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Inulin-coated Virgin Coconut Oil (VCO) powder produced by spray drying

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ABSTRACT

The aim of this study is to produce inulin-coated virgin coconut oil (VCO) powder using spray drying technology. VCO, known for its high content of medium-chain fatty acids and antioxidants, has faced challenges in food and pharmaceutical applications due to its susceptibility to oxidation thus reducing its shelf-life. Inulin as the encapsulating agent, presented an effective solution, offering not only encapsulation efficiency but also added health benefits as prebiotics. The process parameters, such as inlet air temperature (110–180 °C), feed flow rate (5–8 mL/min), aspiration rate (80–100 %), and air pressure at nozzle (1–1.8 bar) as well as total solid percentage in the emulsion feed (45–55 %) were varied. The best conditions were identified as inlet air temperature 150 °C, feed flow rate 5 ml/min, aspiration rate 100 %, air pressure at nozzle 1 bar, and 50 % total solid content to produce powder with high yield (~88 %), low moisture content (2.9 %), and other desirable characteristics, such as density, particle size, morphology, and flowability. This study provides a framework for producing scalable inulin-coated VCO powder with enhanced shelf-life, functionality, and versatile applications in health-oriented food and pharmaceuticals.

1. Introduction

Virgin coconut oil (VCO) has gained increasing attention due to its numerous health-promoting properties and wide applicability in various industries such as food, nutraceuticals, cosmetics, and pharmaceuticals (Babu et al., 2014; Ng et al., 2021; Srivastava et al., 2016; Zeng et al., 2024). Extracted from the fresh meat of mature coconuts (*Cocos nucifera*), VCO is particularly rich in medium-chain fatty acids (MCFAs), especially lauric acid, which accounts for nearly 50 % of its fatty acid content (Araújo de Vasconcelos et al., 2023). Lauric acid is renowned for its potent antimicrobial, antiviral, and antifungal properties (Araújo de Vasconcelos et al., 2023). Furthermore, VCO is rich in antioxidants, including tocopherols and polyphenols, which contribute to its protective effects against oxidative stress and inflammation (Mansouri et al., 2024).

Despite its many advantages, the liquid form of VCO presents certain challenges related to stability, storage, handling, and incorporation into food and pharmaceutical formulations (Jafari & Samborska, 2021). One major issue is its susceptibility to oxidation, which can lead to rancidity and loss of beneficial properties over time (Corrêa-Filho et al., 2022). In addition, the liquid nature of VCO limits its versatility in certain product applications where powdered ingredients are preferred due to their ease of transport, longer shelf life, and ability to mix more uniformly in dry formulations (Sánchez-Osorno et al., 2023).

Spray drying is one of the most widely used microencapsulation techniques for converting oils into powders (Jafari & Samborska, 2021; Quispe et al., 2020; Sánchez-Osorno et al., 2023). This process involves atomizing the liquid feed (such as VCO) into small droplets, which are then rapidly dried using hot air, resulting in fine powders (Sánchez-Osorno et al., 2023). The spray drying technique is favored for its scalability, cost-effectiveness, and ability to produce powders with good flow properties (Gharsallaoui et al., 2007; Jafari & Samborska, 2021; von Halling Laier et al., 2019). However, the success of the spray drying process largely depends on the choice of wall materials used for encapsulation (Quispe et al., 2020; Sánchez-Osorno et al., 2023).

In recent years, inulin, a natural polysaccharide, has emerged as a

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promising wall material for the microencapsulation of sensitive compounds like oils (Sánchez-Osorno et al., 2023). Inulin is a soluble dietary fiber extracted from plants, such as chicory root, agave, and Jerusalem artichoke (Mazloom et al., 2012). It is composed primarily of fructose units linked by β-(2→1) glycosidic bonds, and its degree of polymerization can vary from 2 to 60 fructose units (Mazloom et al., 2012). Inulin is recognized not only for its technological properties but also for its numerous health benefits (Corrêa-Filho et al., 2022; Mazloom et al., 2012).

In the context of microencapsulation, inulin offers several advantages as a wall material (Corrêa-Filho et al., 2022). It has excellent film-forming properties, which allow for the formation of a protective barrier around the encapsulated oil (Corrêa-Filho et al., 2022; Sánchez-Osorno et al., 2023). Moreover, inulin is resistant to digestive enzymes in the human gastrointestinal tract, which enables the controlled release of encapsulated bioactive compounds, such as VCO, in the lower intestine where it can exert its full functional effects (Corrêa-Filho et al., 2022; Mazloom et al., 2012). Inulin is belonged to soluble dietary fiber which helps stabilize blood sugar and reduce the diabetes risk (Giuntini et al., 2022; Niero et al., 2023; Wijaya et al., 2022). The recommended fiber intake per day is 25–40 gram/day, however, the average fiber consumption of the local people is still below 21 gram/day (Novianti et al., 2023).

Previous research has demonstrated the potential of spray drying to encapsulate oils, including VCO, using various wall materials (Jafari & Samborska, 2021; Mazloom et al., 2012). For instance, recent studies have explored the use of maltodextrin and other polysaccharides as wall materials for spray drying VCO (Jafari & Samborska, 2021). However, while maltodextrin is a commonly used wall material due to its low cost and good solubility, it lacks the additional health benefits provided by inulin (Corrêa-Filho et al., 2022; Mazloom et al., 2012). In contrast, recent investigations have shown that inulin contributes significantly to the encapsulation efficiency and enhances the antioxidant properties of the final product when used as a wall material for encapsulating oils (Corrêa-Filho et al., 2022; Sánchez-Osorno et al., 2023). Additionally, inulin also functions as stabilizing agent for the oil-in-water (O/W) emulsion due to its thickening power (Sapei et al., 2023), which contributes to the enhancement of the encapsulation efficiency during spray drying process. This highlights the potential of inulin as an alternative or supplementary wall material for encapsulating oils, especially for functional foods designed for health-conscious consumers.

The objective of this study is to evaluate the feasibility of producing inulin-coated virgin coconut oil (VCO) powder using spray drying as a microencapsulation technique. The research focuses on optimizing spray drying parameters—such as inlet air temperature, feed flow rate, aspiration rate, air pressure at the nozzle, and feed formulation—to achieve high encapsulation efficiency and desirable physical properties, including low moisture content, appropriate particle size, and good flowability (Jafari & Samborska, 2021; Sánchez-Osorno et al., 2023). Additionally, the study examines the pH and rehydration behavior of the spray-dried VCO powder in aqueous systems to assess its suitability for functional food formulations (Corrêa-Filho et al., 2022). By exploring the potential of inulin as an encapsulating agent for functional oils like VCO, this research aims to develop a stable, nutrient-rich ingredient with enhanced shelf life and broader applications in health-oriented food and nutraceutical products.

2. Materials and methods

2.1. Materials

Virgin coconut oil (VCO) comprising of 0.5 % caproic acid, 4.5 % caprylic acid, 5.85 % capric acid, 45 % lauric acid, 20 % myristic acid, 11 % palmitic acid, 3.5 % stearic acid, 8 % oleic acid, 1.6 % linoleic acid, and 0.05 % linolenic acid; sodium caseinate; glycerol monostearate (GMS) powder with total monoglycerides min. 95 %; phosphates salts (K_2HPO_4); inulin (dry matter content 96.8 %; pH 5.5; inulin 90 %, fructose/glucose/sucrose 10 %); anti-caking agent (SiO_2); demineralized water.

2.2. Preparation of oil-in-water (O/W) emulsion

Demineralized water as the continuous phase was prepared according to the total solid content in the whole emulsion (45 %, 50 %, and 55 %) and then heated to 70 °C and poured into a 1 L stainless steel vessel. Afterwards, other ingredients were added in a consecutive manner according to each component percentage (% weight/ weight) dry basis of total solid content. All components except demineralized water were perceived as total solid. Inulin of about 61.5 % was firstly added and the mixture was homogenized using a rotor-stator (IKA T25 digital ULTRA TURRAX, Germany) at 15,000 rpm for 5 min followed by the addition of phosphate salts of 2.5 % and mixing at 15,000 rpm for 3 min. Sodium caseinate of 2.5 % was added followed by mixing at 15,000 rpm for 5 min. Afterwards, GMS of 1 % was added and the mixture was dispersed at 15,000 rpm for 3 min. Eventually, VCO at 60 °C was added to the mixture of about 32 % followed by homogenization at 15,000 rpm for 10 min. The water loss after rotor-stator homogenization was compensated by adding water into the mixture. Finally, the mixture was subjected to the probe sonicator (Sonicator Q-700, QSonica, USA) with a replaceable tip Ea ½ inch for 5 min using the amplitude of 100 %.

2.3. Production of VCO powder

The temperature of O/W emulsion was kept at 70 °C using a waterbath (Joanlab WB100–1F, China) when being fed into the mini spray dryer (BÜCHI B-290, Büchi Labortechnik AG, Switzerland) by means of hot air as drying medium. Several drying parameters such as temperature of inlet air (110 °C; 130 °C; 150 °C; 180 °C), aspiration rate of inlet air (80 %; 100 %), air pressure at nozzle (1 bar; 1.8 bar), and flow rate of the emulsion feed (5 ml/min; 8 ml/min) were adjusted using O/W emulsion with the total solid of 50 %. The obtained best drying parameters were then applied for other total solids of 45 % and 55 %. The overall experimental variations were depicted in Table 1. The emulsion entered the 0.7 mm two-fluid nozzle and atomized into droplets which in turn were in contact with the hot air. The hot air contacted with the droplet in a co-current manner. The air left at the temperature ranges of 75–100 °C. Water was evaporated from the droplets and inulin-coated VCO powders were collected at the bottom of drying chamber. The spray dried particles conveyed by the drying air was separated by the cyclone. The overall free-flowing VCO powders were collected, mixed with 0.5 % anti-caking agent, and weighed for the yield determination. The powder was placed in an aluminum pouch and stored at the room temperature for further characterization.

Table 1
The overall experimental variations.

Sample	Inlet Air Temperature (°C)	Feed flow rate (ml/min)	Aspiration rate (%)	Air Pressure at Nozzle (bar)	Total Solid (%)
T180	180	5	100	1	50
T150	150	5	100	1	50
T130	130	5	100	1	50
T110	110	5	100	1	50
A80	150	5	80	1	50
P18	150	5	100	1.8	50
F08	150	8	100	1	50
TS45	150	5	100	1	45
TS55	150	5	100	1	55

Note: The sample code T was assigned for the variation in inlet air temperature; A for the variation in aspiration rate; P for the variation in air pressure at nozzle; F for the variation in feed rate; and TS for the variation in total solid.

2.4. Analysis of VCO powder

The characteristics of produced inulin-coated VCO powder such as yield, moisture content, pH of 10 % solution, untapped/ bulk density and tapped density, wettability, particle size distribution, flowability properties, and morphology were determined.

2.4.1. Powder yield

The powder yield was calculated according to Eq. (1), whereby%MC is moisture content of powder in percentage and% TS is total solid content of the O/W feed emulsion in percentage.

$$\text{Yield } (\%) = \frac{\text{Total mass powder}}{(1+\%\text{MC})\text{x (total mass feed x }\%\text{TS)}}\text{x } 100\% \tag{1}$$

2.4.2. Moisture content

The moisture content of 2 g VCO powder was measured using the moisture balance (MOC-120H, Shimadzu, Japan) operated at 105 °C. The moisture content (% wet basis) was reported.

2.4.3. Bulk density and tapped density

Untapped or bulk density was calculated by dividing the weight of the powder with the volume occupied by the powder in g/cm^3. About 10 g of powder was placed into a 100 ml volumetric flask and the occupied volume of the powder was recorded. The tapped density was similarly measured while tapping the powder for about 100 times prior to volume recording.

2.4.4. pH of reconstituted powder

Reconstituted VCO powder was prepared by dissolving 10 g of VCO powder into 100 ml demineralized water at 70 °C and stirred using a magnetic stirrer at 60 rpm. The pH of dissolved VCO powder at 10 % (w/ v) in aqueous solution was measured at room temperature using a pH-meter (inoLab® pH 7110, WTW, Germany).

2.4.5. Time of rehydration

The determination of rehydration time was based on modified procedures described by Salimi et al. (2018). It was determined by monitoring time required to hydrate and dissolve 10 g VCO powder in 100 ml water at 70 °C while stirring using a magnetic stirrer at 60 rpm.

2.4.6. Powder fractionation

Powder of about 20 g were sieved using a test sieve shaker consisting of a set of sieves with different mesh sizes (40, 70, 100, and 200 mesh) (Retsch, Germany) at amplitude of 40 for 2 min. The powder retained in each sieve was weighed to determine the proportion of mass fraction in each sieve. Particle size distribution (*supplementary data*) and the average particle size ($\overline{D}$) was determined according to Eq. (4)

$$D_n = \frac{D_p + D_{p-1}}{2} \tag{2}$$

$$x_i = \frac{\textit{mass of retained powder at sieve i}}{\textit{total mass of feed powder}} \tag{3}$$

$$\overline{D} = \sum x_i . D_{n,i} \tag{4}$$

where D_p is opening diameter of sieve with certain mesh size, $x_i$is mass fraction of the powder retained at the certain sieve.

2.4.7. Flowability properties

Flow behavior of the powder in term of flowability was determined using two empiric parameters, namely Carr's index (%CI) and Hausner ratio (HR) based on bulk density and tapped density according to Eqs. (5) and (6), respectively (Mahdi et al., 2020).

$$\%CI = \frac{\textit{Tapped density} - \textit{Bulk density}}{\textit{Tapped density}} x100\% \tag{5}$$

$$HR = \frac{\textit{Tapped density}}{\textit{Bulk density}} \tag{6}$$

2.4.8. Morphology

The VCO powder morphology was studied using SEM (FEI Inspect S50, FEI, USA). A double-sided tape was attached to the aluminum stub on which a small amount of sample was placed. The specimens were sputtered with gold to improve the conductivity prior to analysis. The analysis was conducted at 20 kV and at the magnification of 2500x.

3. Results and discussion

The production of inulin-coated VCO powder using spray drying process was highly affected by the spray drying process parameters, such as inlet air temperature, aspiration rate, air pressure at nozzle, and feed rate. Furthermore, the composition of O/W emulsion feed such as total solid percentage also played an important role in the drying process, thus influencing the characteristics of the obtained powder. The overall inulin-coated VCO powder characteristics as well as their flowability properties could be seen in Tables 2 and 3, respectively.

3.1. Effect of inlet air temperature on inulin-coated VCO powder characteristics

The inlet drying air temperatures were varied from 110 to 180 °C (samples T110, T130, T150, and T180) using 50 % total solid of the O/W emulsion feed. Other drying process parameters such as feed rate (5 ml/ min), aspiration rate (100 %), and air pressure at nozzle (1 bar) were kept constant. It turned out that powder yield was linearly increased with the increase in inlet air temperature from 110 °C to 150 °C and slightly decreased at 180 °C as shown in Fig. 1A. Higher temperature provided higher rates of water removal thus reducing the stickiness among particles. However, drying at 180 °C seemed to be too high and was likely to induce powder gelatinization thus increasing the cohesion between the particles or adhesion between the particle and chamber wall leading to reduced yield.

Furthermore, the moisture content showed an opposite pattern with the yield (Fig. 1B). The moisture content of VCO powder was decreasing with the increasing inlet air temperature until 150 °C and slightly increased at 180 °C. It has been known that the inlet drying air temperature is the driving force of heat transfer from drying air to the droplet and water vapor mass transfer from the droplet into the air. Therefore, the higher the inlet air temperature, the faster the evaporation rate and the drying process, resulting in the reduction of powder moisture content (Abdullah et al., 2021; Gharsallaoui et al., 2007). However, when the temperature of inlet air was too high, the diffusion of water from the inner droplet to the droplet surface could be impeded due to the onset of crust formation prior to complete water removal. This was called ballooning phenomena (Goula & Adamopoulos, 2012; Salimi et al., 2018), whereby water vapor entrapped inside the powder could explode (Abdullah et al., 2021) leading to particle irregularities. The suppression of powder moisture content has been beneficial in preventing powder agglomeration (Hedayatnia et al., 2016). The moisture contents of the overall VCO powder were low enough, *i.e.*, below 5 % (Abdullah et al., 2021; Hedayatnia et al., 2016) and fulfill the general requirement as food ingredients. However, the higher the moisture content the higher the tendency of the particles to be sticky one another causing powder caking. This could possibly occur based on the fact that the transition glass temperature (Tg) of powder tended to be lowered with the increased of moisture content (Hedayatnia et al., 2016) which would affect the powder shelf-life during storage. Drying at low temperature led to increased water content in the powders which resulted in

Table 2
Inulin-coated VCO powder characteristics.

Sample	Yield (%)	Moisture content (%)	Bulk density (g/cm^3)	Tapped density (g/cm^3)	Average particle size (μm)	pH	Time of Rehydration (minute)
T180	86.38	3.0	0.3714	0.4776	474.45	7.662	6.500
T150	88.10	2.9	0.4351	0.5559	281.84	7.873	5.016
T130	83.76	3.3	0.4173	0.5272	165.88	7.797	4.900
T110	77.55	3.9	0.4668	0.5735	200.60	7.765	4.616
A80	87.50	3.2	0.4320	0.5457	315.72	7.839	4.950
P18	85.65	3.3	0.4438	0.5794	201.33	7.725	4.800
F08	86.01	3.5	0.4170	0.5267	295.29	7.726	4.916
TS45	83.23	3.3	0.4349	0.5557	210.64	7.683	4.783
TS55	77.67	3.2	0.4359	0.5897	187.54	7.713	4.866

Table 3
Flowability properties of inulin-coated VCO Powder.

Sample	Carr's index (%)	Hausner ratio	Flowability
T180	22.24	1.29	passable
T150	21.73	1.28	passable
T130	20.85	1.26	passable
T110	18.61	1.23	fair
A80	20.84	1.26	passable
P18	23.40	1.31	passable
F08	20.83	1.26	passable
TS45	21.74	1.28	passable
TS55	26.08	1.35	poor

higher stickiness and reduced the amount of free-flowing powder (Toro-Sierra et al., 2013).

The influence of inlet air temperature on the powder density was depicted in Fig. 1C. Trends of decreasing both bulk and tapped density with the increase in inlet air temperature were due to faster evaporation rates leading to a more porous or fragmented structure (Goula & Adamopoulos, 2012) and reduction of moisture content (Hedayatnia et al., 2016). Lower inlet drying air temperature provided lower rate of evaporation, thus giving more time for diffusion and rearrangement of the solids dissolved in the droplet resulting in denser particles (von Halling Laier et al., 2019). Similar trends were also observed in the previous investigation conducted by Abdullah et al. (2021). The tapped density was higher compared to bulk density due to the act of tapping increasing the compactness of particle packing and diminishing the volume among particles. Tapped density has become more applied for storage and transportation of powder products.

The average particle size tended to increase with the increase in inlet air temperature (Fig. 1D). This was confirmed by previous investigation (Goula & Adamopoulos, 2012). The remarkable big particle size was observed at high drying air temperature of 180 °C. This could be due to trapped water vapor inside the particles expanding the volume and particle size. Moreover, the average particle size dried with air at 110 °C was larger than that dried at 130 °C. Possibly, the particles were agglomerated due to the higher moisture content since evaporation occurred at a much slower rate at lower temperature. Additionally, the water vapor in the drying air could be easily condensed at a temperature as low as 110 °C triggering agglomeration among the particles.

Interestingly, the rehydration time of VCO powder was increasing with the inlet air temperature increase as could be seen in Fig. 1E. This was aligned with the previous investigation (Salimi et al., 2018). Many factors could influence the rehydration time such as drying conditions, particle size distribution, moisture content, temperature, component degradation and so on. The rehydration time of the powder dried at 150 °C was almost similar with that dried at 130 °C, which was about 5 min. The rehydration time could become an important parameter to be considered for the reconstitution of VCO powder. The pH values of reconstituted VCO powder in aqueous solution were in the range of ~ 7.6–7.9 (Fig. 1F) with the varying inlet air temperatures, which were within the acceptable normal pH.

Flowability properties were of high importance for powdered materials. They were measured using Carr's index (%CI) and Hausner ratio (HR) indicating the cohesiveness and flow characteristics (Mahdi et al., 2020). All%CI and HR of all samples (T110, T130, T150, and T180) could be seen in Table 3. The CI percentage of sample T110 was <20 % and Hausner ratio (HR) was in the range of 1.19–1.25 indicating fair flowability, whereas samples T130, T150, and T180 demonstrated passable flowability with%CI within 21–25 % and HR within 1.26–1.34 (Saifullah et al., 2016). Sample T110 dried by air entering at 110 °C showed a slight better flowability despite of its agglomerated particles. Based on this study, all powders demonstrated cohesiveness among particles within some extent, yet they were considered to be sufficiently flowable regardless of the inlet drying air temperature.

The morphology of inulin-coated VCO powder prepared at different drying temperature could be seen in Fig. 2. It was obvious that sample T150 prepared at drying temperature 150 °C demonstrated the best morphology of inulin-coated VCO powder with spherical appearance and without significant particle agglomeration. Sample T180 showed several big particles with coarse surfaces indicating that some fissures or cracks could be present. Besides that, some small particles were adhered and sticky to big particles (O'Donoghue et al., 2019). These coarse surfaces were formed due to a fast rate drying impeding water removal. The water vapor inside the particle could create high pressure thus explode into the surface leaving some fissures or crack which could reduce encapsulation efficiency (Abdullah et al., 2021; Goula & Adamopoulos, 2012) although spherical particle appearances were still dominant. Morphology of VCO powder prepared under 150 °C demonstrated a larger extent of particles agglomeration. Particle bridges were obviously seen in sample T110 demonstrating a massive stickiness over the particles. The drying air temperature of 110 °C was not sufficient to extensively evaporate water thus quite high moisture content was still retained in the particles causing agglomeration leading to stickiness.

3.2. Effect of feed flow rate, aspiration rate, and air pressure at nozzle on inulin-coated VCO powder characteristics

Influences of other drying process parameters such as feed flow rate, aspiration rate, and air pressure at nozzle on VCO powder characteristics could be seen in Table 2. Emulsion feed flow rates of 5 ml/min and 8 ml/min (sample T150 *vs.* F08) were compared. As feed flow rate was increased to 8 ml/min, the powder yield was decreased and the moisture content was increased. This inferred the lack of drying time as the powder went down to the bottom of the drying chamber column due to a shorter residence time. The feed rate needed to be adjusted to ensure that each droplet reached the desired drying level before it comes in contact with the surface of the drying chamber (Gharsallaoui et al., 2007; O'Sullivan et al., 2019). The increased moisture content led to decrease in powder yield due to enhanced stickiness among the particles. On the other hand, time required for rehydration was decreased. Furthermore, the particle size was increased with the increase in feed rate which was in line with (Gharsallaoui et al., 2007). The formation of crust layer was retarded in larger particle size, thus there was possibility of oil leaching into the surface, lowering the encapsulation efficiency (Geranpour et al., 2020). The droplets produced from the atomizer

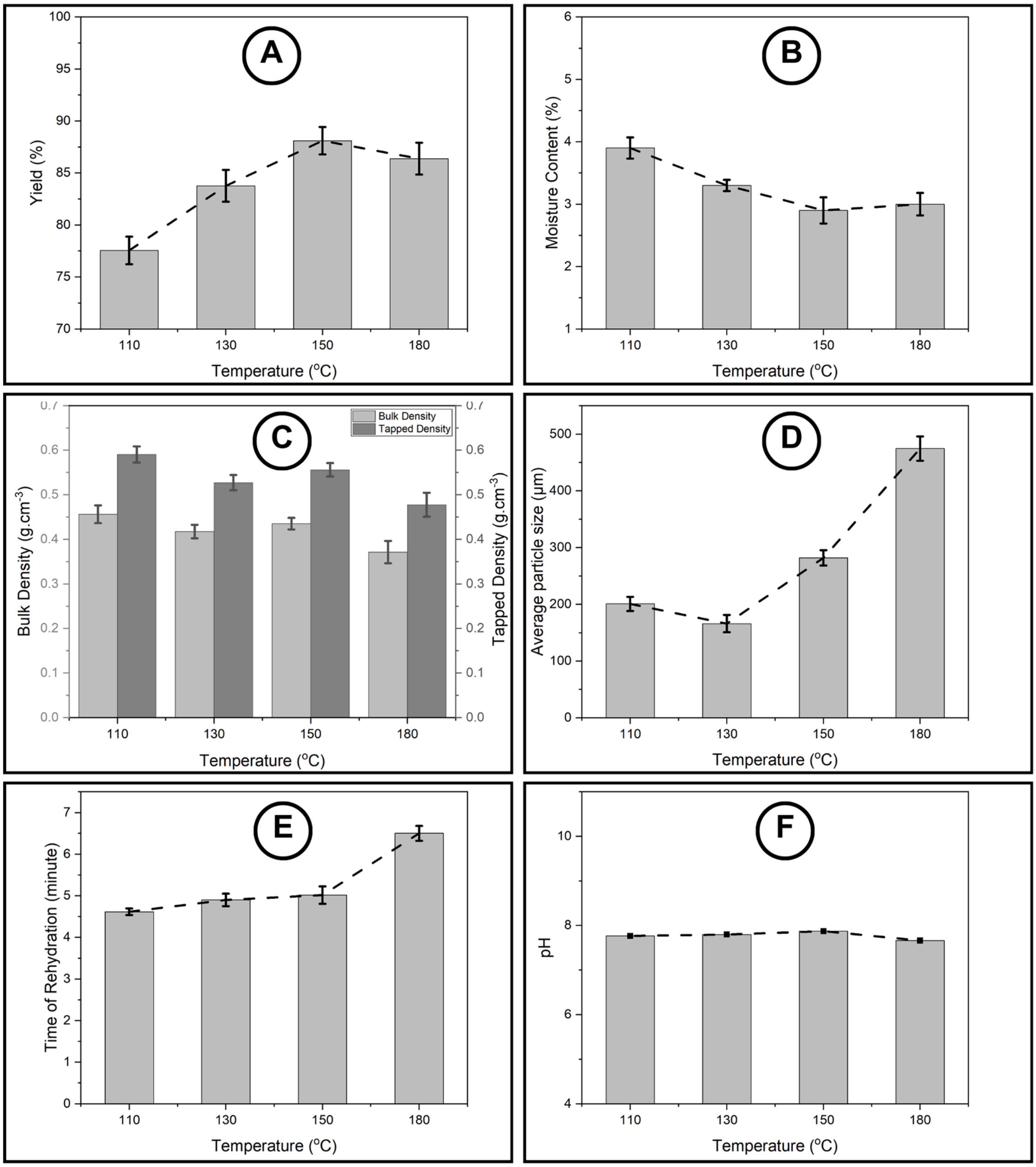

Fig. 1. The influences of inlet air temperatures on powder characteristics. A) Yield; B) Moisture content; C) Bulk and Tapped density; D) Average particle size; E) Time of rehydration; F) pH of 10 % powder in aqueous phase. The other process parameters such as feed flow rate (5 ml/min), aspiration rate (100 %), air pressure at nozzle (1 bar), and total solid percentage in the feed (50 %), were kept constant.

should be not too large or too small. The droplet may not be dried completely if the droplet is too large, and *vice versa*, the recovery of dried product is difficult and may get over heat and become scorched when the droplet is too small (Mounika et al., 2021).

When aspiration rate was decreased from 100 % to 80 % (sample T150 *vs.* A80), similar tendency as the increased feed flow rate was observed. Basically, the powder drying time in the column was increased as aspiration rate or drying air rate was decreasing. High aspiration rate would increase the evaporation rate and water transfer from the droplet surface to the drying air besides it might help improve the separation efficiency of fine particles in the cyclone. The decrease in aspiration rate resulted in lower yield due to increased moisture content of the particles enhancing their proneness to sticking.

The effect of air pressure increase from 1 bar to 1.8 bar (sample T150 *vs.* P18) resulted in a much decrease in average particle size which was in line with the previous investigation (Salimi et al., 2018; Wang et al., 2019).The increased air pressure tended to lower droplet size due to increased energy for the droplets to overcome the surface tension and viscous force (O'Sullivan et al., 2019; Wang et al., 2019). Additionally, air atomizing pressure could deliver good atomization effect and lowering the possibility of clogging (Wang et al., 2019). However, the powder yield was reduced and moisture content was increased with the increase in air pressure. The air pressure was probably too high thus producing fine particles. The fine particles possessed a greater surface area responsible for water uptake during the powder collection enhancing stickiness and lowering powder yield. The selection of air supply pressure on atomization should not be too high or too low (Wang et al., 2019).

The pH values of 10 % VCO powder in aqueous solution ranged from ~7.7–7.9 and were within the acceptable normal pH. Furthermore, %CI

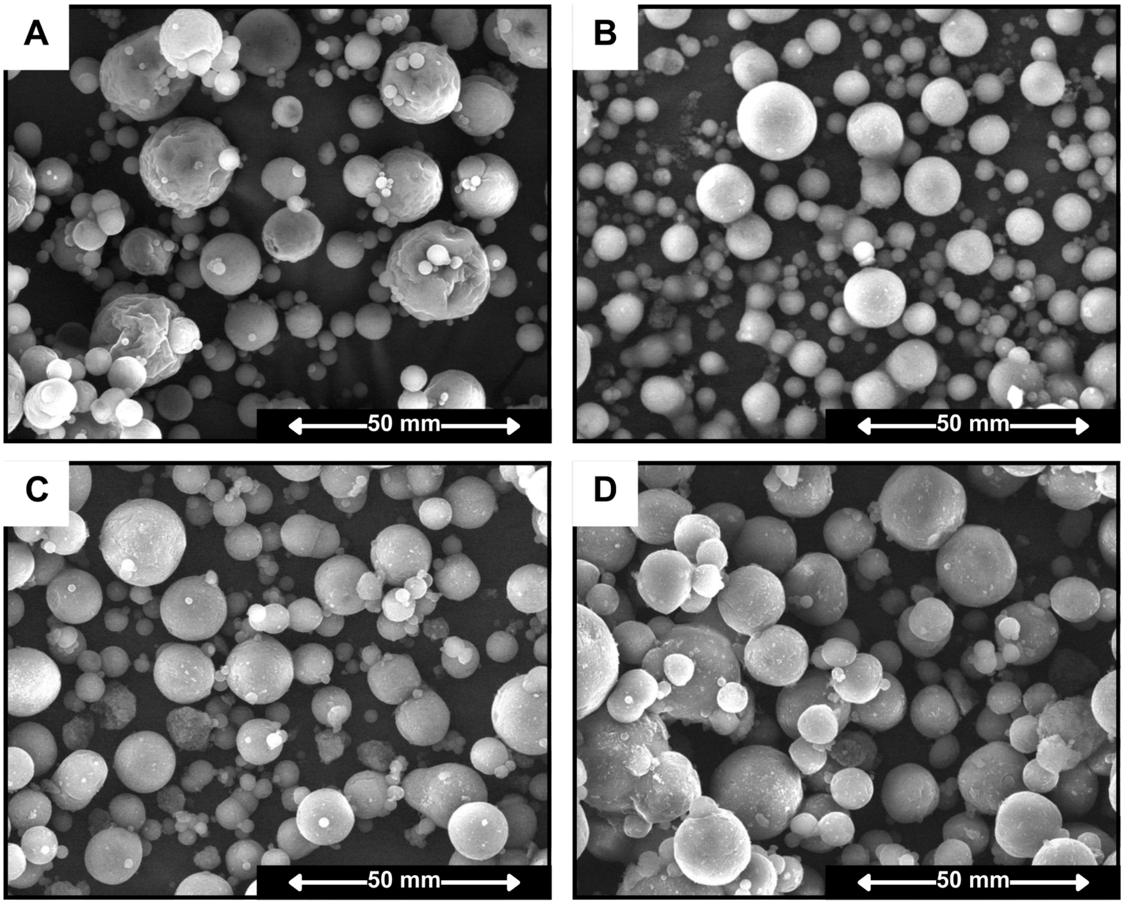

Fig. 2. Scanning electron micrographs of inulin-coated VCO powder dried at different drying air temperature. A) 180 °C; B) 150 °C; C) 130 °C; D) 110 °C. The other process parameters such as feed flow rate (5 ml/min), aspiration rate (100 %), air pressure at nozzle (1 bar), and total solid percentage in the feed (50 %), were kept constant.

and HR of T150, F08, A80, and P18 samples demonstrated passable flow properties independent of feed rate, aspiration rate, and air pressure at nozzle used in this study. This flow behavior would affect the handling operations as well as transportation.

3.3. Effect of total solid percentage on inulin-coated VCO powder characteristics

Total solid percentage (%TS) in the feed O/W emulsion definitely affected the drying process and also the characteristics of VCO powder. Various total solids (45, 50, and 55 %) of the O/W emulsion were prepared and spray dried using several fixed drying process parameters, *i.e.*, inlet air temperature 150 °C, feed flow rate 5 ml/min, aspiration rate 100 %, and air pressure at nozzle 1 bar. The highest yield was obtained at 50 %TS as depicted in Fig. 3A. This highest yield was also reflected by its lowest moisture content (Fig. 3B) indicating reduced potential stickiness among particles. The evaporation rate from the droplet surface was decreased following the increasing feed viscosity due to higher fraction of polymers present in the solution (O'Sullivan et al., 2019) which explained the higher moisture content of particles prepared at 55 % TS after drying. At lower feed concentration, smaller particles were tended to form. However, the tendency of particle agglomeration was higher in fine particles due to increased cohession among the particles and higher tendency to take up water thus lowering the obtained yield.

Even though higher %TS was expected in order to reduce the energy consumption for water removal, a much higher%TS would increase the viscosity which would increase the friction of molecules in the nozzle and retard the droplet formation. Furthermore, larger droplet was generally formed when more viscous concentrated solution was atomized, resulting in larger powder particles (O'Sullivan et al., 2019). However, average particle size of sample TS55 was much smaller than that prepared at 50 % TS (Fig. 3D). This result was probably affected by the applied vibration during sieving process resulting in particle collision leading to particle size reduction. Furthermore, particle density was increased with the increased%TS (Fig. 3C) which was in line with the previous investigation (Quispe et al., 2020). Higher concentration of solid materials in the feed tended to improve the compactness of obtained powder.

Furthermore, the functional properties of VCO powder were measured by the rehydration time and pH (Fig. 3E and 3F). The rehydration time of sample prepared at 50 %TS was a bit higher than others prepared at 45 % and 55 % TS. The pH values of the reconstituted VCO powder were within ~7.6–7.9 with the variations of%TS which were within the acceptable normal pH for further applications. Moreover, the samples prepared at 45 % and 50 % TS showed passable flowability based on%CI and HR whereas the sample prepared at 55 % TS demonstrated poor flowability since %CI were in the range of 26–31 and HR ranged from 1.35 to 1.45 (Saifullah et al., 2016). It turned out that concentrated O/W emulsion feed could have a detrimental effect on the powder flow behavior due to increased cohesiveness among the particles.

The morphology of inulin-coated VCO powders obtained with varying%TS could be seen in Fig. 4. It was obvious that the particles obtained at 45 % TS and 55 % TS demonstrated a higher extent of agglomeration in inulin-coated VCO powder. Less particles were aggregated in the sample prepared at 50 % TS. This again confirmed that

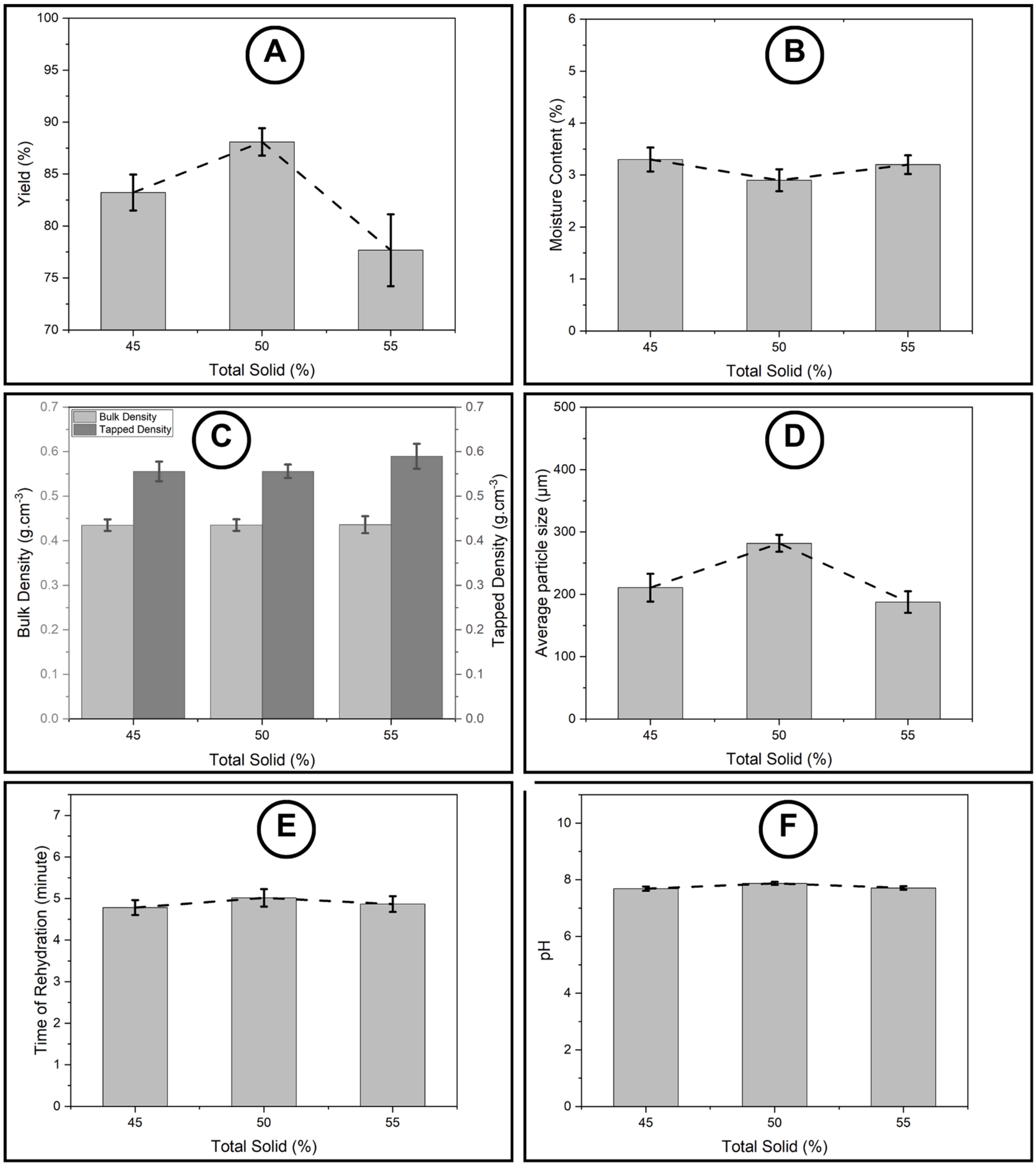

Fig. 3. The influences of total solid percentage in emulsion feed on powder characteristics. A) Yield; B) Moisture content; C) Bulk and Tapped density; D) Average particle size; E) Time of rehydration; F) pH of 10 % powder in aqueous phase. The other process parameters such as inlet air temperature (150 °C), feed flow rate (5 ml/min), aspiration rate (100 %), and air pressure at nozzle (1 bar), were kept constant.

the highest yield obtained at the feed concentration of 50 % TS was contributed by the low degree of particle stickiness.

4. Conclusion

The inulin-coated VCO powder with a lot of health benefits was quite potential to be used as ingredients for the development of functional food products. The inulin-coated VCO powder produced by spray dryer with high yield and desirable characteristics was highly dependent on the process parameters as well as feed formulation. The process parameters with inlet air temperature 150 °C, feed flow rate 5 ml/min, aspiration rate 100 %, air pressure at nozzle 1 bar and emulsion feed with 50 % total solid successfully delivered powder products with the highest yield of ~88 %, lowest moisture content of 2.9 %, and demonstrated the least agglomerated particles based on SEM analysis. There could be complex interactions among numerous factors such as drying process parameters, feed formulation, and the properties of components in the feed which dictated the final characteristics of VCO powder. The increase in inlet air temperature tended to increase yield and lower the moisture content due to a higher evaporation rate. However, the opposite trends were observed when too high inlet air temperature was applied due to early crust formation on the surface hindering water removal process. Furthermore, yield was tended to decrease with the feed flow rate increase, aspiration rate decrease, and air pressure increase due to a much higher moisture content confirmed by a higher extent of particle agglomeration. The total solid concentration in the emulsion feed modulated the feed viscosity which would in turn affect the atomization process. It turned out that total solid of 45 % and 55 % produced lower yields with higher degree of agglomerated particles compared to feed emulsion with 50 % TS. Stickiness was commonly

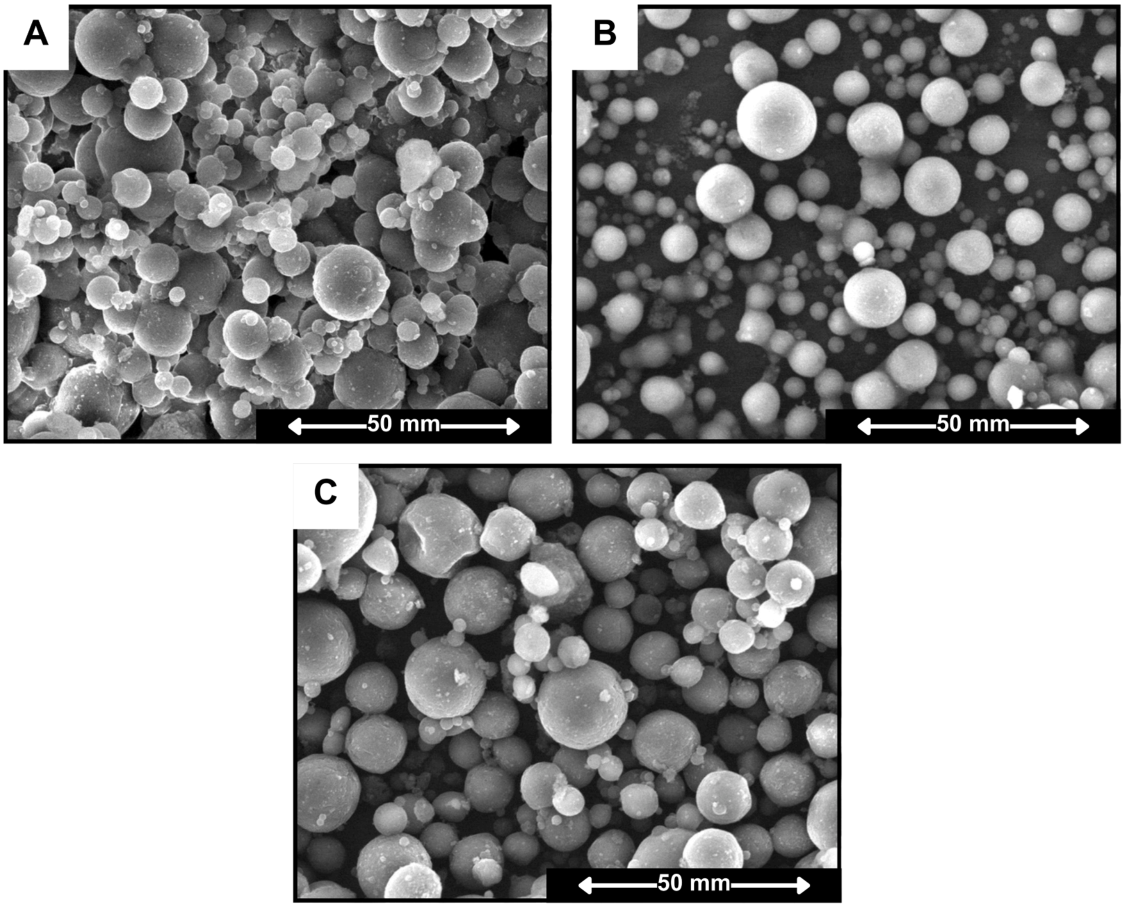

Fig. 4. Scanning electron micrographs of inulin-coated VCO powder prepared at different total solid percentage in the emulsion feed. A) 45 %; B) 50 %; C) 55 %. The other process parameters such as inlet air temperature (150 °C), feed flow rate (5 ml/min), aspiration rate (100 %), and air pressure at nozzle (1 bar), were kept constant.

occurred in the powdered materials due to liquid bridging leading to agglomerated particles resulting in the unexpected yield reduction.

The reconstituted VCO powder had an average pH of ~7.8 and rehydration time of ~ 5 min, suitable for food and beverage applications. Inulin-coated VCO powder demonstrated passable flowability, except for the 55 % TS variation, which exhibited poor flow properties due to stronger particle cohesiveness. Optimizing the drying process, feed formulation, encapsulation efficiency, and economic feasibility is recommended for large-scale production.

Ethical statement

All authors disclose no studies in humans and animals.

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Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used ChatGPT in order to improve the language and writing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Lanny Sapei: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Pra Cipta Buana Wahyu Mustika:** Visualization, Supervision, Software, Resources, Project administration, Formal analysis, Data curation. **Putu Doddy Sutrisna:** Writing – review & editing, Software, Resources. **Rudy Agustriyanto:** Writing – review & editing, Resources, Formal analysis. **Puguh Setyopratomo:** Conceptualization, Resources. **Grace Vita Santoso:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Justinus Putra Utama:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Rochmad Indrawanto:** Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors have declared that no conflict of interest exists.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2025.100721.

Data availability

Data will be made available on request.

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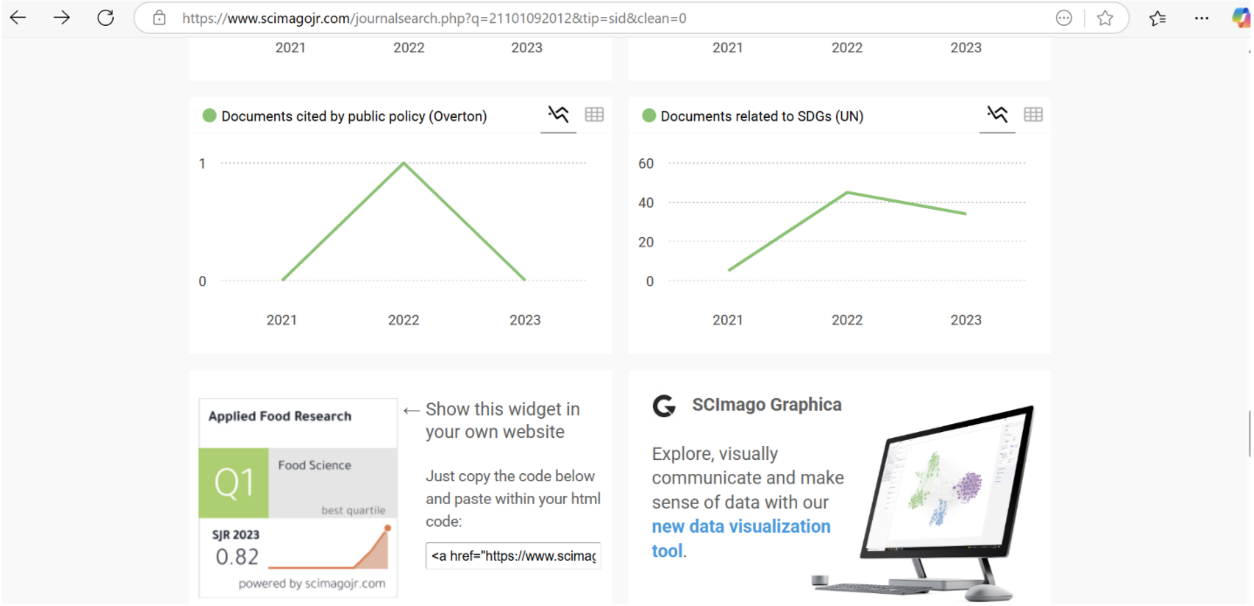

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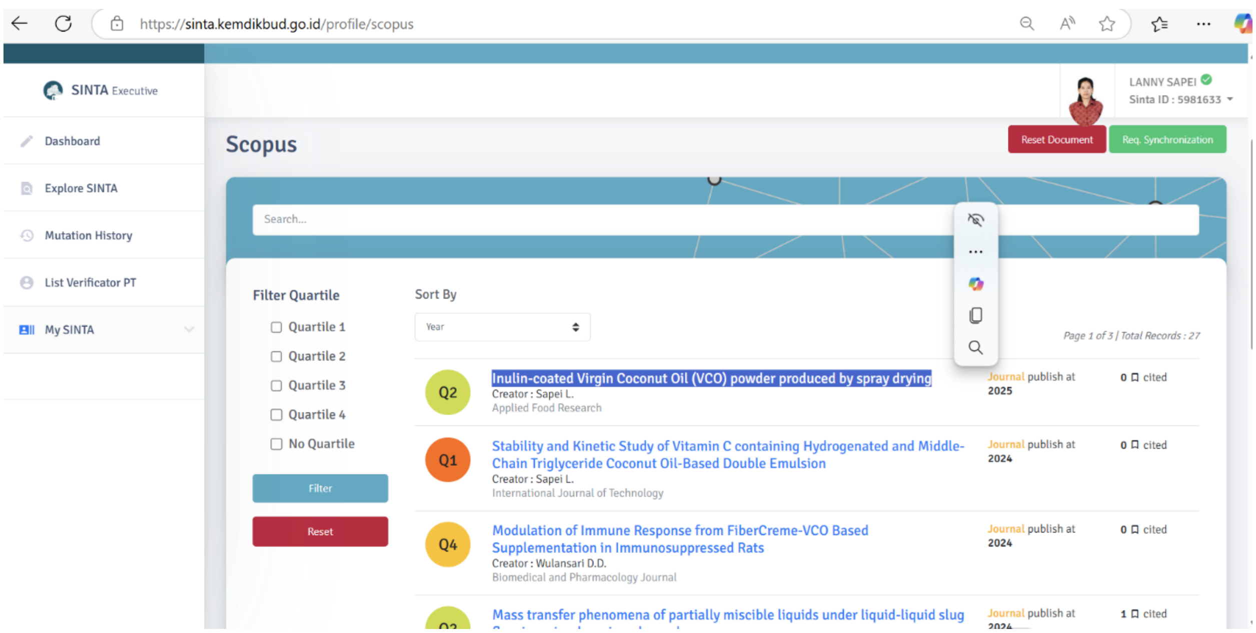

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Abstract

The aim of this study is to produce inulin-coated virgin coconut oil (VCO) powder using spray drying technology. VCO, known for its high content of medium-chain fatty acids and antioxidants, has faced challenges in food and pharmaceutical applications due to its susceptibility to oxidation thus reducing its shelf-life. Inulin as the encap- sulating agent, presented an effective solution, offering not only encapsulation efficiency but also added health benefits as prebiotics. The process parameters, such as inlet air temperature (110–180 °C), feed flow rate (5–8 mL/min), aspiration rate (80–100 %), and air pressure at nozzle (1–1.8 bar) as well as total solid percentage in the emulsion feed (45–55 %) were varied. The best conditions were identified as inlet air temperature 150 °C, feed flow rate 5 ml/min, aspiration rate 100 %, air pressure at nozzle 1 bar, and 50 % total solid content to pro- duce powder with high yield (~88 %), low moisture content (2.9 %), and other desirable characteristics, such as density, particle size, morphology, and flowability. This study provides a framework for producing scalable in- ulin-coated VCO powder with enhanced shelf-life, functionality, and versatile applications in health-oriented food and pharmaceuticals.

Item Type: Article
Uncontrolled Keywords: Inulin; O/W emulsion; Spray drying; VCO; Yield

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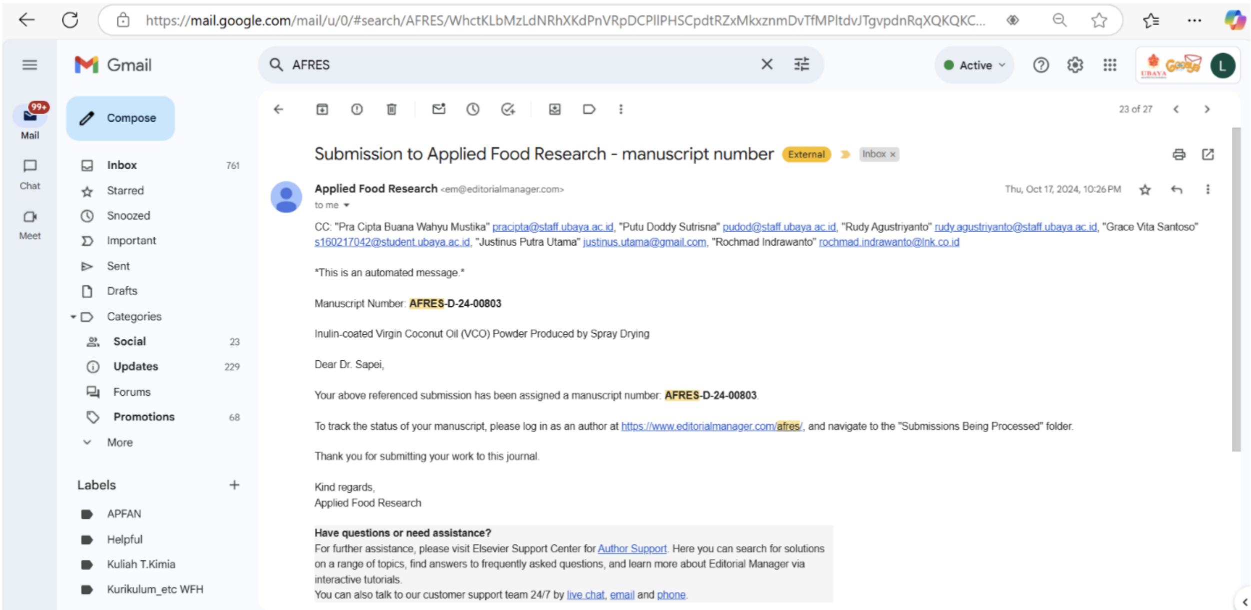

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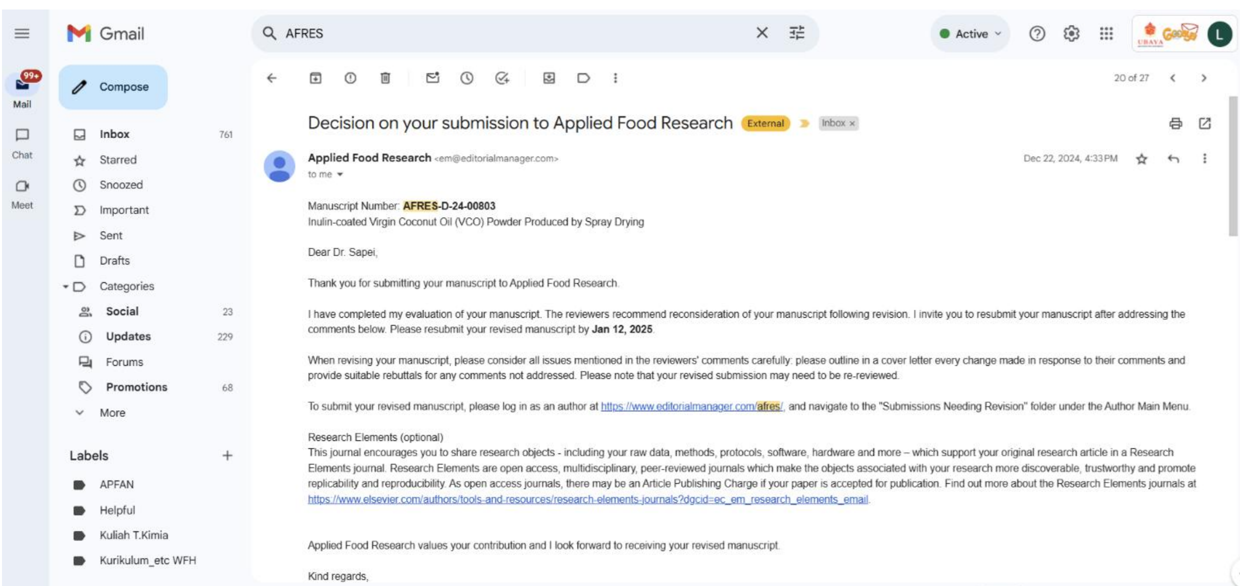

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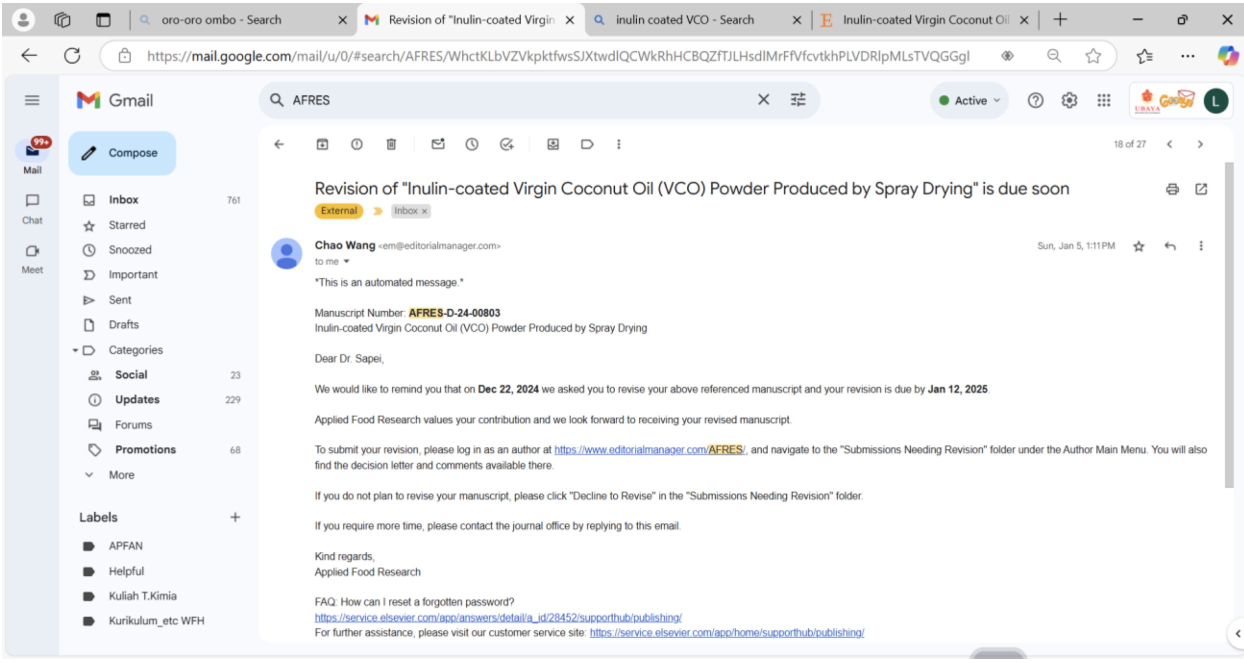

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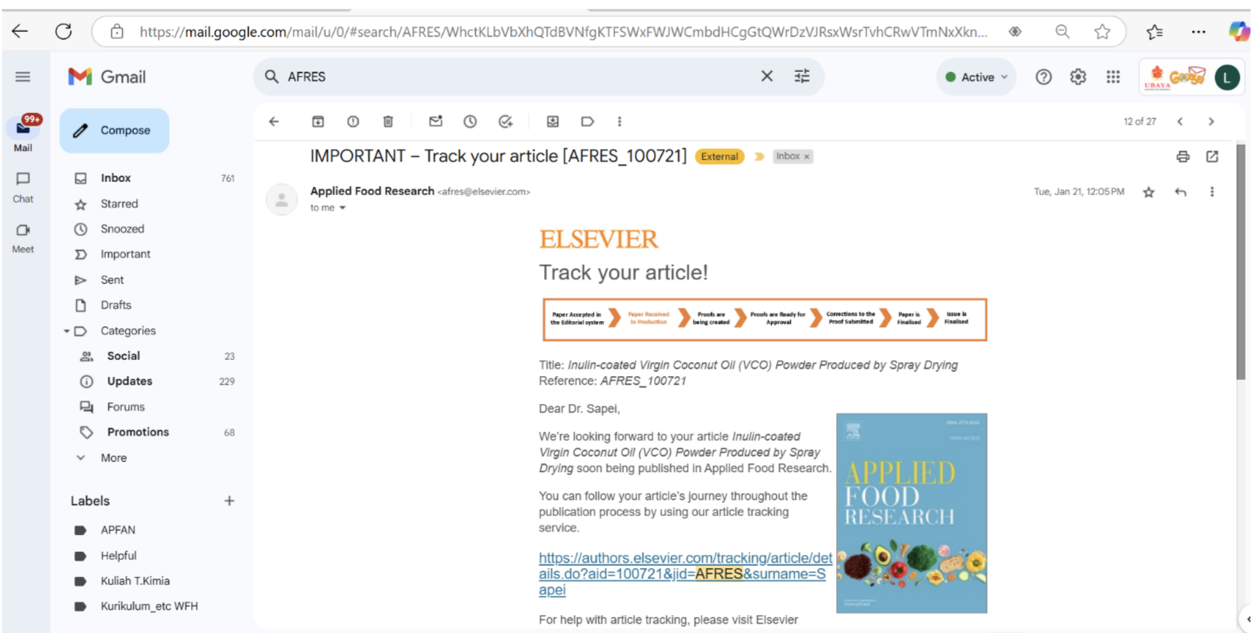

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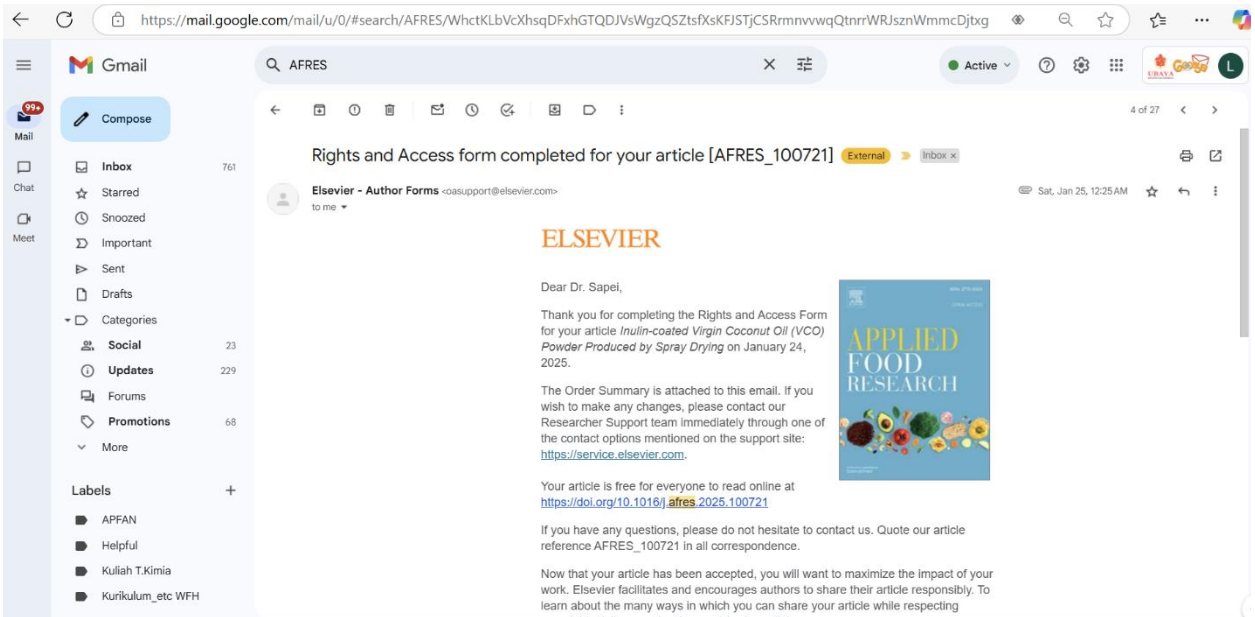

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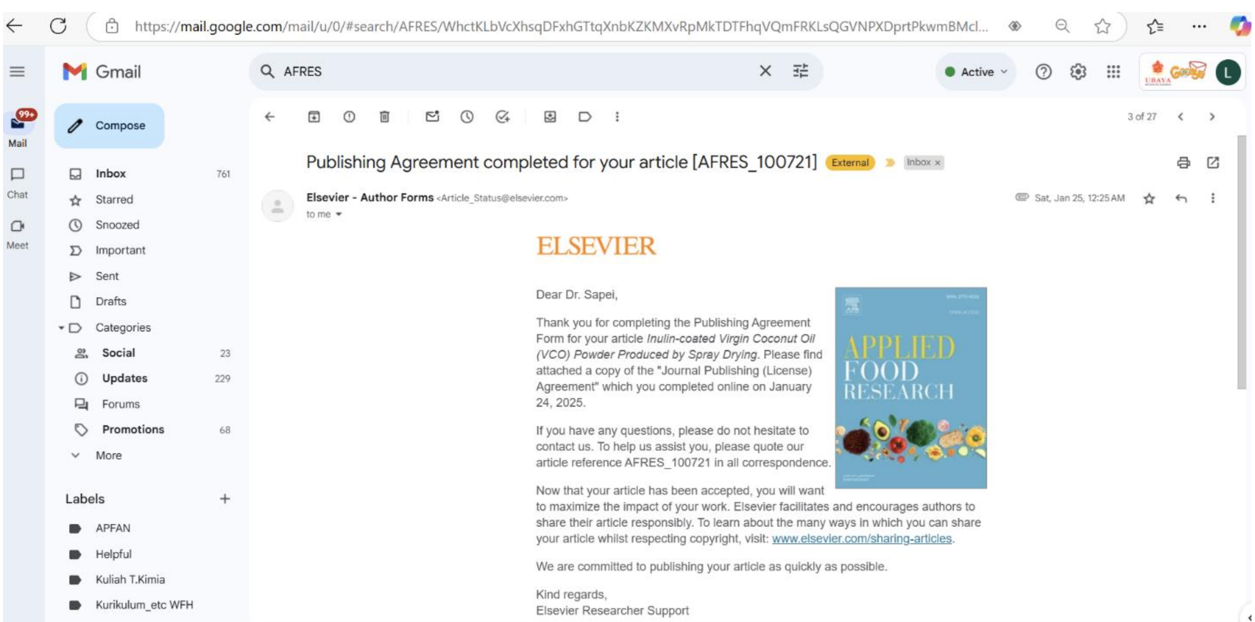

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