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Hydrolyzed Glucomannan-Maltodextrin Matrices for High-Efficiency Spray-Dried Iron Encapsulation

(Matriks Glukomanan-Maltodekstrin Terhidrolisis untuk Pengkapsulan Besi Kering-Sembur Berkecekapan Tinggi)

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ABSTRACT

Efficient encapsulation of iron is crucial to enhance its stability, maintain functionality, and ensure cost-effective application in food systems. In this study, a novel encapsulation matrix combining hydrolyzed glucomannan and maltodextrin was developed to produce spray-dried iron particles with improved physicochemical properties. The effects of drying temperature (60-90 °C), glucomannan concentration (1-3%), and iron content (20-30 mg/g matrix) were systematically evaluated. Increasing these parameters significantly enhanced water-particle interactions, resulting in higher solubility, swelling capacity, and wettability. The best-performing formulation - 30 mg iron/g matrix, 3% hydrolyzed glucomannan, and 30% maltodextrin - achieved an encapsulation efficiency of 98.4%. Morphological and structural analyses showed that the particles contained uniformly distributed iron, had reduced particle size, and exhibited superior thermal stability. These characteristics not only contribute to improved storage stability but also facilitate rapid dispersion in aqueous systems, enhancing bioavailability potential. Overall, this work demonstrates the effectiveness of hydrolyzed glucomannan-maltodextrin blends as encapsulation matrices for producing stable, functional iron powders. The approach offers a promising, energy-efficient strategy for food fortification, with potential applications in addressing iron deficiency through more effective and consumer-friendly delivery systems.

Keywords: Encapsulation efficiency; engineering; morphology; thermal stability; water interaction

ABSTRAK

Pengkapsulan besi yang berkesan adalah penting untuk meningkatkan kestabilannya, mengekalkan fungsinya dan memastikan aplikasi yang menjimatkan kos dalam sistem makanan. Dalam kajian ini, satu matriks pengkapsulan baharu yang menggabungkan glukomanan terhidrolisis dan maltodekstrin telah dibangunkan untuk menghasilkan zarah besi kering-sembur dengan sifat fisikokimia yang dipertingkatkan. Kesan suhu pengeringan (60-90 °C), kepekatan glukomanan (1-3%) dan kandungan besi (20-30 mg/g matriks) telah dinilai secara sistematik. Peningkatan parameter ini dengan ketara memperkukuh interaksi air-zarah, menghasilkan kelarutan, kapasiti pembengkakan, kebasahan dan higroskopisiti yang lebih tinggi. Formulasi terbaik - 30 mg besi/g matriks, 3% glukomanan terhidrolisis dan 30% maltodekstrin-mencapai kecekapan pengkapsulan sebanyak 98.4%. Analisis morfologi dan struktur menunjukkan bahawa zarah mengandungi zat besi yang diedarkan secara seragam, mempunyai saiz zarah yang lebih kecil dan menunjukkan kestabilan terma yang unggul. Ciri ini bukan sahaja menyumbang kepada kestabilan penyimpanan yang lebih baik, tetapi juga memudahkan penyebaran pantas dalam sistem berair, meningkatkan potensi kebolehserapan bio. Secara keseluruhannya, kajian ini membuktikan keberkesanan gabungan glukomanan terhidrolisis–maltodekstrin sebagai matriks pengkapsulan untuk menghasilkan serbuk besi yang stabil dan berfungsi. Pendekatan ini menawarkan strategi peneguhan makanan yang menjimatkan tenaga dengan potensi aplikasi dalam menangani kekurangan besi melalui sistem penghantaran yang lebih berkesan dan mesra pengguna.

Kata kunci: Kecekapan pengkapsulan; kestabilan terma; interaksi air; kejuruteraan; morfologi

INTRODUCTION

Iron plays a crucial role in a wide range of metabolic processes in our bodies, making it an essential element (Dehnad et al. 2023). Unfortunately, iron deficiency is the most common nutritional deficiency suffered by about one-third of total world population (Man et al. 2022). These deficiencies often result from monotonous, low-quality diets that do not fulfil nutrient needs. In regions where nutritious foods are lacking or have limited access, which leads to insufficient nutrient intake, food fortification emerges as a promising solution (Zimmermann & Windhab 2010). Nevertheless, directly adding iron to the meals leads to various issues as well as unwanted sensory properties. In addition, contact of the iron with the ambient conditions could also reduce its bioavailability properties (Khosroyar et al. 2012).

Spray-drying encapsulation, one of the most popular encapsulation techniques, requires a feed solution with low viscosity at around 300 cps to avoid nozzle blockage (Wardhani et al. 2020). Due to its high viscosity which is more than 10,000 cps for a 1% solution (Wardhani et al. 2022), glucomannan is limited to be used for spray-drying encapsulation method. Proper glucomannan degradation reduced its viscosity; hence, it was fit for the spray-dried application. The degradation also led to an increase in its antioxidant properties (Wardhani et al. 2022), an important characteristic of protecting iron from oxidation. However, the concentration for the spray-dryer's feed cannot exceed 3% (Wardhani et al. 2024, 2023) due to the thick glucomannan solution, which is capable of blocking the atomizing nozzle. This condition leads the spray drying process to become energy inefficient. Moreover, Yun, Devahastin and Chiewchan (2021) stated that higher solids concentration in a matrix could lead to forming a more compact encapsulation, which increased its encapsulation ability. Hence, glucomannan should be combined with other materials to maximize the goodness of encapsulation and efficient drying process.

Encapsulation using material combination of matrix has been conducted. In spray-drying encapsulation, maltodextrin is a popular polysaccharide for matrix as it is cheaper, easily available, and could act as stabilizing agent in encapsulation and resistance enhancer to external environmental factors (Kaul et al. 2022). However, maltodextrin is not capable of forming a strong protection film, which causes low prevention of bioactive degradations (Mohammed et al. 2021). Kurniasih et al. (2018) successfully produced spray-dried phycocyanin with combination matrix of alginate and maltodextrin. Iron and zinc encapsulation was conducted by Kaul et al. (2022) by combining potato starch and maltodextrin. The combination of glucomannan and maltodextrin has been proven to enhance the encapsulation efficiency of sweet potato leaf extract (Sari, Harmayani & Santoso 2023). The aims of this research were to produce spray-dried iron with a combination of maltodextrin and hydrolyzed glucomannan as the matrix and to determine its physicochemical properties. This work introduces a synergistic matrix system that not only protects encapsulated iron but also enhances its physicochemical properties, paving the way for more efficient and cost-effective applications in food and pharmaceutical industries.

MATERIALS AND METHODS

MATERIALS

Glucomannan powder of 901,175 Da was produced by Now Foods (Bloomingdale, Illinois, US). Food-grade maltodextrin was purchased from a local store. Iron sulfate heptahydrate ($FeSO_4.7H_2O$), HCl, NaOH, and other chemicals were bought from Merck (Kenilworth, NJ, USA) in analytical grade.

GLUCOMANNAN HYDROLYSIS AND IRON ENCAPSULATION

Glucomannan hydrolysis and encapsulation were performed according to the method of Wardhani et al. (2020), but with a different formulation. Glucomannan solutions were prepared in different concentrations (1; 2; 3% w/v, 100 mL). After completely dissolved, cellulase was added to give 50 ppm final concentration. The hydrolysis was conducted under continuous stirring at 3000 rpm for 12 h in ambient conditions. The hydrolysis was stopped by heating the solution for 10 min at 80 °C.

Maltodextrin was added to the hydrolyzed glucomannan solution to form a solution with various weight ratios of glucomannan:maltodextrin (1:30, 2:30, 3:30 w/w), followed by $FeSO_4.7H_2O$ addition (20; 25; 30 mg/g matrix). The feed solution was mixed until homogeneous solution was obtained and was subsequently fed to a spray-dryer with ±20 mL/min flowrate at different temperatures (60; 75; and 90 °C). The obtained powder sample was stored in a closed container at ambient temperature.

SOLUBILITY AND SWELLING

Powder sample (0.1 g) was dispersed in 10 mL of distilled water and heated at 60 °C for 30 min. After cooling down, the sample suspension was centrifuged at 1538 × g for 10 min. The supernatant and the pellet were separated into different containers and weighed. Both the supernatant and the pellet were then oven-dried until constant-weighed. The weights were recorded for solubility and swelling determination using Equations (1) and (2) (Wardhani et al. 2019).

$$solubility\ (\%) = \frac{weight\ of\ dried\ supernatant}{weight\ of\ initial\ supernatant} \times 100\% \quad (1)$$

$$swelling = \frac{weight\ of\ wet\ pellet}{weight\ of\ dried\ pellet} \qquad (2)$$

WETTABILITY AND MOISTURE CONTENT

Wettability was evaluated using the wetting time (immersion) method following Ferrari, Germer and de Aguirre (2012) by immersing 1 g of the powder in 250 mL distilled water at 25 °C. The time required for the powder to be completely submerged was considered. Meanwhile, the moisture content of the sample was measured (AOAC 2005) for the powder after 2 days of storage.

ENCAPSULATION EFFICIENCY

The iron encapsulation efficiency was determined using spectrophotometric method (Correâ-Filho et al. 2019). Iron powder (0.1 g) was dissolved in 20 mL distilled water. After completely dissolved, the solution was mixed with sodium acetate buffer (8 mL, 98.4 g/L), phenanthroline solution (10 mL, 1 g/L), and hydroxylamine hydrochloride solution (1 mL, 100 g/L), and then brought to 50 mL using distilled water. The solution was left for 10 min for colour development, which was then analyzed using UV-Vis spectrophotometer at 508 nm against the iron standard. The encapsulation efficiency (EE) was calculated using Equation (3).

$$EE\ (\%) = \frac{^{Fe}sample}{^{Fe}initially\ added} \times 100\% \qquad (3)$$

SURFACE MORPHOLOGY AND PARTICLE SIZE

Surface morphology, as well as the composition of the iron powder, were determined using Scanning Electron Microscope-Energy Dispersive X-ray (SEM-EDX) JEOL JSM-6510LA (Musashino, Akishima, Tokyo, Japan). The distribution of powder size was determined using a laser diffraction instrument (Malvern Mastersizer 2000, Malvern Panalytical Ltd., Worcestershire, UK). Both analyses were conducted using the instruments used by Wardhani et al. (2021).

FUNCTIONAL GROUPS

Functional groups of the iron powder were analyzed from IR spectra recorded by FTIR PerkinElmer Spectrum Two UATR FT-IR spectrometer (Perkin–Elmer, Waltham, MA, USA) at 4000 - 400 cm^{-1} (Wardhani et al. 2021).

THERMAL PROPERTIES

The thermal properties were determined using simultaneous differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) using NEXTA STA (Hitachi STA200RV with Real View Sample Observation, Hitachi, Tokyo, Japan) at a temperature range of 30-550 °C, heating rate of 10 °C/min (Wardhani et al. 2025). The analysis was conducted on ~6.5 mg of sample using nitrogen as carrier air at 10 mL/min flow rate.

STATISTICAL ANALYSIS

All experimental data were analyzed using SPSS software version 22.0 (IBM Corp., Armonk, NY, USA). Results were expressed as mean ± standard deviation (SD). One-way analysis of variance (ANOVA) was performed to determine significant differences among treatments, followed by Tukey's post-hoc test for multiple comparisons. Statistical significance was established at $p<0.05$.

RESULTS AND DISCUSSION

SOLUBILITY AND SWELLING

Solubility is an important parameter to support fortification process because food additives should be mixed homogeneously with foods, which are commonly water-based. However, the solubility of iron particle in foods must be controlled as soluble iron could cause unacceptable flavor and taste (Hurrell 2021). Figure 1 shows the solubility of iron powder, which is encapsulated with various matrix formulations and drying temperatures. The solubility of the powder is significantly influenced by glucomannan content and drying temperature ($p<0.05$). Glucomannan interacts highly with water as it contains abundant hydroxyl groups which promote hydrogen bonds (Zhao et al. 2024). Hence, adding glucomannan to the matrix formula could improve powder solubility significantly. An inline relation between matrix concentration and powder solubility was also found by Şahin-Nadeem et al. (2013).

Besides glucomannan content, increasing iron content in powder also caused the particle to be more soluble ($p<0.05$). $FeSO_4.7H_2O$ was used in this study as iron source, which is listed as hygroscopic compound (Tsiura et al. 2021). This hygroscopicity is related to higher hydration rate of particles, which also accelerates the dissolution process. Furthermore, more hygroscopic iron contained in particles could attract more water and improve iron particle solubility.

Meanwhile, higher drying temperature enhanced powder solubility ($p<0.05$) as more porous particle was formed during drying process. Higher temperatures accelerated the drying of outer layer of particles, which created more hollows inside them (Wardhani et al. 2020). More pores in particles helped the water penetrate the powder. A similar result was also found by Jafari, Ghalegi Ghalenoei and Dehnad (2017), who found an insignificant increase in the solubility of pomegranate juice powder at different drying temperatures. Pores formation in particles also lowered their density, which eased the particle to be sunk in water (Fazaeli et al. 2012).

Swelling describes the process where particles absorb water and expand, influencing structure, flavor, functionality, and nutritional attributes (Jia et al. 2023). As part of release mechanism, swelling occurs before dissolution process and indicates the easier water molecules absorption through the wall material (Srivastava et al. 2022). The drying temperature, iron content, and glucomannan concentration significantly affected ($p<0.05$) the swelling degree of iron particles (Figure 1). The trend of swelling power as the effect of drying temperature, iron content, and glucomannan concentration is similar to the trend of solubility. Solubility and swelling of spray-dried powder have in-line correlation as both of the properties are influenced by the water absorption ability of a material, which is related to the formation of covalent bonds between water molecules and hydroxyl groups of the matrix (Wardhani et al. 2020).

WETTABILITY

Wettability refers to the required time for the powder to be completely wet without any agitation. In this state, the powder absorbs water and overcomes the surface tension differences with it (Caliskan & Nur Dirim 2013). Matrix composition and drying temperature significantly affected the wettability time (Figure 2). Glucomannan and $FeSO_4.7H_2O$ attracted water easily, which accelerated the wetting process of iron powder and shortened the wetting time.

Pores formation during drying at higher temperature increased the rate of water penetration to iron particle. Hence, less time is needed to make the particle totally wet. The wetting time needed was around 382-487 s at 60-90 °C drying temperature. Compared to the result of Wijayanti et al. (2024), who conducted spray drying process of garlic extract-maltodextrin feed at 165-225 °C, these wetting times are shorter. In this study, feed solution contained more solid content and glucomannan, which caused faster water interaction. Wettability improvement of higher solid content of matrix was also found by Hardy and Jideani (2018) on Bambara groundnut milk powder encapsulated by maltodextrin. Besides, thermal structural change might occur in maltodextrin after 200 °C (as shown in DSC results in the following section), leading to physicochemical properties of the powder, which prevent the particle from wetting.

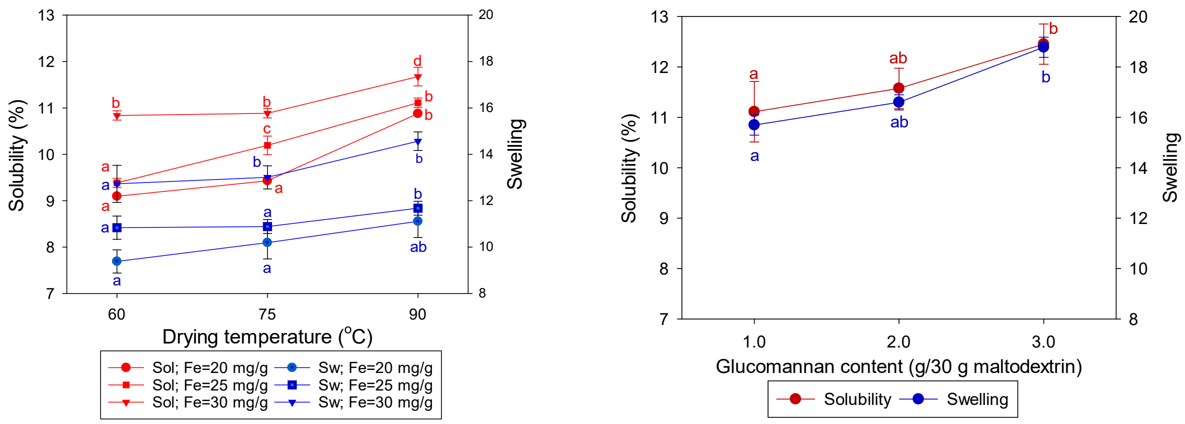
MOISTURE CONTENT

Figure 2 described that the spray-dried iron particles have moisture content of around 18-24%. This value is above the standard of powder storage (13-14%) (Skřivan et al. 2021) which can promote bacterial growth. Tay et al. (2021) obtained the spray-dried powder with moisture content of 8-10% after drying at 60-100 °C, which was lower than this study. In this study, the powder is not directly analyzed after drying process, hence, some moisture had probably been absorbed during storage. Moreover, immediate moisture analysis after drying and controlled storage conditions are expected to reduce moisture absorption further and improve powder stability.

The figure also shows that the moisture contents of iron particles are decreased by increasing air-inlet temperature, but are in line with glucomannan concentration and iron content. With more heat applied, more water was removed during drying process. Besides air-inlet temperature, the properties of feed solution also affected the drying process. Pang, Yusoff and Gimbun (2014) stated that the moisture content of spray-dried particles was affected by air-inlet temperature, feed composition, and hygroscopicity of each matrix material. In this study, the use of higher concentration of glucomannan and $FeSO_4.7H_2O$ increased the moisture content. Both compounds formed stronger water bindings, hence hindering the water removal and increasing the amount of water left after drying process. However, the effect of iron content on moisture content is not significant. Although polysaccharides are commonly water soluble, some of them have superior water bonding, including glucomannan. Arabic gum is another polysaccharide which was found to bind more moisture compared to other starch derivatives (Şahin-Nadeem et al. 2013).

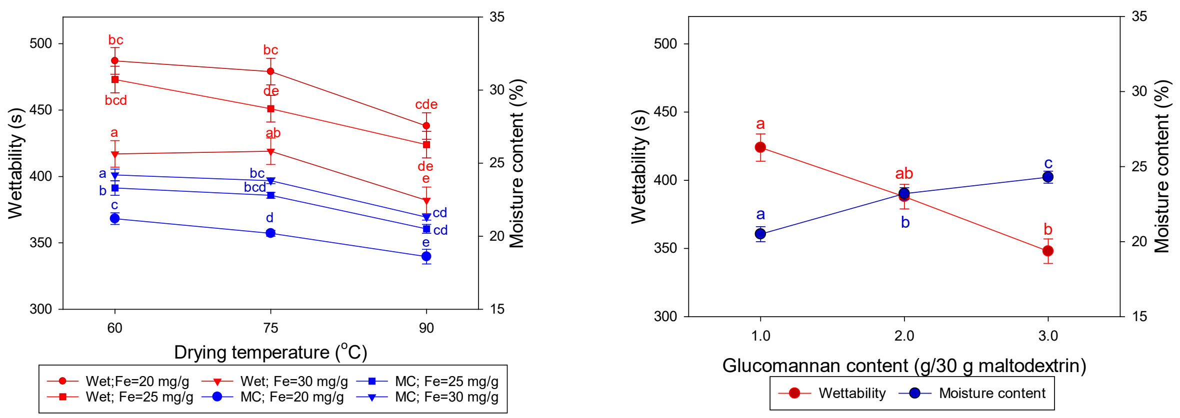
ENCAPSULATION EFFICIENCY

The encapsulation efficiency was significantly affected by the iron content and glucomannan concentration (Figure 3). With the same amount of maltodextrin, more glucomannan addition increases the solid content of the feed solution. Higher soluble solids accelerated the formation of semi-permeable barriers during drying, which prevented iron loss (Akhavan Mahdavi et al. 2016). With 30 g of maltodextrin and 1 g of glucomannan, the lowest encapsulation efficiency in this study was 97.94%. This result was higher than the result of Kaul et al. (2022), who found 92.75% active agent entrapped in 24 g of maltodextrin and 1 g of potato starch. Therefore, more solid content was important to form a stronger protection barrier of bioactive and increase the encapsulation efficiency. Besides the ratio of solids and active agents, the properties of carrier agent also impacted the encapsulation efficiency of spray-dried particles (Huang, Wang & Yang 2020; Tupuna et al. 2018). Maltodextrin has low film-forming ability, which lacks its ability to prevent oxygen interaction with active agents (Loksuwan 2007). Glucomannan has a better ability to entrap iron which is water-soluble, as glucomannan is highly hydrophilic and has high water absorbency properties. Therefore, glucomannan binds the iron with maltodextrin and maintains it during the drying process. The polysaccharides blend to improve encapsulation ability was also found by Cano-Higuita, Malacrida and Telis (2015).



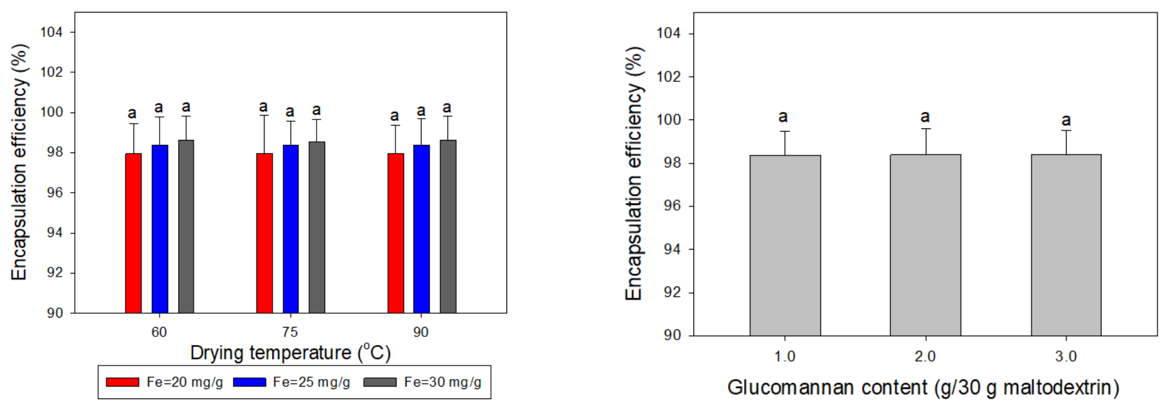
(a) (b)

FIGURE 1. Solubility (Sol) and swelling (Sw) of spray dried powder as the effect of (a) air-inlet temperature, iron addition, and (b) glucomannan content



(a) (b)

FIGURE 2. Wettability (Wet) and moisture content (MC) of spray-dried powder as the effect of (a) air-inlet temperature, iron addition and (b) glucomannan addition



(a) (b)

FIGURE 3. Encapsulation efficiency of spray dried powder as the effect of (a) air-inlet temperature, iron addition and (b) glucomannan addition

MORPHOLOGY

The surface morphologies of iron particles listed in Table 1 are shown in Figure 4. Compared to the spray-dried maltodextrin without iron (Figure 4(a)), other formulas formed particles with more regularly spherical shapes with hollows. The spherical shape gave better encapsulation protection (Yang et al. 2009). In general, glucomannan addition decreased the wrinkles on the surface particles. However, the feed composition and drying temperature affected the surface's smoothness and the particles' regularity. Figure 4(b) and 4(c) shows the effect of iron addition in the feed, while Figure 4(c) and 4(d) compares the particle morphology by the impact of matrix composition. Both iron and hydrolyzed glucomannan addition increased the particle size, as shown in Figure 4(b) and 4(d), respectively. This addition increased total soluble solids in the feed solution, which tends to form bigger particles during the spray drying process (Dadi et al. 2019). Polekkad et al. (2021) explained that the soluble solids created a thicker layer on the droplet and slowed down the drying rate. Thus, the dried particle was bigger with a smoother surface. However, the increase in iron concentration in Figure 4(b) and 4(c) does not show a significant difference in the smoothness of the surface. The small amount of iron addition may affect the similar surface compared with the matrix.

Figure 4(c) and 4(e) shows the morphology difference as the effect of drying temperature. Figure 4(c) shows that lower drying temperature formed a smoother surface. In spray drying system, increasing drying temperature fastened the crust formation on the droplet surface followed by quick inner moisture evaporation, thus, creating shrunk particles with hollows. A similar phenomenon was also found by Wardhani et al. (2020). Although more hollows were created, that structure did not decrease iron encapsulation efficiency. Faster drying might harden the outer barrier of iron particles and protect the iron particles.

The surface iron from several points of spray-dried particles is analyzed from EDX results. The iron added in GM1, GM2, GM3, and GM4 formula appears in EDX curve as the peak of iron. The weight percentage of iron from EDX result are 3.93±1.36; 9.97±0.47; 8.91±0.83; and 9.61±0.66% for GM1, GM2, GM3, and GM4, respectively. The weight percentages were not correlated with the encapsulation efficiency as it did not describe the entrapped iron inside of the particle. Hence, the presence of surface iron indicated that the encapsulation produced iron particles in matrix form.

PARTICLE SIZE

The particle size distributions of spray-dried particles are shown in Figure 5. The biggest particle size was shown by the lone maltodextrin matrix particle. The addition of glucomannan decreased the particle size in a similar trend of size distribution and produced the smallest iron particle with the formulation of GM3, which contained a high concentration of hydrolyzed glucomannan. Therefore, matrix formulation had a significant impact on particle size distribution. Glucomannan consists of mannose and glucose groups, which have different solubility in water, thus, forming a polydisperse solution. This polydisperse system of glucomannan created an antagonism interaction to maltodextrin, which promotes the formation of smaller particles (Atalar, Besir & Kurt 2023). Hence, more addition of glucomannan decreased the particle size of spray-dried particles. Meanwhile, the impact of drying temperature is not significant (GM2 & GM4). However, our previous study found that there was significant size difference between dried particles produced at 110 °C and 140 °C (Wardhani et al. 2020). In this study, the drying temperatures are lower than 100 °C, which may cause an insignificant difference in the drying rate, thus, producing a similar particle size distribution. An insignificant difference in particle size is also observed as the different iron content is added to the matrix formulation.

THERMAL PROPERTIES

The thermal properties of spray-dried powder were observed at 30-300 °C (Figure 6). For maltodextrin powder without the active compound, the first degradation occurred from the initial temperature to ~110 °C. In this first degradation, ~10% mass loss from spray-dried maltodextrin which related to moisture loss at temperature below 120 °C (Khoshakhlagh et al. 2017). For iron-maltodextrin-glucomannan formulation (GM1, GM2, and GM3), the powders were linearly degraded from 30 °C to ~225 °C. The degraded weights were higher than spray-dried maltodextrin, i.e., ~0.16%, ~0.18%, and ~0.13%, for GM1, GM2, and GM3, respectively. The different degradation trends may be related to the presence of glucomannan and $FeSO_4.7H_2O$, which enhanced the moisture bond in the iron powder. As a result, the water was evaporated slower than the one in the lone maltodextrin sample. In addition, more heat was needed to remove a similar amount of water in the glucomannan-maltodextrin powder than that in the single maltodextrin matrix.

The second degradations were started at similar temperatures (~200 °C) for all samples. Thirty-eight percent of the mass was degraded in this stage for the spray-dried maltodextrin. Lower mass losses were identified for iron-glucomannan-maltodextrin samples, i.e., 19%, 17%, and 17%, for GM1, GM2, GM3, respectively. However, for iron-glucomannan-maltodextrin particles, another degradation stage occurred after ~250 °C. The different trends of the thermogram may be affected by the matrix composition difference. Maltodextrin and glucomannan consist of different monomers linked with different linkage. Hence, different heat energy was needed during the depolymerization.

DSC results inform glass transition temperature (T_g) of the spray-dried samples are 55.7 °C, 70.23 °C, 67.55 °C, and 57.82 °C for spray-dried maltodextrin, GM1, GM2, and GM3. T_g can be used to determine the material stability as molecular change occurred at this temperature, which led to product deterioration (Santhalakshmy et al. 2015). A higher T_g indicated that the material has better thermal stability. Increasing T_g of spray-dried powder by the presence of glucomannan indicated that glucomannan has a higher molecular weight. A similar T_g increase was also found by Yousefi et al. (2011) while mixing various polysaccharides and cellulose. T_g is influenced by the moisture content, chemical composition, and molecular weight of the substance (Karrar et al. 2021).

TABLE 1. Sample code for morphology, particle size, functional groups, and thermal properties analyses

Sample name	Glucomannan concentration (g/L)	Maltodextrin concentration (g/L)	Iron concentration (mg/g matrix)	Spray-drying temperature (°C)
GM1	1	30	30	90
GM2	1	30	25	90
GM3	3	30	25	90
GM4	1	30	25	60

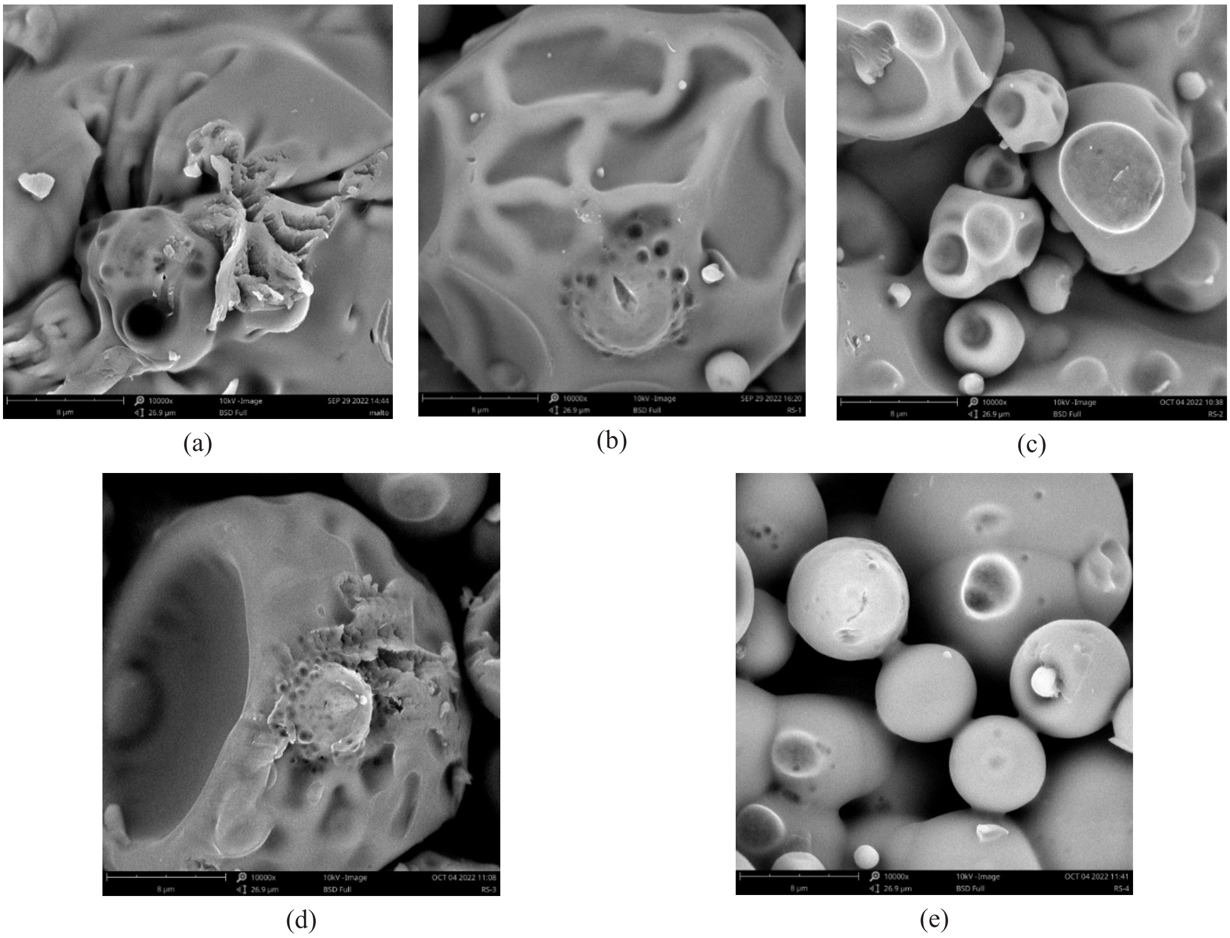


FIGURE 4. Surface morphology of spray-dried particles of (a) single matrix of maltodextrin without bioactive, (b) GM1, (c) GM2, (d) GM3 and (e) GM4

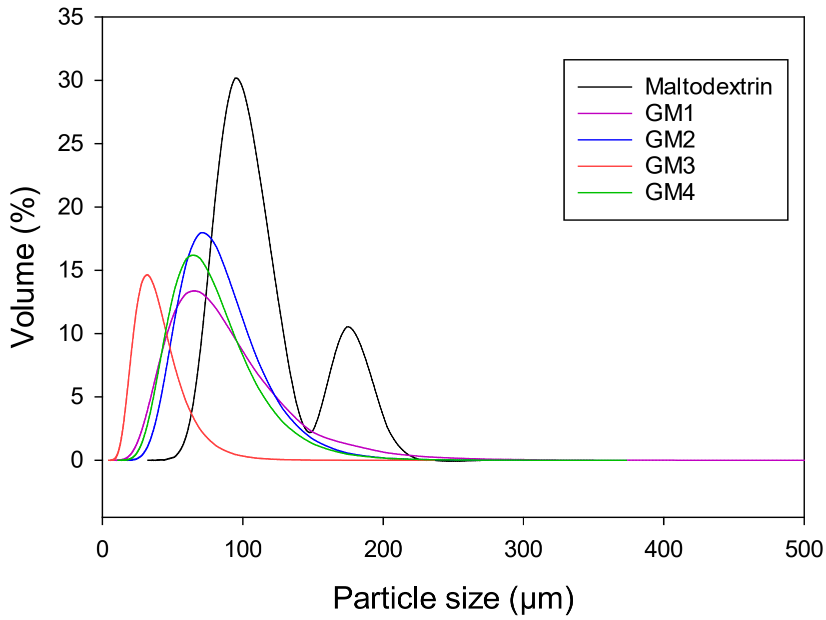


FIGURE 5. Particle size distributions of spray-dried particle

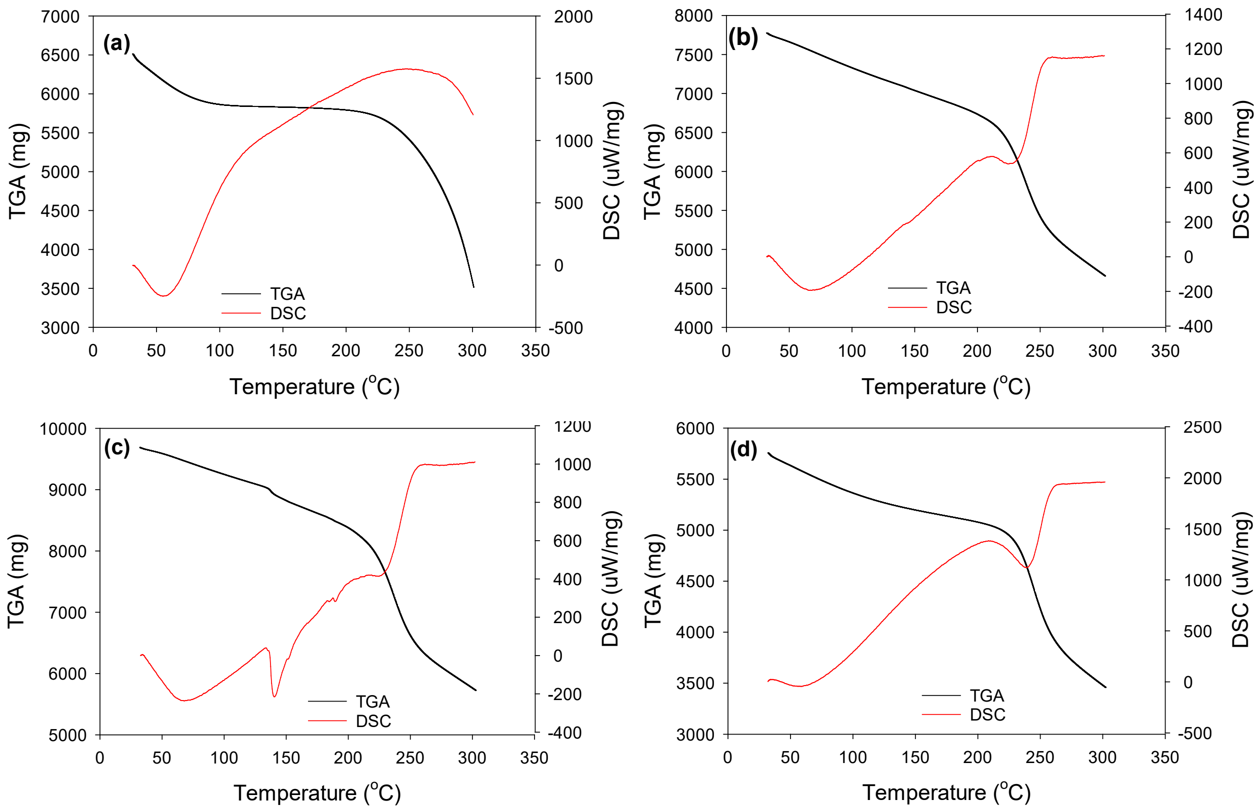


FIGURE 6. Thermogravimetry analysis (TGA) and differential scanning colourimetry (DSC) results of (a) single-matrix maltodextrin, (b) GM1, (c) GM2, and (d) GM3

CONCLUSIONS

Higher iron content and drying temperature increased the solubility and swelling of spray-dried iron particles but decreased their moisture content. However, the moisture content still exceeded the powder storage standard due to due to moisture reabsorption. More glucomannan concentration in encapsulation matrix increased the solubility, moisture content and swelling power of iron powder. Iron particles performed faster wettability as the increase of drying temperature, glucomannan concentration, and iron content. The encapsulation efficiency of iron particles was improved by increasing glucomannan and iron content in the matrix solution but was decreased by applying a higher drying temperature. In general, the spray-dried particle was in spherical form with hollows. The presence of iron in the spray-dried particle was also confirmed by SEM-EDX analysis. Besides producing smaller particles, glucomannan addition to the maltodextrin matrix also improved the thermal stability of encapsulated iron particles. Hence, the results show that the glucomannan and maltodextrin matrix combination has the potential for encapsulating active agents using the spray-drying method.

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