encapsulation efficiency of oils (Munin & Edwards-Lévy, 2011). Maltodextrin is commonly employed in microencapsulation due to its low-cost, excellent aqueous solubility, and provides protection against oxidation. Maltodextrins are derived from the hydrolysis of starch, a process carried out under controlled acidic or enzymatic partial hydrolysis condition. The encapsulation of oils typically involves the use of protective matrix materials, which may consist of synthetic polymers or biomaterials such as carbohydrates and proteins (Ekasit & Wiriya, 2019). On the other hand, plant-derived ingredients have also shown potential as wall materials for oil encapsulation (Can Karaca, 2020). A study performed by Le Priol et al. (2019), had demonstrated how sunflower oil was microencapsulated using various plant derived protein isolates including those from pea, soy, brown rice, hemp, and sunflower, as encapsulating wall materials. Among these, pea protein isolate and soy protein isolate functioned effectively as wall materials for encapsulation and ensure the protection of sunflower oil. SPI is a plant-based globulin structured protein that consist of β-conglycinin (7S), glycinin (11S) and convicilin where it provides moderate solubility in aqueous systems, strong interfacial adsorption properties at the oil-water interface, and beneficial gelling and film forming properties (Tian et al., 2018). The anhydrous glass transition (Tg) temperature of SPI has been reported to exceed 150 °C in the dry state, providing resistance to physical degradation during spray drying encapsulation (Mizuno et al., 2000). PPI has garnered demand in the food industry as an encapsulating agent due to its material's economic viability, high protein content, non-allergenic properties and excellent functional properties. PPIs reveal an amphiphilic molecular structure, and are primarily composed of three main globulin fractions—legumin (11S), vicilin (7S) and convicilin (Barac et al., 2010). These proteins facilitate rapid adsorption at oil-in-water interfaces where their emulsifying performance are influenced by factors such as hydrophobicity, solubility and molecular arrangement (Xia et al., 2024). PPIs are used as a substitute for animal-derived proteins and for allergenic plant proteins, such as soy in diverse food applications (Bajaj et al., 2017). PPIs have been incorporated into diverse food products due to its unique multifunctional properties including its emulsifying ability, foaming capacity, gelation behaviour, water holding capacity, and fat absorption characteristics (Samborska et al., 2021). Spray-dried pea protein concentrates yield microparticles with high encapsulation efficiency (~99 wt.%), smooth morphology deprived of visible pores, and a higher Tg temperature (66.4 °C at a_w ≈0.3) (Francisco et al., 2022). Comparative studies have indicated that pea proteins exhibit effective efficacy in inhibiting lycopene degradation within oil-in-water emulsions than conventional dairy proteins such as casein and whey proteins (Ho et al., 2017). Also, Gum Arabic (GA), a structurally complex polysaccharide polymer composed mainly of primarily d-glucuronic acid, α-l-rhamnose, β-d-galactose, and L-arabinose, contains approximately 2 % of protein within its formulation (Arshad et al., 2020). GA has a range of desirable functional properties as a wall material, including surface hydrophobicity, high molecular weight, film forming capacity and interfacial interactions. GA serves multiple functional roles as an emulsifying agent, humectant, surface-finishing agent and an inhibitor of sugar crystallization. It remains one of the most extensively used wall materials in encapsulation to maintain emulsion stability across a broad pH spectrum. Furthermore, it has a high Tg temperature (97.02 °C), compared to other polysaccharide carriers and thereby indicating better amorphous matrix stability (Toledo Hijo et al., 2017). The CAPSUL® TA, modified starch (MS), derived from waxy maize starch containing ≥ 95 % amylopectin, is characterized by its highly branched α-(1,6)-linked glucan structure, consisting of 24–30 glucose units. This branching provides a large number of accessible hydroxyl groups, thereby facilitating chemical modification, and the resulting esters exhibit distinctive physicochemical and functional properties (Xia et al., 2025). The globular molecular conformation of starch in solution enhances their diffusion kinetics to the oil in water interface during emulsification and promotes the formation of a more cohesive interfacial film surrounding dispersed oil droplets, thereby enhancing emulsion stability. Spray dried microcapsules formulated with octenyl succinic anhydride (OSA)-modified starch have been reported to exhibit a Tg temperature of approximately 85 °C (Zhang et al., 2022). MS display high emulsifying activity, low viscosity and it is highly effective as a wall material in encapsulating volatile flavor compounds such as D-limonene oils (Paramita et al., 2012). Spray drying is a commonly adopted microencapsulation technique, valued for its ability to transform emulsified systems into stable dry powders while retaining the core bioactive compounds such as seed oils, essential oils and flavour compounds (Balci-Torun & Ozdemir, 2021; Lim et al., 2012). Numerous studies have utilized spray drying techniques for the encapsulation of oils such as flaxseed oil (Carneiro et al., 2013) and macadamia oil (Laohasongkram et al., 2011) into dry powder particle forms that show greater versatility and ease of handling than liquid oils. The spray drying method presents a practical alternative to encapsulation substances and it has higher efficiency compared to other encapsulation methods. It consist of a large yield, low cost, economically feasible technology (Xu et al., 2024). Besides that, spray drying technique facilitates the targeted release of encapsulated core materials, upon specific environmental or processing conditions (Mukurumbira et al., 2022). Effective microencapsulation must yield a powdered formulation with minimal surface oil presence and maximal retention of the active core materials. The global business for plant-based proteins is estimated to expand from USD 18.2 billion in 2025 to approximately USD 42.5 billion by 2034, corresponding to a compound annual growth rate of 8.6 % (United Nations Department of Economic and Social Affairs, Population Division, 2024; Morder, 2024). The increasing demand for plant-derived proteins is reflective of a global shift in dietary preferences toward vegan and vegetarian lifestyles, further driven by growing consumer awareness of sustainability and food security. Despite this awareness, spray drying microencapsulation systems employing plant-based wall materials with high medium-chain triglycerides (MCTs) oil loading (40 %, w/w) have received limited attention in the literature. Therefore, this study aimed to evaluate the performance of MCTs oil microcapsules prepared via spray drying by assessing their physicochemical properties and encapsulation efficiency, in comparison to conventional animal-derived counterparts. In addition, this work sought to extend the potential application of the produced microcapsule powders as functional lipid-based ingredients in food and beverage formulations through microparticle delivery systems.

2. Materials and methods

2.1. Materials

The Medium Chain Triglycerides (MCTs) oil used in this study was procured from LipidChem Sdn. Bhd., Masai, Johor, Malaysia. Pea protein isolate (PPI) and CAPSUL®TA starch (MS) were donated by Ingredion Singapore Pte Ltd. Maltodextrin DE10 (DE10) and sodium caseinate (SC), soy protein isolate (SPI) and gum Arabic (GA) were purchased from a local food ingredient supplier (VIS FoodTech Ingredient Supplies, Malaysia). All chemicals used in this study were of analytical grade and purchased from Merck Co., Ltd. (Darmstadt, Germany) and Sigma-Aldrich Chemical Co. (Milan, Italy).

2.2. Emulsion preparation

The fixed ratios of core/plant-derived wall materials were at 1:2 which was selected as the average proportion ratio of wall materials used throughout this study; this was determined based on formulations established in previous studies (Chew et al., 2018; Lim et al., 2012). The plant-derived wall materials mixture for the emulsion gum Arabic (GA), soy protein isolate (SPI), CAPSUL®TA starch (MS), pea protein isolate (PPI), sodium caseinate (SC) with maltodextrin (DE10) were well dispersed in deionized water and maintained at 50 °C using a T25 digital Ultra-Turrax homogenizer (IKA, Germany) to ensure uniform dispersion and subsequently stored overnight under controlled conditions at 4 ± 2 °C to ensure complete hydration. The MCTs oil-to-wall ratio was maintained at core/wall materials ratio 1:1.5 throughout the study and was kept constant to determine the influence of varying wall material compositions. The composition of wall material was 20 % (w/w) for SC, PPI and SPI, whilst 30 % (w/w) for MS and GA, respectively. MCTs oil was then incorporated into the wall materials mixture and subjected to pre-homogenization using a shear homogenizer (Silverson L5M-A, Buckinghamshire, UK) at 3000 rpm for 5 min. The resultant emulsion was further homogenized through a high-pressure homogenizer (Panda Plus 2000, GEA Niro Soavi, Parma, Italy) at pressure of 400 bars for two passes to obtain the final emulsion. Emulsions formulated were named *SM* sodium caseinate/maltodextrin; *SPIM* soy protein isolate/maltodextrin; *PPIM* pea protein isolate/maltodextrin; *AM* gum Arabic/maltodextrin and *MSM* modified starch/maltodextrin, respectively.

2.3. Microencapsulation of MCTs oil by spray drying

Spray drying was performed on the emulsions using a Mini Spray Dryer B-290 (Büchi Labortechnik AG, Switzerland). A glass dryer chamber (0.45 m in height and 0.14 m in diameter) was used. A two-fluid nozzle system achieved atomization. The internal capillary had a 0.7 mm in diameter orifice and the external annular ring had a 1.5 mm in diameter opening. The drying air was set to 150 ± 2 °C internal temperature and 80 ± 2 °C, the outlet temperature, respectively. The emulsion was introduced into the drying chamber for subsequent dehydration under controlled processing condition, facilitated by a peristaltic pump operating at 20 % capacity, corresponding to a flow rate of 8 ± 2 g/min. The resultant MCTs powder was collected from both the interior surfaces of the drying chamber and the cyclone separator. Subsequently, the dehydrated MCTs powder was placed in a desiccator and kept at ambient temperature for further analysis.

2.4. Emulsion characterization: emulsion creaming stability

The creaming stability was assessed through a modified method based on the approach described by Carneiro et al. (2013). A 25 mL of the emulsion was carefully transferred into a graduated cylinder for subsequent assessment and maintained at a temperature of 25 °C for a duration of 24 h. After incubation, the extent of phase separation was quantified by calculation of the percentage ratio of the height of the upper layer to the original total height of the emulsion after 24 h.

Creaming index was determined and expressed through the following equation:

$$\mathrm{CI} = \left(\frac{H_c}{H_i}\right) \times 100$$

where, H_c the height of cream layer; H_i the total height of the emulsion

2.5. Emulsion droplet size distribution & microparticle characterization

The droplet size distribution of the freshly prepared emulsions was characterized using Malvern Mastersizer 3000 (Malvern Instruments Ltd, Worcestershire, UK) equipped with a MAZ3400 & MAZ2020 Hydro EV and wet cell (Li et al., 2019; Phonphimai et al., 2025). Measurement obscuration was regulated within ± 5 % through incremental water addition. Dry microparticles were analysed using the Mastersizer 3000 equipped with MAZ3500 & MAZ2070 Aero S modules designed for automated dry powder dispersion. Samples were introduced to a vibratory hopper and were directed to the detector for continuous measurement under ambient temperature conditions. The refractive index of MCTs oil was established at 1.453 for optical parameter calibration. Particle size data for both emulsion samples and dry microparticle powders were reported as surface weighted mean diameter (D[3,2]), and calculated using Eq. (1) and the volume-surface mean diameters (D[4,3]) were derived from Eq. (2) where n_i represents the number of droplets with diameter d_i. The droplet size distribution of the emulsion was subsequently further calculated using Eq. (3), as follows:

$$\mathrm{D}_{3,2} = \frac{\sum n_i \mathrm{d}_i^{\,3}}{\sum n_i \mathrm{d}_i 2} \tag{1}$$

$$\mathrm{D}_{4,3} = \frac{\sum n_i \mathrm{d}_i^{\,4}}{\sum n_i \mathrm{d}_i 3} \tag{2}$$

The following equation was used to determine the span, d_{10}, d_{50}, d_{90} corresponding to the 10 %, 50 %, 90 % of the cumulative volumes' distribution, respectively:

$$\mathrm{Span} = \frac{d_{90} - d_{10}}{d_{50}} \tag{3}$$

2.6. Moisture content and water activity

The moisture content of the powders was measured gravimetrically by drying 5 g of the powder in a hot air oven at 105 °C for 8 h until constant weight was achieved (Le Priol, 2019). The data was expressed as a percentage of the change in weight. The water activity was determined at 25 °C using a calibrated water activity meter (Aqualab Lite, Decagon Devices, Inc, USA). The sample was carefully placed in a plastic container with its entire surface sealed, then transferred into a sealed chamber maintained at temperature of 25 ± 2 °C. After 10 min of sample equilibration period within the instrument (AOAC, 1995) water activity was measured in accordance with standard procedures.

Moisture content was quantified and expressed through the following equation:

$$\mathrm{Moisture}\ (\%) = \left(\frac{W_{microparticles} - W_{dry\ microparticles}}{W_{microparticles}}\right) \times 100$$

where, $W_{microparticles}$ represents the weight of sample prior to drying and $W_{dry\ microparticles}$ represents the weight of the sample after oven drying.

2.7. Microencapsulation efficiency

The microencapsulation efficiency (MEE) was determined via an adapted method reported by Bae and Lee (2008). 2 g of sample was

dissolved in 15 mL of analytical grade hexane and subjected to vigorous mixing using a vortex mixer operated for 2 min at room temperature to extract free oil (Bae & Lee, 2008). The resulting solvent mixture was subsequently decanted and subjected to filtration using Whatman No. 1 filter paper to remove particulate matter. The retained solid residue was then further washed three times with 20 mL of hexane to maximize the recovery of soluble constituents and ensure thorough extraction efficiency. The combined solvent was then concentrated using a vacuum rotary evaporator at 60 °C until constant weight was achieved. The amount of extractable free oil content was determined by calculating the percentage of the weight loss of the powder before and after hexane extraction and solvent rinsing. The MEE was expressed as a percentage and calculated using the following equation:

$$\text{MEE}\ (\%) = \frac{\text{Oil}_{\text{Total}} - \text{Oil}_{\text{Surface}}}{\text{Oil}_{\text{Total}}} \times 100$$

2.8. Bulk density and tapped density

Bulk density (g cm^{-3}) was assessed by the method (Goula et al., 2004) and Amidon et al. (2017), with minor modifications. 2 g of each sample were gradually added into an empty 10 mL graduated cylinder. Bulk density was quantified by measuring the volume displaced by a known mass of powder introduced into a graduated cylinder without compaction. The tapped density (g cm^{-3}) was obtained by recording the volume occupied of an equivalent mass of powder after subjecting to ten consecutive tapping cycles. The powder density was determined using the following equation:

$$\text{Bulk Density}\left(\frac{\text{g}}{\text{cm}^3}\right) = \frac{\text{mass of powder}}{\text{volume of powder}}$$

$$\text{Tapped Density}\left(\frac{\text{g}}{\text{cm}^3}\right) = \frac{\text{mass of powder}}{\text{final tapped volume}}$$

2.9. Flowability and cohesiveness

The flowability and microparticles cohesiveness of the powder samples were characterized by Carr's Index (CI) and Hausner ratio (HR) (Amidon et al., 2017).

$$\text{Carr's Index (CI)} = \frac{\text{tapped density} - \text{bulk density}}{\text{tapped density}}$$

$$\text{Hausner Ratio (HR)} = \frac{\text{tapped density}}{\text{bulk density}}$$

2.10. Powder wettability and solubility

Powder wettability was assessed using the method of Silva et al. (2016). 0.1 g of powder was sprinkled onto the surface of 50 mL of distilled water at 20 °C under continuous magnetic stirring at 350 rpm (Silva et al., 2016). The duration (in seconds) required for complete immersion and disappearance of powder particles from the aqueous surface was recorded as a quantitative measure of wettability. Powder solubility was assessed using a modified method reported by a previously established method (Chranioti et al., 2016). Briefly, 1 g of powder was dispersed in 100 mL of distilled water and subjected to continuous stirring at 110 rpm for 30 min. The mixture was then centrifuged at 4000 rpm for 5 min. A 10 mL aliquot of the supernatant was carefully transferred into pre-weighed petri dishes, and subsequently dried in a convection oven at 105 °C until a constant weight was attained (Chranioti et al., 2016). Solubility was determined based on calculating the mass of the dried residue using the following equation:

$$\text{Solubility}\ (\%) = \frac{\text{Mass of soluble in supernatant}}{\text{Mass of solid powder dissolved}} \times 100$$

2.11. Surface morphology

The surface morphology and surface appearance of the spray dried microparticles were examined using a scanning electron microscope (SEM). Samples of the dried powder were mounted onto aluminium stubs using double sided adhesive tape and subsequently coated with a thin layer of gold using a sputter coater to improve electrical conductivity (BAL-TEC, SCD 005, Witten, Germany). Imaging was conducted using a Philips XL 30 ESEM (FEI Co., Eindhoven, Netherlands) operated at an accelerating voltage of 5 kV with a magnification of 1000× to elucidate the microstructural characteristics of the microencapsulated particles.

2.12. Fourier transform infrared spectroscopy (FT-IR)

FT-IR spectroscopy was used to analyse MCTs oil, individual raw wall materials, and the resulting microencapsulated MCTs oil powder formulated with different wall materials using the method proposed by Chew et al. (2018). Spectral data were acquired at ambient temperature using (Perkin Elmer Frontier FT-IR), operating within the wavenumber range of 650−4000 cm^{-1} and a spectral resolution of 4 cm^{-1} at ambient temperature. The resulting FT-IR spectra were expressed as transmission (%) plotted against wavenumber (cm^{-1}).

2.13. Statistical analysis

All characterization assessments of emulsions and microparticle samples were conducted in triplicate to ensure reproducibility. Data were reported as mean values ± standard deviation. Statistical evaluation was performed using one-way analysis of variance (ANOVA) followed by Tukey's post hoc test to identify significant differences among group of means at a confidence level of $p < 0.05$. All statistical procedures were conducted using SPSS software, version 21.0 software program (IBM Corp., Armonk, NY, USA).

3. Results & discussion

3.1. Properties of Medium Chain Triglycerides (MCTs) oil emulsion

Formulations of Medium Chain Triglycerides (MCTs) oil emulsions were prepared at a constant fixed oil proportion with various combinations each of plant-derived wall materials as encapsulating agents. The four formulations were *PPIM* pea protein isolate/maltodextrin, *SPIM* soy protein isolate/maltodextrin, *MSM* modified starch/maltodextrin, *AM* gum Arabic/maltodextrin. They were compared to animal-based wall material (*SM* sodium caseinate/maltodextrin). The pre-drying stability is another factor essential for the successful encapsulation, as it shows the droplet size and interfacial stability. Fig. 1 illustrates the creaming stability of emulsions prepared with various plant-derived wall materials. Creaming index (CI) is a measure of phase separation attributed to the upward migration of dispersed droplets typically oil in the emulsion system (El Bouchikhi et al., 2021). A lower CI indicates enhanced emulsion stability as it shows reduced phase and uniform distribution of droplets particles within the continuous phase (El Bouchikhi et al., 2021). Separation was observed for the samples without high pressure homogenization (HPH) treatment; specifically, the *PPIM* emulsion which indicated two layers of separation with creaming index (32 %), followed by one layer of separation for *SM* (71 %), *AM* (73 %), *MSM* (82 %) compared to *SPIM* (87 %). Thermal treatment on both microstructural and stability characteristics of emulsions prepared from pea proteins resulted in changes in droplet size distribution, the extent of flocculation state and the destabilization phenomena of emulsion systems such as creaming separation (Olsmats et al., 2025). Protein concentration is said to influence the stability of emulsion as an increased concentration provides more proteins and thereby more flocculation occurs and this enhances creaming stability

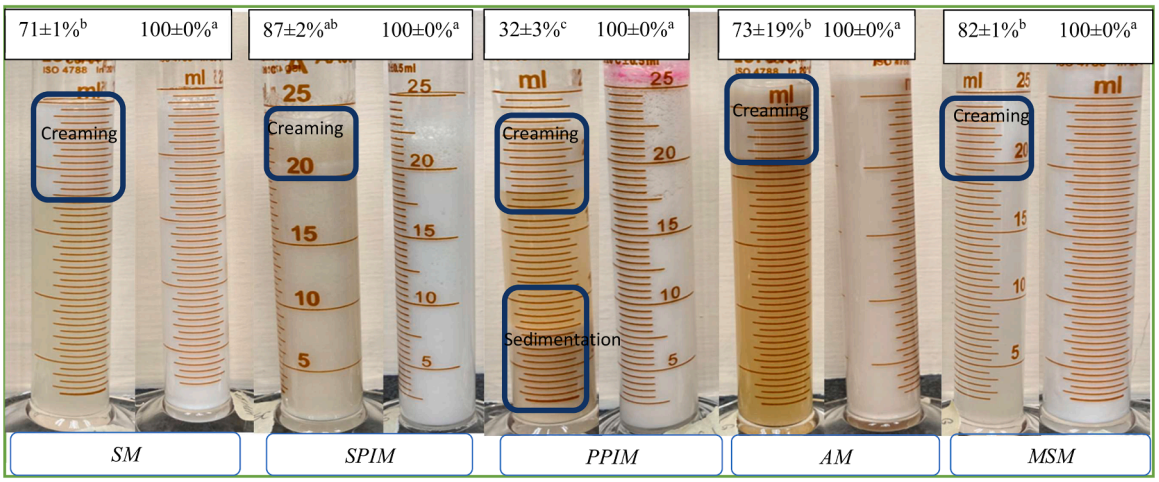

Fig. 1. Pictures and creaming stability of emulsion formulated with *SM* sodium caseinate/maltodextrin, *MSM* modified starch/maltodextrin, *PPIM* pea protein isolate/maltodextrin, *AM* gum Arabic/maltodextrin, *SPIM* soy protein isolate/maltodextrin. For each formulation, the cylinder on the left hands the emulsion before high pressure homogenisation (HPH) treatment and the cylinder on the right hands the emulsion after HPH treatment at 400 bars for four passes. Data are presented as means ± standard deviation of triplicate determinations. Means value followed by the different letters (a, b, c) are significantly different ($p < 0.05$).

(Meijers et al., 2023). It was observed that the emulsification behaviour of pea protein substantially influences the droplet size distribution. The formation of physically stable liquid emulsion is required for successful spray-drying encapsulation. Stability of emulsion is a result of the interfacial properties, functionality of wall materials and effectiveness of the homogenization process (Díaz-Montes, 2023). The incomplete emulsification of the systems resulted in the layers observed in the samples due to creaming effect, where proteins were confined to the bottom and a protein deficient emulsion in the middle. The stability of emulsion against creaming is influenced by factors including droplet size distribution, the density differential between dispersed and continuous phases, and the rheological properties particularly the viscosity of the aqueous medium (L'Estimé et al., 2024). The emulsion formulated with *PPIM* and subsequently processed through high-pressure homogenization (HPH) exhibited remarkable kinetic stability after 24 h of storage under ambient temperature, maintained complete phase stability and showed no visible separation after 24 h (Fig. 1). The effectiveness in the developed emulsion is a matter where fine dispersed droplets formed physically stable emulsions (Hossain et al., 2021). Controlled homogenization parameters were used throughout the preparation of the emulsion to ensure reproducible droplet distribution and dispersion and facilitate the development of a stable colloidal system. During high pressure homogenization, mechanical forces such as high-speed shear and cavitation disrupted coarse liquid particles into finer and more uniformly distributed droplets. The emulsifying agents rapidly adsorbed to the formed interfaces, reducing interfacial tension and preventing coalescence by providing steric and electrostatic stabilization; and with the result that the proteins exhibited partial conformational changes at the interface, thus contributing to the formation of an interfacial membrane that enhanced emulsion functional properties (Wu et al., 2023). Also, the efficacy of high-pressure homogenization in producing stable emulsions is well reported. For instance, Yesiltas et al. (2023) demonstrated the use of high-pressure homogenization in high-fat systems, creates uniformly fine droplets which aligns with the observation of a homogenous emulsion in this study, where it supports an effective spray drying. Consequently, the high-pressure homogenization had resulted in emulsions that had uniformly dispersed droplet size, high narrow distribution and dispersed.

3.2. Emulsion droplet sizes distribution

The characterisation of droplet size distribution shows heterogeneity across formulations containing different plant wall materials as seen in

Table 1
Particle distribution size of MCTs oil-in-water emulsion stabilized with different wall materials.

Emulsion sample	Particle size, D[3,2] (μm)	Particle size, D[4,3] (μm)	Span
SM	2.5 ± 0.1^{c}	2.9 ± 0.1^{d}	1.0 ± 0.1^{c}
MSM	4.2 ± 0.0^{bc}	8.5 ± 0.0^{c}	1.8 ± 0.0^{b}
PPIM	3.5 ± 0.0^{bc}	8.0 ± 0.0^{c}	1.3 ± 0.0^{c}
AM	6.5 ± 0.0^{b}	26.5 ± 0.6^{b}	2.5 ± 0.0^{a}
SPIM	16.2 ± 3.8^{a}	65.0 ± 5.6^{a}	2.7 ± 0.6^{a}

SM sodium caseinate/maltodextrin, *MSM* modified starch/maltodextrin, *PPIM* pea protein isolate/maltodextrin, *AM* gum Arabic/maltodextrin, *SPIM* soy protein isolate/maltodextrin.
Data are presented as mean ± standard deviation of triplicate determinations. Within columns, means followed by the different letters (a, b, c) are significantly different at ($p < 0.05$).

Table 1. The physical stability of emulsion is strongly influenced by droplet size where it reflects the characteristics of the disperse phase and interfacial behaviour. Among these, the span index serves as the descriptor of droplet size heterogeneity representing the width distribution independent of the median diameter. A lower span value indicates a narrow particle size distribution, thereby indicating a more homogenous system with uniformly dispersed droplets. Representative particle size distribution profiles for all MCTs oil containing emulsions were compared with *SM* emulsion—they demonstrated consistent trends. Droplet size analysis of emulsion prepared from different wall materials revealed significant differences ($p < 0.05$) among the formulations, except *SM, MSM* and *PPIM* emulsion. The selected plant-derived wall materials were found to influence the droplet size distribution of the emulsions, as evidenced by variations in the surface-weighted mean diameter D[3,2] and the volume-weighted mean diameter D[4,3] of the dispersed oil phase. The emulsions exhibited variability in droplet size distributions in the range of 2.5–16.2 μm and 2.9–65 μm, respectively after HPH treatment. These findings illustrated the importance of the wall materials chosen in developing a stable emulsion. The emulsions *SM* and *PPIM* emulsion displayed the smallest surface-weighted mean diameter D[3,2] droplet sizes of (2.5 ± 0.1 μm and 3.5 ± 0.0 μm) and narrowest distribution (span value of 1.0 and 1.3); they were homogenous in their droplet's sizes. The emulsions with smaller droplet sizes showed greater stability, demonstrated greater interfacial activity by rapid adsorption to the oil-water interface during homogenization, preventing coalescence. Stability was enhanced as a result of the

Table 2
Particle distribution size of MCTs encapsulated powders stabilized with different wall materials.

Microcapsule Sample	Particle size, D[3,2] (μm)	Particle size, D[4,3] (μm)	Span	Specific surface area, m^2/kg
SM	6.11 ± 0.12^{d}	18.09 ± 0.34^{b}	2.52 ± 0.04^{b}	1102.44 ± 20.70^{b}
MSM	5.18 ± 0.09^{e}	11.17 ± 0.14^{c}	1.88 ± 0.02^{c}	1303.78 ± 24.65^{a}
PPIM	9.16 ± 0.32^{b}	13.17 ± 0.38^{c}	1.80 ± 0.05^{c}	737.54 ± 26.59^{d}
AM	7.35 ± 0.44^{c}	17.01 ± 0.58^{b}	1.71 ± 0.07^{c}	921.40 ± 54.30^{c}
SPIM	12.22 ± 0.27^{a}	50.84 ± 5.47^{a}	3.94 ± 0.69^{a}	552.83 ± 11.73^{e}

SM sodium caseinate/maltodextrin, *MSM* modified starch/maltodextrin, *PPIM* pea protein isolate/maltodextrin, *AM* gum Arabic/maltodextrin, *SPIM* soy protein isolate/maltodextrin.
Data are presented as mean ± standard deviation of triplicate determinations. Within columns, means followed by the different letters (a, b, c, d, e) are significantly different at ($p < 0.05$).

hydrated polymer matrix. This matrix bound more water thereby increasing the emulsifying action of the matrix; thus, coalescence of the dispersed oil droplets was retarded. Also, the *PPIM* emulsion had the smallest droplet size because the pea protein is recognized for their heterogeneous composition, which is a combination of different protein fractions including globulins, albumins, and glutelins. The globulin fraction in pea protein contains three subcomponents: legumin, vicilin, and convicilin each of which contributes to interfacial activity and emulsifying properties of the proteins system (Guidi et al., 2022). Smaller droplet diameters in emulsions and narrower distributions of diameter indicate higher emulsion stability, since the dispersion uniformity of dispersion prevents coalescence and phase separation (L'Estimé et al., 2024). Protein in emulsions form interfacial membranes that protect oil-water emulsion and protect the lipids from aqueous pro-aqueous that are detrimental to oxidizable lipids. This additionally enhances the oxidative stability of the emulsions. Findings from the research further demonstrated that legumin, vicilin and convicilin together exhibit an amphiphilic characteristic as they able to stabilize the emulsions. Of the formulations tested, emulsions had similar droplet size distributions and span value, with no statistically significant differences ($p > 0.05$) observed, except for *AM* and *SPIM* emulsions that had higher span values 2.5 and 2.7, respectively indicating that emulsions had consistent emulsifying capabilities. This phenomenon also corroborates previous studies, which reported span values suggesting higher cohesiveness within the emulsion, while still maintaining a homogenous distribution of droplet diameters. Microencapsulation of fish oil has been conducted using modified starch, gum Arabic and cashew gum as the wall materials provided with mean diameters of 2.2–3.5 μm (Perez-Palacios et al., 2022). In contrast, emulsion stabilized with soy protein isolate, however, showed a larger volume-weighted mean diameter D[4,3] of 65.0 ± 5.6 μm and a broader span 2.7, indicating less effective surface coverage and possible droplet flocculation. Larger droplet sizes indicate reduced atomization efficiency, a condition that typically extends the drying times, characterized with broader particle size distributions, and less uniform morphology (Garcia et al., 2026). The result findings are consistent with the reported literature that monodisperse and more uniform droplets enhance spray drying efficiency and improve powder dispersibility by promoting faster drying and produce a more reproducible particle formation (Anandharamakrishnan & Padma Ishwarya, 2015). This is also consistent with the findings of Leister et al. (2022) who stated that protein aggregation at the interface can affect emulsion interface by promoting droplet coalescence. The small, uniform size distribution and stability of creaming and oxidation, as a larger total interfacial area is more effectively stabilized by the wall materials. The droplet size may be due to the intrinsic tendency of polysaccharide-based systems to aggregate or coalesce, which can disrupt interfacial stabilization and emulsion uniformity (Botrel et al., 2017). According to Chen et al. (2019), the high molecular weight of polysaccharides such as soy protein isolate contributes to its interfacial tension, stabilizing emulsion droplets more efficiently than low molecular weight proteins or polysaccharides. This is due to the high molecular weight being fully partitioned through the oil-water interface phases. Despite high pressure homogenization significantly reducing the average droplet size, it has also caused a broader size distributions indicating polydispersity. Wall materials do not cover the oil droplet surface sufficiently resulting in incomplete encapsulation and irregular droplet sizes. The variation in the protein concentration (~90 %), identified in the compositional specification is explained due to weak emulsifying ability of soy protein isolate. This weak emulsifying partially affects its ability to stabilize dispersed oil droplets in the complex emulsion system. According to Dias et al. (2024), the concentration of protein fractions, the overall composition profile of protein fractions in the final powder, along the pH conditions and the extraction procedures used during the production of protein isolates were reported to affect the protein solubility. Higher protein content was found in sodium caseinate (88–92 %) followed by soy protein (~90 %) and pea protein isolate (77–80 %). The emulsion system destabilization appears when dispersed oil droplets and the subsequent aggregation of proteins molecules are adsorbed at the interfacial layers. The protein solubility profiles and the emulsion droplet sizes to the emulsion stability, are importance because these properties dictate the extent to which protein can absorb and reorganize at the oil-water interface. By having smaller emulsion droplets, the smaller total available interface surface area, naturally increases contributing to the stabilization of the emulsion system with presence of smaller emulsion droplets and soluble protein (Guo et al., 2025). Nevertheless, emulsion stability is not fully determined based on its droplet diameter, as it represents only one among several contributing factors including interfacial composition and droplet interaction.

3.3. Microparticles characterization

Table 2 and Fig. 2. shows the microstructural characteristics of spray dried Medium Chain Triglycerides (MCTs) powder that were characterized by D[4,3] volume-weighted mean diameter, D[3,2] surface-weighted mean diameter, the span value and the specific surface area. These parameters are the result of laser diffraction measurement for evaluating the microstructure of MCTs oil powder after spray drying. Spray drying stable emulsions that were stabilised resulted in powders with different particle characteristics. The D[4,3] volume-weighted mean diameter of the microparticles ranged within 11.17to50.84 μm; with *MSM* yielding the smallest particles (Table 2). A unimodal particle distribution indicates the uniformity of the atomization and drying. Statistically significant differences ($p < 0.05$) were observed in both D[4,3] volume-weighted mean diameter and D[3,2] surface-weighted mean diameter and across various encapsulated powder using varied wall materials—this revealed the effect of formulation factor in controlling the droplet size and its dispersion. The microcapsule's D[4,3] particle size reported in (Table 2) was varied across formulations ranged from 11.17 ± 0.14 to 18.09 ± 0.34 μm except for *SPIM* powder (50.84 ± 5.47 μm). These results were in line with Zhou et al. (2017), where walnut oil was encapsulated using soy protein isolate (SPI) and maltodextrin and the mean particle size were approximately 11 μm, most microcapsules having a particle size distribution in the range of 2–20 μm. The findings are consistent with Cáceres et al. (2020), who showed that microcapsules obtained by spray drying stabilize with

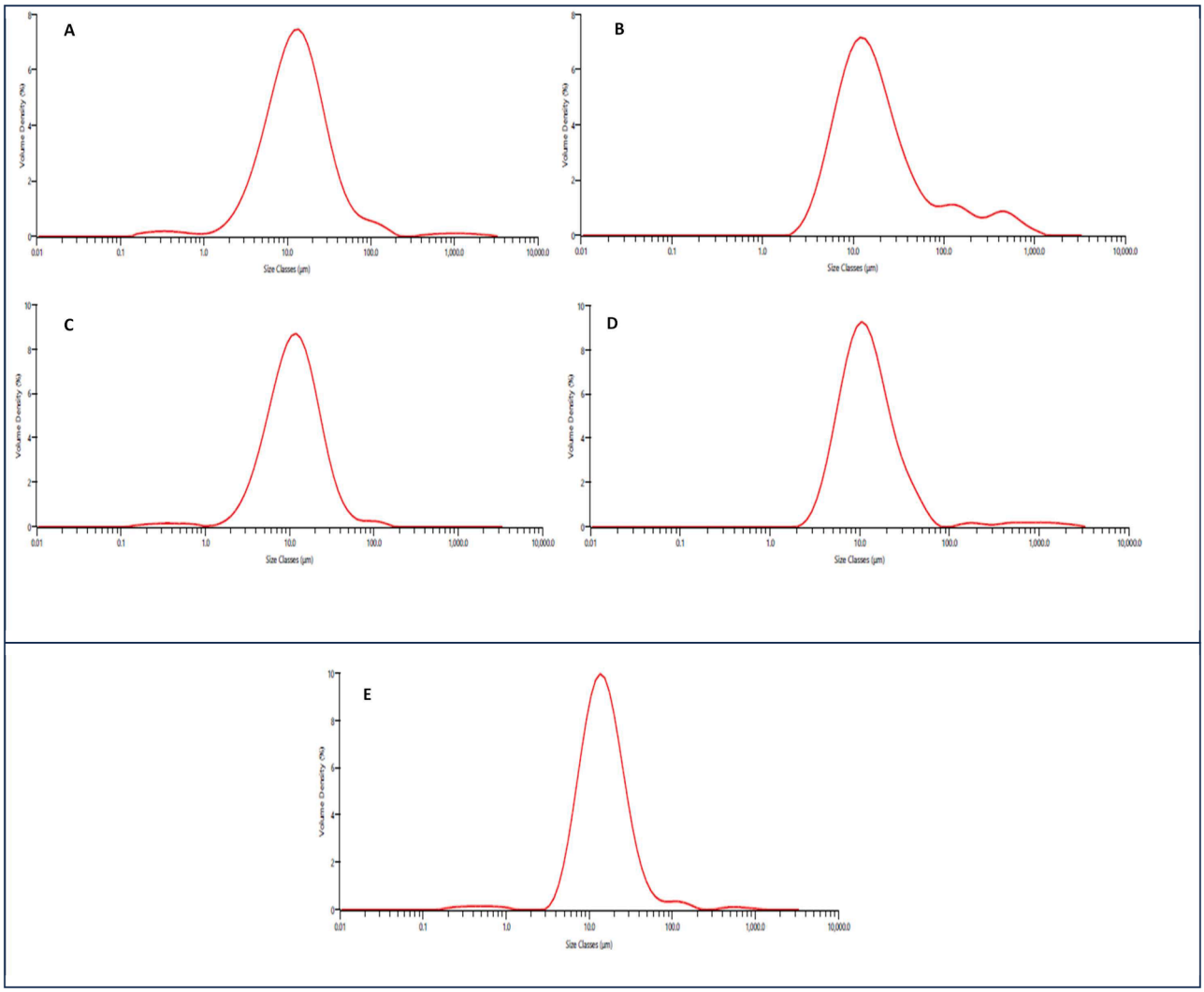

Fig. 2. Average particle size distribution of microencapsulated MCTs oil powder with different wall materials. A. *SM* sodium caseinate/maltodextrin; B. *SPIM* soy protein isolate/maltodextrin; C. *PPIM* pea protein isolate/maltodextrin; D. *AM* gum Arabic/maltodextrin and E. *MSM* modified starch/maltodextrin.

protein-polysaccharides are also in the same range. According to Szczap and Jacobs (2023), at a constant atomization velocity, the droplet size obtained is inversely proportional to the viscosity of the emulsion. High viscosity levels tend to yield larger droplets during atomization process, which subsequently produces larger powder particles. A previous study conducted by Yang et al. (2024), in which soy protein matrices were used to encapsulate ω−3 medium- and long-chain triacylglycerols showed that larger microcapsules were obtained which is expected to have unimodal particle size distribution. The increased stability and functional properties of the encapsulated system resulted from a larger interfacial surface. The selection of wall material is important because it can determine the encapsulated powder particle size distribution, and specific surface area which can influence the performance of the product in terms of solubility and stability (Yang et al., 2024). This data suggests that the choice of wall materials significantly influence the particle size distribution obtained, and thereby the encapsulating matrices are shown to have considerable influence on the microstructural characteristics. In this study, *MSM* powder produced the smallest particle size, followed by

Table 3
The characteristics of spray dried microencapsulated MCTs powders with different wall materials of moisture content, water activity, wettability, solubility and microencapsulation efficiency (MEE %).

Microcapsule Sample	Moisture Content (%)	Water activity	Wettability (s)	Solubility (%)	Microencapsulation efficiency (MEE) (%)
SM	3.35 ± 0.92^{a}	0.20 ± 0.02^{d}	67.11 ± 1.17^{c}	99.27 ± 0.53^{a}	90.85 ± 4.11^{a}
MSM	3.50 ± 0.35^{a}	0.23 ± 0.01^{c}	67.78 ± 0.67^{c}	99.09 ± 0.66^{a}	80.85 ± 4.13^{bc}
PPIM	1.38 ± 0.43^{c}	0.30 ± 0.00^{a}	31.44 ± 1.01^{d}	72.22 ± 3.90^{c}	80.72 ± 8.32^{bc}
AM	3.33 ± 0.29^{a}	0.26 ± 0.01^{b}	70.67 ± 1.12^{b}	86.65 ± 0.78^{b}	75.21 ± 7.86^{c}
SPIM	2.25 ± 0.05^{b}	0.22 ± 0.01^{c}	84.44 ± 0.88^{a}	73.74 ± 1.65^{c}	86.14 ± 5.20^{ab}

SM sodium caseinate/maltodextrin, *MSM* modified starch/maltodextrin, *PPIM* pea protein isolate/maltodextrin, *AM* gum Arabic/maltodextrin, *SPIM* soy protein isolate/maltodextrin.
Data are presented as mean ± standard deviation of triplicate determinations. Within columns, means followed by the different letters (a, b, c, d) are significantly different at ($p < 0.05$).

SM and *PPIM* while *AM* and *SPIM* powder had a larger particle size. These results agree with the most recent studies which show that the physical properties of encapsulated systems are influenced by the wall materials and emulsifier under varying processing and environmental conditions (Yeddes et al., 2022). The smaller particle sizes correspond with higher microencapsulation efficiency (MEE). Previous studies have demonstrated that reduced droplet size improves atomization performance and drying kinetics, leading to higher encapsulation yields (Adhikari et al., 2025). The results agree with the MEE data (Table 3), where SC resulted in the highest MEE value. This can be due to its balanced molecular weight, and structure containing both polar and non-polar characteristics that are useful in the adsorption at the oil-water interface. Based on previous studies reported, the combination of higher Tg and maltodextrin increased the transition glassy state of the matrix that was formed around the particles during drying, so that the MCTs oil encapsulation was preserved (Xu et al., 2024). The smaller size of particles however is probably more prone to oxidation and agglomeration. Hence, the accelerated oxidative stability studies were of great importance. The span values did not differ significantly ($p > 0.05$) for the microcapsules produced, with the exception of the formulation using *SM* and *SPIM* where samples with higher span values were recorded of 2.52 ± 0.04 and 3.94 ± 0.69, respectively and deviation was distinct. This suggests that most microcapsules that were produced had uniformity in particle dispersion, while the droplets were also of different particle size. The measured span values for *AM, MSM* and *PPIM* were 1.71 ± 0.07; 1.88 ± 0.02 and 1.80 ± 0.05, respectively showed a dispersion in narrower particle size distributions than the dispersion in the other samples. This indicates the improved flowability and the solubility of the powder. Microcapsules with narrower particle size distributions such as those produced by *MSM* and *PPIM* demonstrated an increase in flowability as opposed to the microcapsules which contained the larger particle size distributions. The emulsion stabilized by *MSM* showed the least average D[3,2] surface-weighted mean diameter and least amount of creaming over 24 h which explained its high microencapsulation efficiency.

Considering the combinations of wall material, the observed reduced homogeneity of *SPIM* emulsion resulted in wider particle size distribution sizes in the sample subsequent to encapsulation. This dispersion indicates more variability due to the atomization and interfacial stabilization mechanism during the process of encapsulation and can potentially have negative impact on bulk handling and functional performance. These findings agree well with the recent research which confirmed the impact of emulsion composition on microencapsulated powders and their structural response to emulsion composition physical properties (Li et al., 2023). The destabilized feed emulsions with *SPIM*, were consistent with the result corresponding to the emulsifier type and levels used to determine the emulsion formation and stability (Kelmer Müller & Costa, 2025). The findings suggest that *MSM* emulsion can improve dispersibility and most likely increase the rate of MCTs oil release and control its release. The specific surface area of the encapsulated powders were defined as the cumulative surface area of encapsulated powder particles and it was normalized with the unit mass which serves to be the primary attribute to measures its microstructural and functional properties. Specific surface area and average particle diameter are inversely correlated; the average particle diameter of *SM* powder (18.09 ± 0.39 μm) had the highest MEE value among all the formulations; the other formulation of *MSM* had the lower particle size distribution of (11.17 ± 0.14 μm). The results suggest that apart from the wall materials, other factors such as the particle size encapsulation efficiency, surface area and interfacial system need to be considered. The results are aligned with previous reports, where encapsulation efficiency and stability have a relationship with size of the microcapsule, the surface oils and the stability of the protein-polysaccharide microcapsules (Lobel et al., 2024).

3.4. Properties of microparticles

The determination of moisture content and water activity are critical in determining the physicochemical stability and the quality of spray dried powders. Moisture content and water activity are importance in controlling the shelf life and maintaining the functionality of the product. In food processing, a moisture content of approximately 4 % is usually taken to be the upper moisture limit for most of the dehydrated powder formulations to provide adequate storage stability, and to minimize the risk of microbial growth. MCTs microcapsules are required to have sufficient low storage moisture content and high solubility in combination which is a pre-requisite for stability during storage for use in the food industry. The spray-dried microcapsules moisture content, showed that 3.50 ± 0.35 %, 3.35 ± 0.92 %, 3.33 ± 0.29 %, 2.25 ± 0.05 % and 1.38 ± 0.43 % for *MSM, SM, AM, SPIM* and *PPIM* of wall materials, respectively. *SM, MSM* and *AM* reflected significantly higher ($p < 0.05$) moisture content than *SPIM* and *PPIM* samples. In this study, spray drying was conducted using standardized inlet temperature, feed rate, atomizer speed, and outlet temperature. Within these controlled parameters, the interaction of water with various formulation constituents was influenced by its binding behaviour and the selection of specific types of wall material incorporated into the emulsion matrix. As the process variables were the same for all samples, the changes in moisture content can be due to the materials affinity to water and water diffusion through the polymer matrix (Mohammed et al., 2020). The different characteristics of the wall materials would influence its water retaining ability, thus leading to the discrepancy in moisture content. A lower moisture content reduces the microbial growth and oxidation of the lipids. These results are also consistent with the previous study by Bae and Lee (2008) which reported microencapsulated avocado oil with the combination of whey protein isolate and maltodextrin, which had the moisture content in the range of 2.24–2.89 %. Other studies have shown that materials with low moisture content tend to show an increased hygroscopicity behaviour. This phenomenon is the result of an increased pressure differential of water vapor between the relatively dry product and its surrounding environment (Cui et al., 2020). The physical stability of the powders was physically stable for all the formulation. Moisture content was below the 4 % threshold which for microencapsulated powder is an average value based on the range commonly reported for spray dried dairy powders.

In general, all microcapsule formulations exhibited moisture content below 4 %, a threshold favourable for the stability and shelf-life of MCTs powders. The reduction in moisture values were largely due to the incorporation of maltodextrin, a wall material known for its effective film-forming abilities and moisture barrier properties (Xiao et al., 2022). Recent studies confirm that the use of maltodextrin produces a dense matrix that restricts water permeability, thereby reducing residual moisture content and enhancing retention of the encapsulated oil fraction; whereas, whilst whey protein exhibits strong emulsification properties and interfacial-film forming, it tends to interact with water molecules, contributing to higher moisture content in dried powder (Lourenço et al., 2020). In contrast, gum Arabic, effective in retaining volatile aroma compounds, was more hygroscopic and resulted in higher residual moisture content (Khodabakhshi Tabar Ahangar & Eslami, 2026). However, there are other factors to consider, aside from moisture content, such as water activity, particle morphology and encapsulation efficiency that determine functional performance in food powders (Vera Zambrano et al., 2019). Water activity (a_w) in spray dried powder describes water content in powders but it also provides information on how the interaction of water molecules with various other constituents embedded in the powder matrix influence both the aqueous phase and the surrounding characteristics (George et al., 2023). An important indicator of powder stability is a_w, which is a crucial and important parameter of food quality and safety, where microorganisms cannot grow in foods with an a_w below 0.6, thereby enhancing shelf life and reducing spoilage risk (İlhan Dincer & Temiz, 2023). Besides microbial

Table 4
Mean values and standard deviations for the bulk density, tapped density, Carr's Index and Hausner ratio of the microencapsulated MCTs powder produced.

Microcapsule Sample	Bulk Density (g cm^{-3})	Tapped Density (g cm^{-3})	Carr's Index	Hausner Ratio
SM	0.23 ± 0.01^{b}	0.32 ± 0.01^{d}	28.25 ± 4.11^{b}	1.39 ± 0.08^{c}
MSM	0.26 ± 0.01^{a}	0.33 ± 0.01^{cd}	19.50 ± 2.49^{c}	1.24 ± 0.03^{d}
PPIM	0.24 ± 0.02^{b}	0.38 ± 0.02^{b}	37.67 ± 2.26^{a}	1.60 ± 0.06^{a}
AM	0.27 ± 0.01^{a}	0.41 ± 0.03^{a}	34.14 ± 3.37^{a}	1.52 ± 0.08^{ab}
SPIM	0.23 ± 0.01^{b}	0.35 ± 0.01^{c}	33.85 ± 1.27^{a}	1.51 ± 0.03^{b}

SM sodium caseinate/maltodextrin, *MSM* modified starch/maltodextrin, *PPIM* pea protein isolate/maltodextrin, *AM* gum Arabic/maltodextrin, *SPIM* soy protein isolate/maltodextrin.
Data are presented as mean ± standard deviation of triplicate determinations. Within columns, means followed by the different letters (a, b, c, d) are significantly different at ($p < 0.05$).

stability, a_w also influences oxidative stability thus making it is essential for minimizing the lipid oxidation deterioration in microencapsulated lipid powder (Kurtz et al., 2026). The investigation revealed a statistically significant difference in water activity among the tested samples ($p < 0.05$) indicating that the formulations differed in moisture under the applied processing conditions. Variations in the hygroscopic properties of the spray dried powders could be due to factors such as the composition of the wall material, the efficiency of encapsulation and the kinetics of the drying process. According to the results, the a_w of *PPIM, SPIM* and *SM* ranged from (0.20 ± 0.02 to 0.30 ± 0.00) while *MSM* and *AM* ranged from (0.26 ± 0.01 to 0.23 ± 0.01), respectively. Powdered products with a_w levels below 0.3 are generally considered microbiologically stable, and have long-term storage stability (Drusch & Schwarz, 2006; George et al., 2023). The data indicate that the incorporation of maltodextrin decreased water activity levels, as a result of its moisture binding and film forming properties. Overall, the findings in relation to both moisture content and water activity are consistent with previously published reports, thereby confirming that maltodextrin enhances the physicochemical stability of spray-dried powders (Chng et al., 2020). The reconstitution behaviour of spray dried powders serves as an indicator of its dispersibility and solubility in aqueous system. This property reflects the capability to interact with water and thus, wettability is a critical property of dried bulk powders to absorb and rehydrate in water. It determines the ease of powder reconstitution and is considered critically importance for handling powder characteristics, manufacturing efficiency and formulation design (Murphy et al., 2020). Table 3 presents the wettability profiles of the freshly spray-dried microcapsules quantified by the time required for complete dispersion upon contact with water. In this study, wettability was assessed based on the time required for the tested powder particles to completely dissolve—the shorter the dissolution time, the better the wettability performance. A shorter dissolution time indicates faster water penetration and interaction with the powder particles. Powders containing maltodextrin were found to have better wettability dissolving due to the high hydrophilicity of the polysaccharide. The microcapsules produced using different wall material exhibited a wettability ranging from (31.44 ± 1.01 s to 84.44 ± 0.88 s). The statistical analysis indicated a significant variation ($p < 0.05$) of the wettability among the microcapsule's samples as indicated in Table 3. The microcapsules represent a heterogenous system composed of different wall materials, which exert a significant influence ($p < 0.05$) on the wettability. The favourable wetting performance observed in formulation containing maltodextrin may be due to a reduction in contact angle and a diminished proportion of free oil, and the abundance of hydrophilic functional groups distributed within the microcapsule's matrix, all of which display strong affinity toward aqueous environments (Dima et al., 2016). The dispersal of entire powders in water showed its ability to absorb water and form a homogenous suspension. Higher degrees of wettability can improve the dispersibility of microparticles in water and faster release core contents when consumed. The microcapsules made with *SPIM* have the lowest wettability (84.44 ± 0.88 s), taking the longest time to sink in water, while the *PPIM* had the highest wettability (31.44 ± 1.01 s), respectively. Variations in particle size and bulk density of the microcapsules are presented in Tables 2 and 4. The observations are aligned with previous studies, which demonstrate that wettability powdered materials are strongly influenced by physicochemical parameters including particle size, packing density, porosity, surface charge, specific surface area, the presence of amphipathic compounds and the overall surface activity of the powders (Brubaker & Moghtadernejad, 2024).

Powder solubility represents another important functional parameter that must be considered prior to its incorporation in food product formulation—as it significantly influences ingredient performance and overall product quality (Ueda et al., 2023). Powders with inadequate solubility can affect manufacturing efficiency, resulting in product inconsistency (Shah et al., 2023). The solubility of *SM* and *MSM* samples (99.27 ± 0.53 % and 99.09 ± 0.66 %) were significantly more soluble ($p < 0.05$) than *AM* samples (86.65 ± 0.78 %) while other formulations showed lower solubility values as presented in Table 3. No statistically significant difference was reported between the *PPIM* and *SPIM* formulations ($p > 0.05$), given the solubility values ranging from (72.22 ± 3.90 % to 73.74 ± 1.65 %). The enhanced solubility profiles for SM and MSM showed higher solubility exceeding 90 %, which is attributed to the low retention of surface oil after spray-drying. This observation is consistent with a recent finding that improved encapsulation efficiency enhances dispersibility and solubility in lipid-based spray-dried powders (Kurtz et al., 2026). Moreover, samples *PPIM* and *SPIM*, also showed the same solubility, and the difference was minimal. These findings are consistent with a recent report by Lan et al. (2019) indicating that lower protein solubility of commercial pea protein powders is due to a heat-induced denaturation and potential aggregation that occurs during the spray-drying process. This result may be due to the high-water solubility of maltodextrin which was included in the formulation, contributing to improved dispersibility compared to other wall materials: and this might also be due to the presence of hydrophobic MCTs oil inside all the microcapsule samples. Higher solubility suggests that MCTs oil and wall materials combine well with maltodextrin to become more hydrophilic. This contrasts with the presence of sodium caseinate which can be slightly hydrophobic and less hydrophilic of modified starch. According to Le Priol et al. (2019), the ability of protein extracts to stabilize small droplets of emulsion closely relate to their aqueous stability. When protein extracts possess high aqueous solubility, a larger fraction of protein molecules can migrate to the oil-water interface, thereby facilitating the formation and stabilization of smaller emulsion droplets. Also, limited solubility, reduces the availability of protein chains at the interface, leading to the formation of larger oil droplets. Hence, characterizing the solubility characteristics of protein extracts is necessary to evaluate the influence of wall material solubility on the microencapsulation process efficiency. In this study, the solubility and moisture content of the samples analysis showed that there were no statistically significant differences ($p > 0.05$) in either solubility and moisture content across the different formulations, with solubility values remaining consistently high 99.27 % and 99.09 % this is an attribute of significant importance for the food industry (Table 3). The increased solubility is due to the use of maltodextrin—a highly hydrophilic polysaccharide structure—as a wall material; and its

incorporation into aqueous food systems subsequent increased the moisture content in the samples. These findings are consistent with the observations of Etzbach et al. (2020) who showed that powders formulated with maltodextrin tend to retain higher moisture retention for a significant period of time than those prepared with other encapsulation materials. Furthermore, according to Chen et al. (2019), the compositional analysis of protein sources showed that pea protein isolates typically contain approximately 30 % (w/w) vicilins, whereas soy proteins isolates are mostly globulins, exceeding 80 % with a 7S/11S ratio varying ranging between 0.5 and 1.3, depending on the cultivar variety. The smaller molecular size 7S globulin fraction, tends to exhibit conformational flexibility, and have better emulsifying capacity compared to the 11S globulin fraction (Chen et al., 2019). Indeed, the solubility profiles and compositional characteristics of both soy and pea protein extracts suggest their potential as effective wall materials, for the microencapsulation of MCTs oil systems.

Microencapsulation efficiency (MEE) is one of the major determinants of wall material suitability for oil microencapsulation. Spray drying is one of the most efficient techniques, for microencapsulating oil when appropriate wall materials are chosen and optimal processing conditions are set, which are capable of achieving MEE exceeding 90 % (Carneiro et al., 2013). The comparative analysis of MEE values, sorted in ascending order according to the wall material type revealed the following pattern: gum Arabic < pea protein isolate < modified starch < soy protein isolate < sodium caseinate. The high MEE indicates the stability of emulsion droplets formed, demonstrating that the combination of wall materials has strong film-forming properties and is able to form a denser barrier during drying process. This is supported by Lima et al. (2023) for modified plant-based proteins. Although sodium caseinate has a relatively higher MEE, 90.85 ± 4.11 %, the statistical analysis showed no significant differences ($p > 0.05$) among the values obtained for modified starch, pea protein isolate, and soy protein isolate (80.85 ± 4.13 %, 80.72 ± 8.32 % and 86.14 ± 5.20 %), respectively. This finding suggests that some of plant-derived proteins also have the ability to provide comparable encapsulation performance that is similar to that of animal protein. The encapsulation efficiency of 86.14 ± 5.20 % using *SPIM* was lower than those reported previously (Premjit & Mitra, 2023), where soy protein isolate was combined with sunflower oil and yielded microcapsules of higher efficiency 90.15 %. Nevertheless, when comparing the microcapsules obtained with the same protein, the efficiency observed in the present study was consistent with previously published data (Korma et al., 2019). The structural modifications of soy protein induced by high-pressure homogenization, resulted in enhanced molecular flexibility and interfacial molecular activity. These changes promote the formation of smaller and more uniform emulsion droplets while increasing electrostatic repulsion among the dispersed phases, thus improving the encapsulation efficiency. The lower MEE values for gum Arabic (75.21 ± 7.86 %) are solely due to the characteristics of the materials used. The Tg temperature of gum Arabic (72.0 ± 0.2 °C) is significantly lower than (PPI) (99.0 ± 2.9 °C) and this is consistent with the findings reported in previous study (Can Karaca, 2020). Minimal heat treatment was used during the emulsion formation process, which may have caused the polymer matrix to unfold and hydrate insufficiently, thus reducing its encapsulation capabilities. The increase of protein concentration within the emulsion promotes the interfacial protein packing, resulting in the formation of smaller droplets in protein-stabilized emulsions (Hinderink et al., 2024). The ability of maltodextrin to influence the emulsion stability is highly dependent on the homogenization conditions, emulsion formulation, and maltodextrin type (Malaki Nik et al., 2010). A single wall material may not contain all the characteristics of an excellent encapsulating agent; hence a combination of wall materials is recommended (Chew et al., 2018). Different wall materials such as *MS, PPI* and *SPI,* in combination with maltodextrin DE10, were selected to improve the functionality of the encapsulating matrix. This was achieved by occupying voids within the matrix, reducing oxygen permeability, and enhancing encapsulation of oil efficiency. In this study, the usage of higher solid concentration within the plant-based protein formulation significantly enhanced MEE. This is due to the formation of semi-permeable crust during the initial stages of spray drying, which effectively reduced the migration of MCTs oil towards the spray dried particle surface. The development of semi-permeability during the spray drying process is a critical determinant of oil retention within encapsulated particles. This structural layer enables selective water vapor diffusion while entrapping larger hydrophobic compounds such as flavour and oil compounds (Alvarenga Botrel et al., 2012).

3.5. Bulk density, tapped density, Carr's index, and Hausner ratio (HR) of microparticles

The measured values of the bulk density, tapped density, Carr's index, and Hausner ratio (HR) for the powders are shown in Table 4. In this study, the bulk densities of the spray dried powders were found to vary within a defined range from 0.23 to 0.27 g cm^{-3} and with a progressive increase observed in the *MSM* and *AM* formulations (Table 4). Fundamentally, density increases with a reduction in particle volume at a given constant mass. The higher bulk densities recorded for *MSM* and *AM* samples are related to extensive agglomeration and partial structural collapse as shown in Fig. 3 which decreased particle volume, and as a result, increased particle packing efficiency. A higher bulk density reduced air entrapment within the powder matrix, a property that contributes to mitigating lipid oxidation during storage (Zungur Bastıoğlu et al., 2017). The powders *SM, PPIM* and *SPIM* with wall materials that had higher protein content, were found to have lower bulk densities ranging from 0.23–0.24 g cm^{-3}. Similar observations were made earlier by Chew et al. (2018), where the encapsulated powder with protein-derived wall materials were found to have the lowest bulk density. This is because high drying air temperatures promote the formation of hollow particles influencing the surface crusting and internal vapor expansion thereby, reducing the particle density (Alvarenga Botrel et al., 2012). It has been shown that the reduced bulk density observed in the MCTs encapsulated powders may be due to the porous structures of the microcapsules of the sodium caseinate which make it able to retain residual moisture and contributes to a spongy microstructure (Areekal et al., 2024). The tapped density measurements indicated statistically significant differences ($p < 0.05$) among the samples in powder flowability and cohesiveness as determined by variation in Carr's index, and the Hausner ratio (HR). Tapped density is an important parameter for packaging considerations, since higher values of Carr's index suggests reduced flowability while a higher Hausner ratio indicates greater cohesiveness lower flowability. The *MSM* and *SPIM* formulations showed comparable to *SM* samples—higher tapped density powder generally require smaller storage containers (Suhag et al., 2024). The Carr's Index serves as an indicator of powder flowability, whereas the Hausner Ratio (HR) provides a measure of cohesiveness. Accordingly pharmacopeial standards benchmark, Carr's index values ≤ 15 and Hausner ratios ≤ 1.18 as indicators of good flow properties, whereas higher values correspond to progressive deterioration in powder handling characteristics (Pharmacopeia, 2024). Carr's index range was (19.50 ± 2.49) to (37.67 ± 2.26), with HR range from (1.24 ± 0.03) to (1.60 ± 0.06). Smaller and more irregularly shaped particles may be more susceptible to agglomeration in the presence of surface oil. The slightly poorer flow in *PPIM* could be due to its broader particle size distribution and irregulate shape, which increased particulate fraction, and the flowability characteristics of the microencapsulated MCTs powders (Suhag et al., 2024). Future studies might seek to investigate the wall material properties and the surface characteristics of the encapsulated powder.

3.6. Surface morphology of microparticles

Fig. 3 shows the surface morphology of the MCTs microcapsules

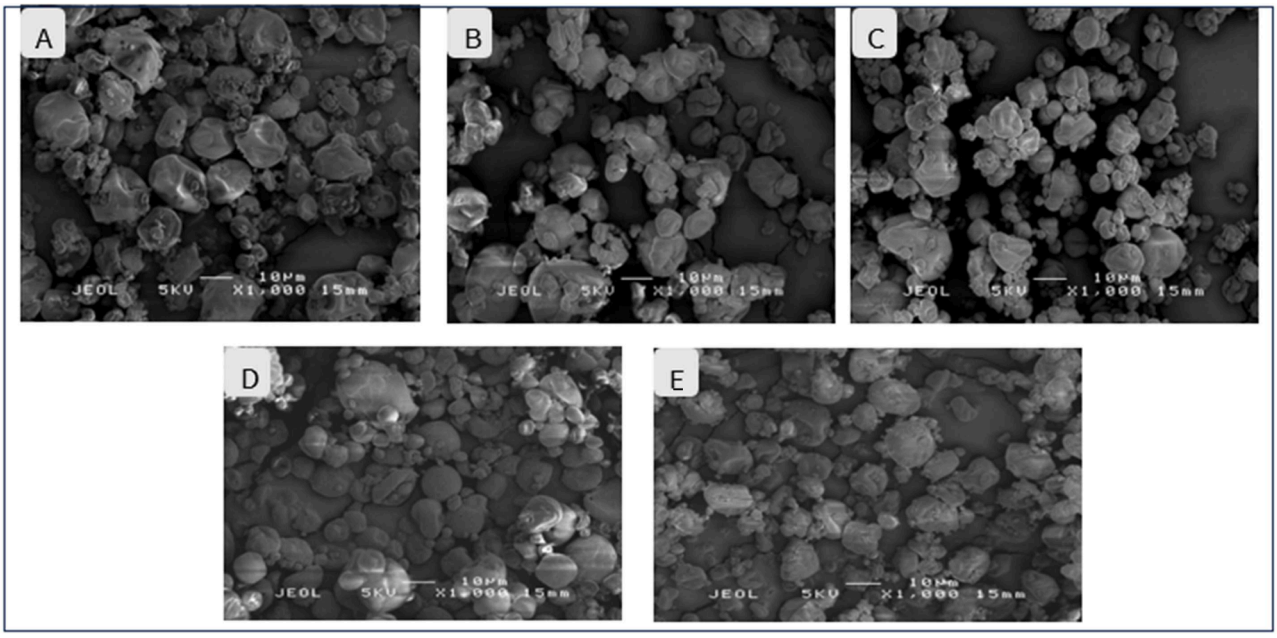

Fig. 3. Microstructure and morphology of microencapsulated MCTs oil powder with different wall materials (Magnification = × 1000). A. *SM* sodium caseinate/maltodextrin; B. *SPIM* soy protein isolate/maltodextrin; C. *PPIM* pea protein isolate/maltodextrin; D. *AM* gum Arabic/maltodextrin and E. *MSM* modified starch/maltodextrin.

consisting of different wall materials evaluated using scanning electron microscopy (SEM). The results from morphological analysis showed that microencapsulated MCTs oil particles were intact, non-fractured and had spherical shapes with smooth surfaces in varying sizes. The different wall materials used for encapsulation did not have significant effects on the surface morphology of the microcapsules. The presence of low molecular weight polysaccharides of maltodextrin contributed to the smooth particle surfaces. In contrast, the *MSM* formulation with carbohydrates-based wall materials such as gum Arabic, showed different morphological features, often appearing shrivelled (Díaz-Montes, 2023). This is a common phenomenon in spray drying, which is frequently caused by the shrinkage of a semi-permeable matrix after drying, as reported by Gomes and Kurozawa (2024) in their work on polysaccharide systems. Despite the wrinkling, no significant cracks were identified suggesting that the core material remained well contained.

The structural deformation could also be caused by the differences in solid contents and the viscoelastic properties of the wall materials used for encapsulation (Díaz-Montes, 2023). Moreover, *PPI* encapsulated microcapsules were seen to be shrivelled with the spray drying conditions, unlike those microcapsules obtained with carbohydrates-based walls (Li et al., 2019). The wrinkled surfaces are due to the result of rapid crust formation on the particle exterior, followed by intense high moisture flux during drying. These observations align with a previous study by Lin et al. (2024), who noticed that microparticles composed of soy protein isolate and soy oil reported similar morphological behaviour. Similarly, studies involving sunflower oil encapsulated with whey protein isolate and maltodextrin (Gomes & Kurozawa, 2024) have reported similar structural characteristics. The observed surface morphology aligns with the phenomenon reported by Walton and Mumford (1999), wherein rapid surface crust formation leads to the collapse of microparticle structures of the encapsulated powders. Nevertheless, further investigation into the internal features through microstructural analysis is recommended to provide a more comprehensive elucidation. Although the presence of a shriveled surface morphology may negatively influence powder flowability, there were no cracks or fissures observed in most of the samples. These findings suggest that the microencapsulation of MCTs oil using the selected wall materials contributes to enhanced core retention and improved structural stability of the powder (Areekal et al., 2024). The wall material appears to play a critical role in maintaining the stability of the microcapsules throughout the drying process and storage. High solid content may contribute to the development of shriveling surface morphology in microcapsules, because it prevents complete drying and cooling during spray drying. This incomplete process promotes inward collapse of the protein matrix, resulting in structural deformation (Walton & Mumford, 1999). According to Oliveira et al. (2025) proteins such as casein and soy have amphiphilic and gel-forming properties that contributes to this behaviour especially under high temperatures drying conditions, where the outer shell solidifies before internal moisture escapes (Oliveira et al., 2025). Despite the irregular morphology, the encapsulation often remains high, demonstrating that shrivelling does not necessarily affect the functionality of the encapsulated powder performance (Gomes & Kurozawa, 2024). The presence of surface shriveling is a characteristic commonly related to spray-dried particles and is due to rapid moisture loss and crust formation.

3.7. FT-IR spectra of microparticles

Fig. 4. displays the FT-IR spectra of the individual raw wall materials, maltodextrin, MCTs oil, and the resulting microcapsules prepared with different combinations of wall materials such as sodium caseinate/maltodextrin, soy protein isolate/maltodextrin, pea protein isolate/maltodextrin, gum Arabic/maltodextrin and modified starch/maltodextrin. In this study, FTIR analysis provided qualitative confirmation of encapsulation by identifying the presence of functional groups associated with the encapsulated MCTs oils and the coexistence of all material components within the microcapsules. The identification of functional groups was achieved through analysis of vibrational characteristics related to all components involved in the microencapsulation process. The FT-IR spectral data provided information on the formation of microcapsules as evidenced by alteration in peak morphology and intensity of IR adsorption across the samples. MCTs oil vibrational modes were observed and associated with (C-H stretching) vibration in aliphatic hydrocarbons at 2954.88, 2924.12, 2855 cm^{-1} and 1741.03 cm^{-1}, (C=O stretching) vibration in ether groups, building blocks of

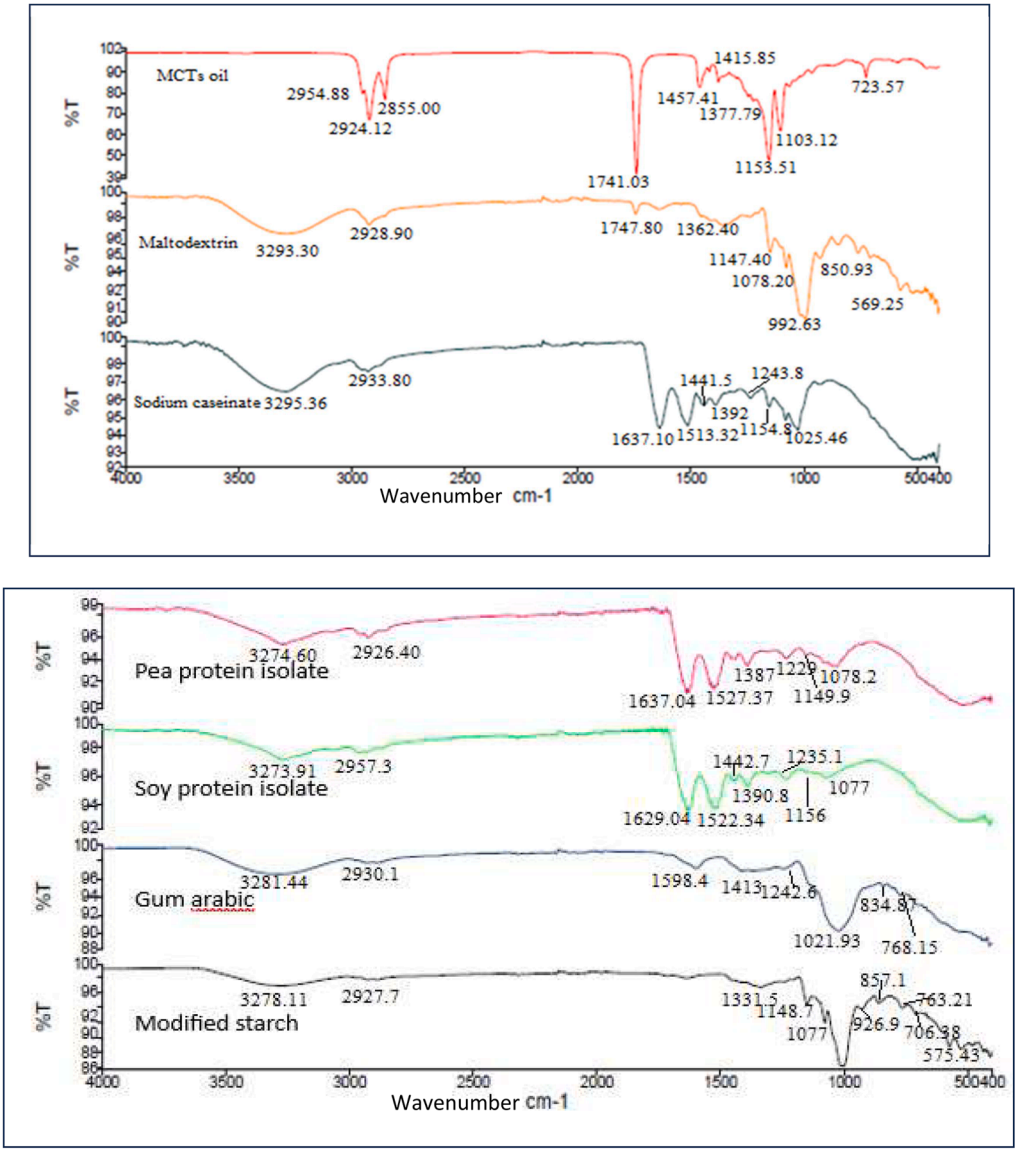

Fig. 4. FT-IR spectra of raw wall materials, MCTs oil and the MCTs encapsulated produced using different wall materials combination, sodium caseinate/maltodextrin, soy protein isolate/maltodextrin, pea protein isolate/maltodextrin, gum Arabic /maltodextrin and modified starch/maltodextrin.

triglycerides and 1457.41 cm^{-1} associated with (C-H bending) vibrations in methylene groups and band at 1153.51 cm^{-1} which corresponded to the C-O-C stretching indicate of ester linkages (Šebek, Knaanie et al., 2013). In the MD spectrum, prominent O-H stretching band (3293.3 cm^{-1}) confirmed the presence of hydroxyl groups while additional C-H stretching from the carboxylic group (2928.90 cm^{-1}) whilst signals due to carboxylic moieties and ether groups 1747.80 cm^{-1} (C=O stretching), 1362.40 cm^{-1} (O-H bending), 1147.40, 1078.20, 992.63 cm^{-1} C-O stretching/C-O-H bending substantiated its polysaccharide structure. These spectral findings are aligned with previously reported data by Chew et al. (2018). As a wall material, maltodextrin demonstrates favourable hydrophilicity, film-forming capacity, and adhesive properties, all of which enhance its encapsulation performance. Sodium caseinate, an amphiphilic protein molecule presented strong amide I and amide II bands, together with absorptions attributable to 1637.10 and 1513.32 cm^{-1} (C-O stretching) and N-H bending vibrations, respectively. Intense stretching at 3295.36 cm^{-1} (O-H stretching) bands indicated extensive intra- and inter-molecular hydrogen bonding, while C-H stretching vibrations suggested a degree of hydrophobic character 2933.8 cm^{-1} (Ardestani et al., 2022). Peaks in the carboxylate region (O-C-O) of 1441.5 cm^{-1} and at 1025.46 cm^{-1}C-O stretching in hydroxyl groups further confirmed its complex structure. Similarly, PPIs displayed absorption bands within the 1527.37 and 1637.04 cm^{-1}, amide I and amide II bands reflecting peptide linkages and secondary structural elements of protein-based wall materials. The spectra of both pea and soy protein isolate were characterized by the prominent amide I (C=O stretching) and amide II (N–H bending vibrations) bands, which are indicative of the secondary structural elements such as α-helices and β-sheets (Kong & Yu, 2007). The presence of these bands confirms the proteinaceous nature of the isolates and their potential role in stabilizing emulsions and contributing to the matrix stability post spray drying. The absorption band at 1229 cm^{-1} indicates the presence of amide III vibrations modes. The FT-IR spectrum of SPI has typical adsorption peaks at 1629.04 cm^{-1}, 1522.34 cm^{-1}, 1235.1 cm^{-1} corresponding to amide I, amide II, and amide III, regions, respectively. This bands are typically associated with C=O stretching, N-H bending, and C-N stretching vibrations, respectively reflecting the secondary structural elements of the protein. These spectral features affirm the

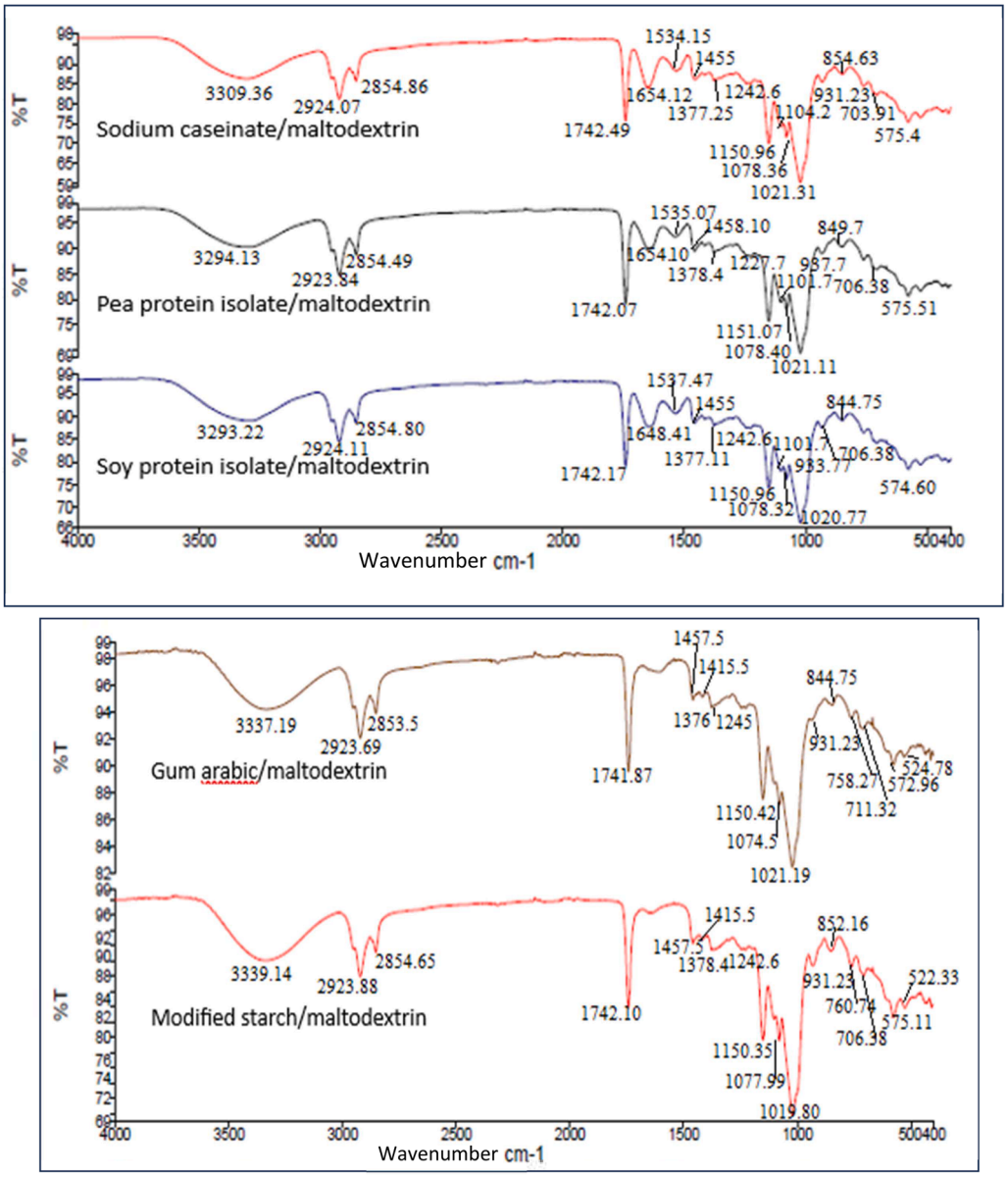

Fig. 4. (*continued*).

structural stability and conformational characteristic of the proteins and are consistent with previously data on protein secondary structures (Qu et al., 2015). The presence of these bands confirms the proteinaceous nature of the isolates and their potential role in stabilizing emulsions and contributing to the matrix stability post spray drying. Gum Arabic, a complex branch of polysaccharides, showed characteristic peaks associated with uronic acid residues typically observed the absorption band at 3281.44 cm^{-1} corresponding to (O-H stretching), indicating the presence of hydrogen-bonded hydroxyl groups. A peak at 2930.1 cm^{-1} was assigned to (C-H stretching from the carboxylic group) while the band at 1598.40 cm^{-1} reflected either C=O stretching or N-H bending which is associated with the carbonyl group of uronic acid residues. The additional signal at 1413 cm^{-1} was due to CH_3 bending and C-H bending vibrations, and the absorption at 1021.93 cm^{-1} was characteristics of (C-O stretching). These spectral features are consistent with the structural presence of arabinogalactan within gum Arabic, and align with previously reported findings by Chew et al. (2018). These bands are consistent with previous reported findings that indicated gum Arabic's unique composition, including arabinogalactan-protein complex and glucuronic acid units, which exhibit excellent emulsifying properties (Ali et al., 2009). In addition, the MS exhibited distinct absorption bands at 3278.11 cm^{-1} corresponding to (O-H stretching) vibrations that confirms the presence of hydroxyl groups typically associated with starch-derived based polysaccharides. The peak at 2927.70 cm^{-1} was due to C-H stretching vibration from carboxylic group, while the band at 1331.50 cm^{-1} reflected O-H bending, further corroborating the hydroxyl-rich molecular structure of the material. These spectral features reflect the functional group composition typical of polysaccharide-based wall materials used in the microencapsulation. Modified starch undergoes partial depolymerization and functional structures, thereby altering the vibrational structures (Zhu et al., 2022). The modifications could enhance emulsification and encapsulation properties making MS a suitable carrier in spray-dried systems. Also, structure peaks around 1148.7 cm^{-1} and 1077 cm^{-1} are associated with C-O stretching vibrations in the polysaccharide backbone. After spray drying, the five encapsulated powders reveal the presence of both oil, protein and maltodextrin. The maltodextrin was 575.10–1021.31 cm^{-1}, and the similarities in the spectra suggest that maltodextrin is the primary component in most of the mixtures, with the presence of C-H stretching peaks. The typical peak of protein components associated

with amide I, amide II, and amide III bands was observed 1242.6–1654.12 cm^{-1}. Variations in peak positions and intensities within the amide I and II regions might reflect differences in protein secondary structure and composition. The identified peaks of MCTs oil at 2853.5–2923.69 cm^{-1} corresponded to (C-H stretching) vibration of aliphatic hydrocarbons typical of medium chain triglycerides, and at 1741.87–1742.90 cm^{-1} associated with C=O stretching vibration of ester groups. These spectral features confirm the successful incorporation of MCTs oil within the microcapsules. The carbohydrate components exhibited absorption bands corresponding to C-O stretching vibrations, with a prominent peak at 1021.93 cm^{-1}. This signal (C-O stretching) is consistent with the presence of arabinogalactan, a major structural component of gum Arabic. The spectral analysis confirms that the encapsulation and molecular integration of the oil phase within the biopolymer network, aligns with previous encapsulation studies (Gharsallaoui et al., 2007).

4. Conclusions

This study elucidates the efficacy of four plant-derived wall materials for MCTs oil microencapsulation that address the emerging demand for sustainable alternatives to animal-based encapsulants. Microcapsules prepared by PPI wall materials demonstrated reduced moisture contents and water activities resulting in enhanced shelf stability. Through comparative analysis of microcapsule structural, encapsulation efficiency, physical properties including surface morphology, the findings demonstrate that selected plant-derived matrices exhibit comparable functional performance to animal-derived materials. These findings are significant in the developments of enriched formulation aimed at achieving higher product yield consisting of MCTs microcapsule 40 % oil (w/w) in diverse functional food and beverages, pharmaceuticals and nutraceuticals. The findings from this study point to a viable sustainable alternative and contribute to advancing encapsulation strategy that enhance process efficiency and wall material selection. Future research should focus on investigating the oxidative stability and in-vitro digestion behaviour of encapsulated microcapsules of MCTs.

CRediT authorship contribution statement

Hoi Chin Hew: Writing – review & editing, Validation, Supervision. **Siok Peng Kek:** Writing – review & editing, Visualization, Validation. **Chin Ping Tan:** Writing – review & editing, Supervision, Funding acquisition, Data curation, Conceptualization. **Siou Pei Ng:** Writing – review & editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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