

Article

Encapsulation of Extract from Tomato Pomace Applicable as Natural Colorant and Antioxidant in Low-Nitrite Sausage

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Abstract

Tomato pomace (TP) is a waste product from tomato processing. This study explored its use as a food ingredient by creating an encapsulated TP extract (ETPE). TP was extracted with ethanol using a microwave-assisted method prior to encapsulating with either gum arabic (GA) or maltodextrin (MD) via spray drying. MD was selected for further studies based on its lower moisture content with higher radical scavenging ability, assessed by DPPH assay. Spray drying at 160 °C was chosen due to highest radical scavenging ability ($\approx 14.02\%$), although lycopene content was not the highest. Application of ETPE in reduced nitrite sausages did not negatively impact the cooking yield, expressible moisture, and textures of samples. The redness and yellowness of sausage were improved significantly ($p < 0.05$). In addition, a reduction in TBARS from approximately 0.46 to 0.31 mgMDA/kg was found during cold storage for two weeks. In conclusion, the encapsulation of tomato pomace extract can serve as a functional ingredient to produce healthier sausage.

Keywords: tomato pomace extract; encapsulation; low-nitrite sausage; antioxidant; natural colorant

Academic Editor: Ana María Díez-Pascual

Received: 08 August 2025

Revised: 24 September 2025

Accepted: 15 October 2025

Published: 17 October 2025

Citation: Chanshotikul, N.; Hemung, B.-O. Encapsulation of Extract from Tomato Pomace Applicable as Natural Colorant and Antioxidant in Low-Nitrite Sausage. *Macromol* **2025**, *5*, 51. <https://doi.org/10.3390/macromol5040051>

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1. Introduction

An industrial processing of tomato generates 5–30% (*w/w*) of the initial raw material to tomato pomace (TP), which includes peel, pulp, and seeds. About 5.4–9.0 million tons of TP are annually produced by food industries worldwide [1]. It is significantly important in the food research area primarily due to its rich nutritional and bioactive composition. Nutritionally, TP offers a substantial amount of protein (16.81–23.25 g/100 g), fat (11.17–16.73 g/100 g), and a high concentration of dietary fiber (48.62–53.97 g/100 g) [2]. Historically discarded or relegated to low-value uses like fertilizer or livestock feed, TP is now recognized as a valuable functional ingredient. It is a rich source of phytochemicals such as carotenoids and polyphenols and exhibits significant antioxidant and antimicrobial properties. Its valorization as a functional food component exemplifies circular economy principles through the effective minimization of food industry waste. Incorporating TP can enhance the nutritional, functional, and sensory profiles of various food products (e.g., bakery, meat, snacks), and contribute to extending their shelf life [3]. Extraction of active ingredients from TP by conventional solvents is still crucial for further development. Although the recovery of valuable carotenoids from TP using innovative, environmentally friendly methods like deep eutectic solvents has been documented, a significant drawback compared to conventional solvents is their high viscosity [4]. Recently, extraction of lycopene from tomato waste with

ethanol through ultrasound-assisted extraction and optimal condition has been achieved by central composite design for response surface methodology [5]. Microwave-assisted extract was used to recover bioactive compounds from tomato waste as well [6]. The carotenoids in these extracts exhibited antiradical powder as well as potential of natural colorants. However, the extraction by microwaves provided the advantage over other techniques by shortening the extraction time [7]. Therefore, microwave-assisted extraction represents an efficient and promising route for isolating valuable bioactive compounds from TP suitable for food industry integration.

The oxidative degradation of unsaturated fatty acids and carotenoids is commonly observed. Carotenoid instability, especially for those sourced from tomatoes, is effectively addressed through encapsulation. Carotenoids, such as tomato-derived lycopene, are protected from degradation through encapsulation. A physical barrier is created that shields the vulnerable polyene chains from pro-oxidative factors like oxygen, light, and heat, thereby preserving their stability and bioactivity [8]. Spray drying is a promising technique for encapsulation and transforming a TP extract into a dried powder by offering a stable dried product. This mechanism thereby improved the stability and maintained its content during storage, a clear advantage over its free form when exposed to oxygen [9]. Several biopolymers have been used as wall material for encapsulation. Gum arabic and maltodextrin are highly effective encapsulating agents for essential oils and bioactive compounds. Their efficacy stems from significant emulsifying and film-forming properties, allowing stable matrices generation for protecting volatile components with a cost-effective point of view [10]. Maltodextrin was used to encapsulate carotenoids extracted from aril of gac fruit [11]. Maltodextrin mixed with inulin was used as the coating agent during spray drying of lycopene recovered from tomato waste [5]. Application of soy protein isolate-peach gum conjugate as the wall material was found to be useful in preventing the degradation of carotenoids after encapsulation [12]. Comparative investigation regarding the effect of maltodextrin and gum arabic concentrations on properties of encapsulated kinnow peel powder by freeze drying has been reported [13]. Besides wall material, the drying temperature may affect the stability of encapsulated compounds although a short time of evaporation occurred during the spray drying process. The impact of various inlet temperatures (125–200 °C) on the physicochemical and antioxidant properties of spray-dried amla juice powder has been studied and optimal temperature was identified as 175 °C [14]. The effects of wall material and drying temperature on the physicochemical properties of extracted TP should be investigated. Moreover, the potential for application of encapsulated TP extract as a natural colorant in health-oriented meat products should be evaluated, especially in the model of low-nitrite sausage.

Nitrite in cured meats yields a characteristic pink color and desirable flavor. The pink hue stems from heat-stable nitrosyl hemochrome, formed when nitrite (NO_2^-) reduces to nitric oxide (NO). This NO binds to myoglobin's (Mb) heme ferrous iron (Fe^{2+}), creating bright red nitrosomyoglobin (MbNO), which thermal processing converts to the stable pigment. Nitrite concurrently reacts with fats and proteins, enhancing flavor. Its critical inhibition of *Clostridium botulinum* growth and toxin formation makes it preferred for use as multifunctional ingredient [15]. Nitrite's multifunctionality is balanced against the risk of residual amounts forming carcinogenic nitrosamines. Regulations, like Codex Alimentarius, strictly limit nitrite residue to 85 mg/kg. This often necessitates researching synergistic alternatives, e.g., adding TP extract to maintain desired functions by enhancing redness and reducing oxidative rancidity [16]. While the extraction and encapsulation of TP have been well-documented, with some applications in meat products explored, a comprehensive study integrating these aspects to harness waste from tomato processing plants as an ingredient for health-oriented sausage remains unaddressed. This

investigation uniquely aims to bridge this critical gap, providing novel contributions for sustainable product development.

Therefore, the aims of the study were to compare gum arabic and maltodextrin as wall materials for encapsulating tomato pomace extract and to assess the effects of the resulting powders on the color, oxidative properties, and microbiological characteristics of sausages with reduced nitrite content.

2. Materials and Methods

2.1. Materials

Tomato pomace was kindly provided as a gift from Srichiengmai Industry Co., Ltd., Nong Khai, Thailand. The TP sample was obtained using the vacuum drier (Binder GmbH, Tuttlingen, Germany) at 60 °C for 48 h until the moisture content was constant at approximately 5% prior to storage in a vacuumed plastic bag in a desiccator.

2.2. TP Extraction and Encapsulation

The TP powder was extracted with absolute ethanol using the microwave-assisted method according to the method described previously [6]. The ratio of GP/ethanol was controlled at 1:20. A household microwave (GE107Y, Samsung, Salangor, Malaysia) was used to heat the mixture at 180 W for 90 s at the working frequency of 2450 MHz. The extracted mixture was centrifuged at 1000×g for 10 min and the supernatant was collected to filter through filter paper. The filtrate was subjected to the removal of solvent by rotary evaporator (R-200, Buchi, Switzerland).

The TP extract was mixed individually with two types of wall materials, which were gum arabic (GA) and maltodextrin (MD), with the dextrose equivalent (DE) of 20% prior to preparation as the slurry. The ratio of extract wall material was fixed at 1:10 and the total solid of slurry mixture was controlled at 30%. The slurry was fed with a speed of 12–14 mL/min to dry at 160 °C in the drying chamber of a spray dryer (B-290, Buchi, Switzerland). The drying air flow rate and compressor air pressure were controlled at 600 L/h and 4 bar, respectively. The dried powders obtained from different core materials were labeled as encapsulated TP extract (ETPE) and kept under dried/dark conditions until physical characterization. The maltodextrin was selected for further study on the effect of drying temperatures at 140, 160, and 180 °C prior to evaluate the remaining carotenoids and radical scavenging ability.

2.3. Characterization of ETPE

2.3.1. Water Activity and Moisture Content

The water activity (a_w) of encapsulated powder was evaluated at 25 °C using an Aqualab digital hygrometer (Series 3 TE, TE Connectivity, Seattle, WA, USA), which determines the dew point of the samples. Moisture content (MC) was determined by oven drying at 105 °C until constant weight of sample was obtained, following the methodology described by AOAC [17].

2.3.2. Bulk Density

For a known mass of powder, the cylinder was tapped until the powder settled completely (trapping ten times each within 10 s). The final compacted bulk density was then calculated by dividing the mass of powder by its volume as shown in the equation below [18].

$$\text{Bulk density} = m(\text{g})/V(\text{cm}^3) \quad (1)$$

where m is the mass of the sample (g) and V is the volume of the compacted powder (cm³).

This method provides a standardized measurement of the powder's density under compaction, facilitating the evaluation of its flow properties and packing behavior.

2.3.3. Total Lycopene Content

The lycopene content was determined according to a previous method [12]. The ETPE sample (1 g) was dissolved in hexane (10 mL) and left under dark conditions for 15 h. Then, the sample was centrifuged at 6000× g for 20 min before determining the absorbance at 503 nm using a UV/Vis spectrophotometer (T80 PG, London, UK). The lycopene content was calculated according to the equation below.

$$\text{Lycopene } \left(\frac{\text{g}}{\text{L}}\right) = \frac{A_{503} \times 536.9}{17.2 \times 10,000} \quad (2)$$

2.3.4. DPPH Radical Scavenging Ability

The ETPE sample (1 g) was dissolved in hexane (10 mL) before analyzing for the DPPH radical scavenging ability, according to a method applied previously [12]. Sample solution (0.5 mL) was mixed with ethyl acetate (1.5 mL) and DPPH solution (1.5 mL) before incubating in the dark for 30 min. Then, the absorbance at 515 nm (A sample) was monitored using a UV/Vis spectrophotometer (T80 PG, PG Instruments Limited, Leicestershire, UK). The control was prepared by taking off sample from the reaction cocktail and used as A control. The DPPH radical scavenging ability was calculated according to the equation below.

$$\text{DPPH radical scavenging ability (\%)} = \left(\frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \right) \times 100 \quad (3)$$

2.3.5. Color Analysis

Color values were determined using a colorimeter (Hunter Lab, Evanston, IL, USA). A standard D65 illuminant with the angle of 2° observer and aperture of 8 mm were employed. The colorimeter was calibrated using standard white and black calibration plates. Color parameters including L, a, and b values were reported as averages from five replications.

2.4. Preparation of Low-Nitrite Sausages

The model sausage of low-nitrite sausage (25 mg/kg) was prepared according to our previous report [11]. The minced pork, back fat, ice, sodium tripolyphosphate, erythro-bate, and sodium nitrite were controlled at 60, 20, 18, 1.5, 0.4, 0.0125%, respectively (Table 1). Effect of ETPE at 1.0% was evaluated in comparison with control (without ETPE). In order to prepare the batter, minced pork was chopped with a quarter amount of ice for 30 s using a hand-type food mixer (Bowl Rest™ mixer, Hamilton Beach, NC, USA). Other ingredients including salt, sodium nitrite, and ice were added before chopping for 1 min. The back fat was added and continued chopping for 1 min. The ETPE was finally added before final chopping for 1 min and the batter with temperature below 16 °C was obtained. The batter (40 g) was loaded into centrifuge tubes (50 mL) before removing trapped air by centrifugation (200× g for 30 s). All tubes were heated at 80 °C for 30 min before cooling down in ice water for 15 min. Quality evaluation of cooked sausages were performed after being kept in a cold room overnight.

Table 1. Recipe for preparing pork sausage.

Component (%)	Sausage Recipe		
	Negative Control (Without Nitrite)	Treatment	Positive Control (Nitrite 125 mg/kg)
Minced pork	60	60	60
Back fat	20	20	20
Ice	18	18	18
Sodium tripolyphosphate	1.5	1.5	1.5
Erythrobate	0.4	0.4	0.4
Sodium nitrite	0.0025	0.0025	0.0125
ETPE	0.0	1.0	0.0
MD	0.9	0.0	0.9

2.5. Quality Evaluation of Low-Nitrite Pork Sausage

2.5.1. Cooking Yield

The cooking yield was determined according to our previous method report [11]. The cooking yield was calculated based on an original weight relative to sample weight before and after cooking) and expressed as percentage relative to the original weight.

2.5.2. Expressible Moisture Content

Pork sausage samples were cut into cubic shape with the weight of 1.5 g prior to determining for expressible moisture according to our previous protocol [11]. The sample was wrapped with three layers of filter paper (Whatmann No. 3) before loading into the centrifuge tube (50 mL). All samples were centrifuged at 1000× g for 15 min at room temperature using centrifuge (Vision Science, Seoul, South Korea). The expressible moisture was calculated from the ratio of moisture absorbed by filter papers and weight of sample, and expressed as percentage.

2.5.3. Color Analysis

Color values were determined according to the method described previously [19] using a colorimeter (Hunter Lab, Evanston, IL, USA). A standard D₆₅ illuminant with the angle of 2° observer and aperture of 8 mm were employed. The colorimeter was calibrated using standard white and black calibration plates. Color parameters including L, a, and b values were reported as averages from five replications.

2.5.4. Textural Profile Analysis

Pork sausage was cut into a length of 13 mm and the puncturing apparatus with a diameter of 12.5 mm was applied to obtain the sample in cylinder shape. The textural profile of the sample was analyzed according to the method described previously [19] using a TA-XT Plus device (Stable Micro Systems, Ltd., Godalming, UK). The compression test was applied for two cycles with the 75% of sample height using the 500 N load cell at the cross speed of 300 mm/min. The textural properties were reported as hardness, springiness, cohesiveness, and adhesiveness based on at least ten measurements.

2.5.5. Thiobarbituric Acid Reactive Substances (TBARS)

The TBARS value was analyzed according to our previous report [20]. The homogenized sample (2 g) was mixed with 17 mL of trichloroacetic acid solution (2.5%) and 3 mL of TBA solution (1%) before being heated at 90 °C for 30 min. After cooling, the upper phase was taken for 5 mL to mix with 5 mL of chloroform and centrifuge at 200× g for 5 min. Then, the upper phase (3 mL) was taken to mix with petroleum ether and centrifuged

again at the same condition. Finally, a lower phase was taken to measure the absorbance at 532 nm using a spectrophotometer (UV-1601, Shimadzu, Kyoto, Japan). Standard curve of malondialdehyde (MDA) was used to calculate the TBARS value and expressed as mg MDA/kg sample.

2.5.6. Total Microbial Count (TPC)

The TPC method was used to quantify the number of aerobic microorganisms in a sausage sample as previously reported [20]. Using a spread plate technique, a 10 g sample was homogenized with 90 mL of sterile water. This mixture was then serially diluted. From each dilution, 0.1 mL was spread onto two plates of Plate Count Agar. After incubating the plates at 37 °C for 24 h, the colonies that grew were counted and recorded as colony forming units per gram (log CFU/g) of the sample.

2.6. Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics (Version 28.0). One-way ANOVA determined significant differences ($p < 0.05$) among multiple independent groups.

3. Results

3.1. Encapsulation Parameters of TP Extract

3.1.1. Effect of Wall Materials

Encapsulation of TP extract by spray drying has been performed successfully. The effect of MT and GA on the properties of obtained powders have been listed in Table 1. It can be seen that water activity and bulk density were not significantly different. This suggested that the flow behavior and storage stability of those powders would be similar regardless of the wall material applied in these studies. Although encapsulation of the TP extract with GA produced a lower MC value than that performed by MD, those values for both samples were at a significant low of 1–3% (Table 2).

Table 2. Effect of wall materials (1:10) on the properties of ETPE at 160 °C.

Properties	Wall Materials	
	Maltodextrin	Gum Arabic
Moisture content (%)	3.01 ± 0.32 a	1.89 ± 0.71 b
Water activity	0.26 ± 0.01 a	0.27 ± 0.06 a
Bulk density (g/cm ³)	0.569 ± 0.029 a	0.561 ± 0.015 a
DPPH Radical scavenging ability (%)	14.022 ± 0.225 a	10.100 ± 0.612 b

Mean ± SD was averaged from four replications. Different letters within the same row indicate the statistical difference at $p < 0.05$.

3.1.2. Effect of Inlet Drying Temperature

The moisture content, water activity, and bulk density of samples were not different statistically regardless of the drying temperature. This suggested that the stable powder was obtained and could be used further as the natural colorant ingredient in foods. The color values of these powders were slightly different, especially the lightness indicated by L value (Table 3). The lycopene content was reduced upon increasing the inlet temperature and the lowest value was observed at 180 °C. However, the radical scavenging ability was highest in the powder obtained from drying at inlet temperature of 160 °C.

Table 3. Effect of inlet drying temperature on lycopene content and radical. Scavenging activity of ETPE encapsulated with MD (1:10).

Properties	Inlet Drying Temperature (°C)		
	140	160	180
Lycopene content (g/L)	0.137 ± 0.003 a	0.112 ± 0.001 b	0.090 ± 0.001 c
DPPH Radical scavenging ability (%)	11.46 ± 1.21 b	14.02 ± 0.23 a	11.12 ± 0.16 b
Color			
L	90.04 ± 0.18 a	89.76 ± 0.41 ab	89.03 ± 0.73 b
a	5.08 ± 0.76 a	5.57 ± 1.54 a	6.09 ± 0.89 a
b	16.87 ± 1.16 a	17.52 ± 2.69 a	18.61 ± 1.48 a

Mean ± SD was averaged from four replications. Different letters within the same row indicate the statistical difference at $p < 0.05$.

3.2. Effect ETPE on Properties of Sausage

3.2.1. Technological Properties

The inclusion of ETPE with in the sausage recipe did not significantly affect its cooking yield, nor did it have a negative impact on the ability to form emulsion or gelation properly during cooking (Table 4).

Table 4. Technological properties of low-nitrite sausage produced with/without ETPE (1.0%).

Technical Properties	Sausage Recipe		
	Negative Control Without ETPE	Treatment with ETPE	Positive Control Nitrite (125 mg/kg)
Cooking yield (%)	97.13 ± 1.25 a	93.55 ± 1.38 b	95.38 ± 1.31 ab
Expressible moisture (%)	23.28 ± 1.06 a	21.98 ± 1.77 a	22.28 ± 1.44 a

Mean ± SD was averaged from two replications with three measurements/replication. Different letters indicate the statistical difference at $p < 0.05$.

3.2.2. Textural Properties

Adding ETPE did not significantly affect the texture profiles (hardness, chewiness, cohesiveness, springiness, and gumminess) of the pork sausage, as shown in Table 5.

Table 5. Textural properties of low-nitrite sausage produced with/without ETPE (1.0%).

Properties	Sausage Recipe		
	Negative Control (Without ETPE)	Treatment (with ETPE)	Positive Control (with Nitrite 125 mg/kg)
Hardness (g)	1922 ± 106	1952 ± 180	1678 ± 88
Chewiness	61.48 ± 0.4	68.71 ± 2.7	59.69 ± 6.7
Cohesiveness	0.0075 ± 0.0005	0.0077 ± 0.0003	0.0071 ± 0.0008
Springiness	4.30 ± 0.55	4.60 ± 0.35	4.95 ± 0.24
Gumminess	14.56 ± 1.8	15.41 ± 1.8	11.97 ± 1.9

Mean ± SD was averaged from two replications with five measurements/replication.

3.2.3. Color Values

This study utilized ETPE to improve or maintain the desirable color of sausage with a low nitrite content. Although the ETPE samples successfully achieved this, they were also the darkest, registering the lowest lightness value among all groups (Table 6).

Table 6. Color values of low-nitrite pork sausage prepared with/without ETPE.

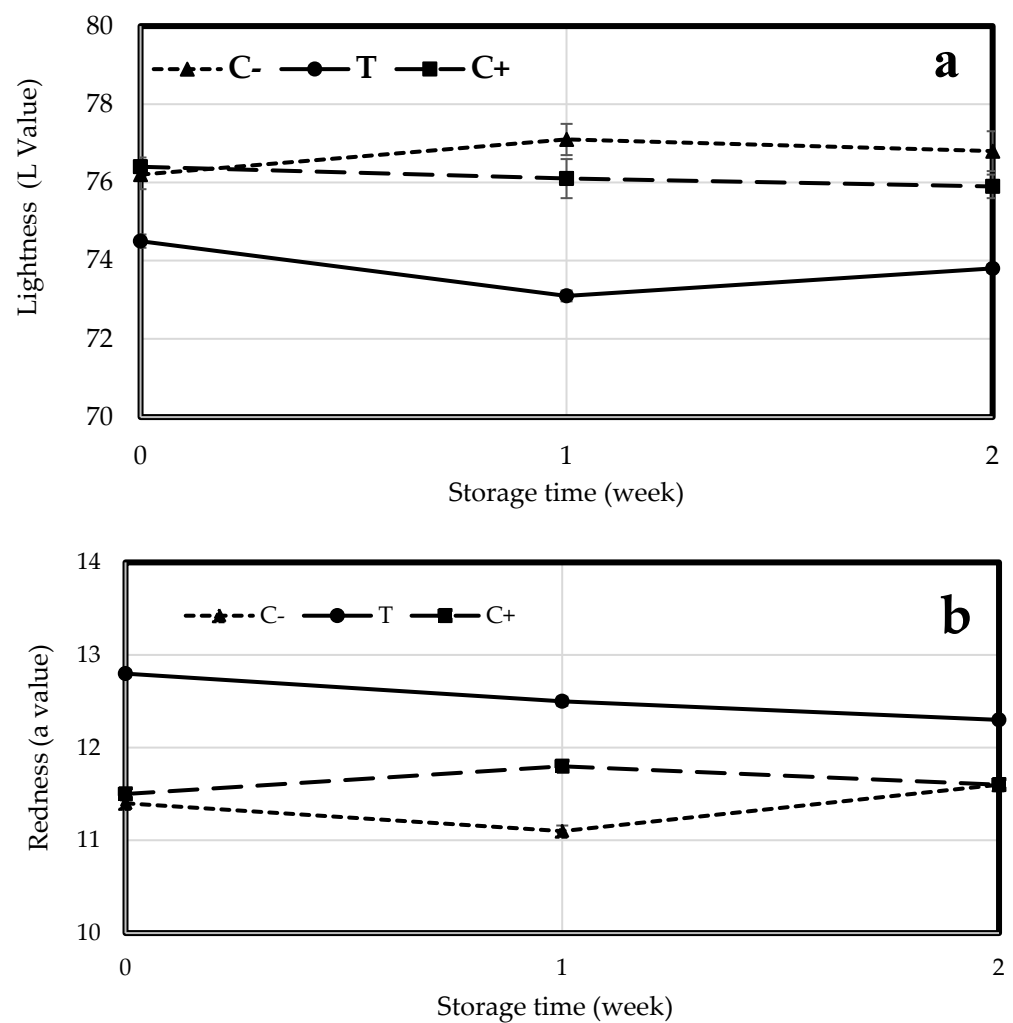
Color Value	Sausage Recipe		
	Negative Control (Without ETPE)	Treatment (with ETPE)	Positive Control (with Nitrite 125 ppm)
Lightness (L value)	76.2 ± 0.37 a	74.5 ± 0.17 b	75.6 ± 0.24 a
Redness (a value)	11.4 ± 0.04 b	12.3 ± 0.04 a	11.5 ± 0.04 b
Yellowness (b value)	5.8 ± 0.11 c	7.4 ± 0.14 a	6.1 ± 0.06 b

Mean ± SD was averaged from two replications with five measurements/replication. Different letters indicate the statistical difference at $p < 0.05$

3.3. Effect of ETPE on Stability of Sausage

3.3.1. Color Stability

The high redness levels maintained over two weeks indicated that this encapsulation technology is an effective way to stabilize the pigment during storage (Figure 1b). The stability of other values of color was observed in either lightness (Figure 1a) or yellowness (Figure 1c).



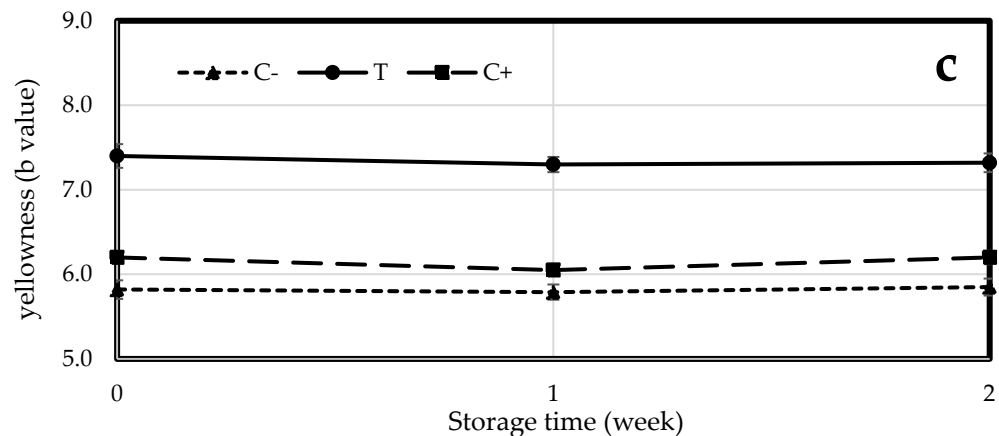


Figure 1. Changes in lightness (a), redness (b), and yellowness (c) of pork sausage during storage for two weeks in air package under chilling condition (10 °C). C- = Negative control, T = Treatment, C+ = Positive control.

3.3.2. Oxidative Stability

At the start of the study (day 0), all sausage samples had very low and similar TBARS values, indicating that lipid oxidation was negligible (Figure 2). However, as the negative control sample was stored in an air-sealed package at 10 °C, its TBARS value gradually increased over time, showing the onset of rancidity.

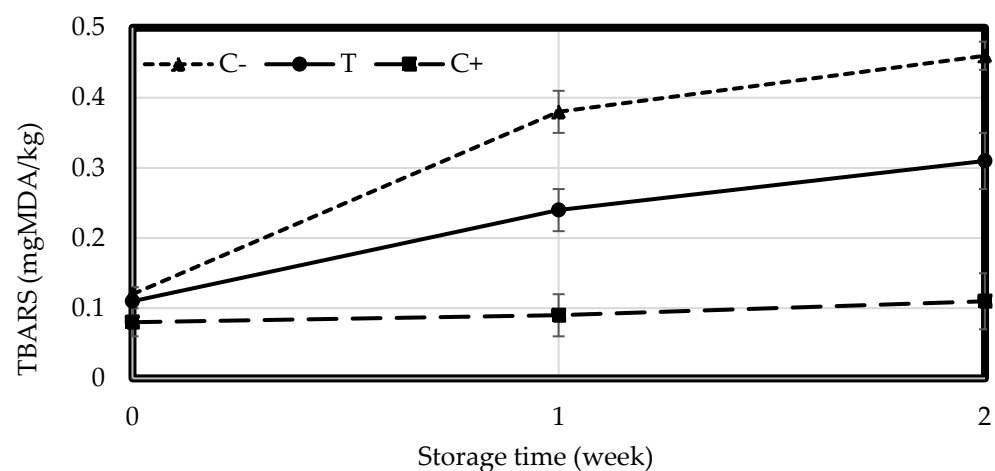


Figure 2. Changes in TBARS of pork sausage during storage for two weeks in air packages under chilling condition (10 °C). C- = Negative control, T = Treatment, C+ = Positive control.

3.3.3. Microbial Stability

Initially, no microorganisms were detected in the sausage samples. However, because the production process did not achieve complete sterilization, the microbial population began to grow during storage. After two weeks of cold storage, the control sausage (which contained only 25 mg/kg of nitrite) had a total microbial count exceeding four log cycles. In contrast, the sausage that included the encapsulated TP extract had a microbial count that was more than one log cycle lower, indicating a notable inhibitory effect on microbial growth.

4. Discussion

4.1. Encapsulation Parameters of TP Extract

4.1.1. Effect of Wall Material

A variety of wall materials can be used to encapsulate natural pigments in food applications, but an ideal encapsulant must possess several key characteristics for optimal performance. It has been reported that MD and GA are widely used as wall materials for encapsulating carotenoids through spray drying for food applications due to their high solubility, low viscosity in aqueous solutions, and good drying properties [21]. It should have both film-forming and emulsifying properties to create a stable, protective barrier around the pigment. The material should also have a low viscosity at high solids content to allow for efficient processing, exhibit low hygroscopicity to prevent unwanted moisture absorption, and be cost-effective for commercial use [22].

The structure of polysaccharide made up in wall materials would likely affect the interaction with water molecules after encapsulation. GA is made of galacturonic acid, rhamnose, arabinose, and galactose, while MD is a cyclic oligosaccharide with glucose units [18]. The difference in saccharide monomer allowed MD to bind less water molecules than GA did. Therefore, different MC could be observed and may attributed to the differing barrier properties. However, encapsulated powders exhibited similar water activity regardless of the type of wall materials. Although MD could bind more water molecules in the wall of the capsule, these water molecules are not able to get involved with chemical reaction or microbial growth. The observed a_w values were <0.3 , suggesting a stable powder. Low a_w could retard chemical deterioration and microbial spoilage. Thus, microencapsulation proves to be a favorable technique for extending product shelf life.

Bulk density is a crucial parameter for both food and therapeutic product development, as it significantly influences handling, packaging, and storage efficiency. In the food industry, a higher bulk density is beneficial because it allows for more compact packaging. This provides lower transportation and storage costs while ensuring the product remains in good condition. This study found no significant difference in the apparent density of the samples, regardless of whether they were encapsulated with GA or MD. This characteristic would likely offer advantages in storage efficiency, making this powder particularly suitable for food applications where optimal bulk density is critical. In the case of encapsulation of the anthocyanin (high polar compounds), GA enhanced particle compactness to a greater extent than MD did [18]. This suggested that different polarity/hydrophobicity of core materials affected the compactness of capsule.

The result from our study also indicated that the radical scavenging ability of TP extract powder encapsulated with MD showed higher value than that with GA (Table 2). The different ability to retain radical scavenging ability was mainly due to the interactions between the core and wall material. Since the core material (TP extract) consisted of either hydrophobic or hydrophilic substances, this would be more immiscible with a wall material with high emulsifying ability like GA. This immiscibility between the core and wall material would reduce barrier properties, resulting in a reduction in radical scavenging ability. Therefore, extracted TP encapsulated in GA exhibited lower radical scavenging activity than it did in MD. GA has been documented to exhibit superior emulsifying activity compared to MD due to the protein fractions in its structure [21]. Thus, GA is often combined with MD for the production of powdered pigment extracts. These results suggested that MD would be the more promising wall material for encapsulation of the extract from TP for further antioxidative ingredients in food application. The important role of MD on the protection of carotenoids extracted from gac fruit aril during spray drying was also previously documented [11]. Based on these results, encapsulation of TP extract

with MD would likely be selected for further study to check the suitable inlet temperature during the spray drying process.

4.1.2. Effect Drying Temperature

Drying temperature generally plays a crucial role on the stability of active compounds encapsulated by spray drying. The higher temperature provides more rapid evaporation of water during drying. At higher inlet temperatures, there is a greater driving force for water removal from atomized feed. However, physicochemical properties of encapsulated powder including MC, a_w , and bulk density, were not statistically different regardless of the drying temperature. The water molecules in the obtained powder bind tightly with MD as the monolayer water and are hard to remove by applied driving forces. An increase in inlet temperature during spray drying of amla powder resulted in a reduction in MC, a_w , and bulk density as reported [14]. More polar of amla powder interact with MD, to different mechanisms, from that which occur in between less polar of TP extract. This fact strongly suggested that different interactions between the core and wall material directly govern the ability to bind with water molecules.

The color values of these powders were slightly different, especially the lightness indicated by L value (Table 3). Drying at the highest temperature (180 °C) resulted in a reduction in lightness, while the yellowness and redness were not affected. This suggested that drying at the highest temperature induced degradation or isomerization of carotenoids to a greater extent. This hypothesis is supported by a reduction in lycopene, major carotenoids in tomato, and content upon increasing drying temperature. It has been reported that high temperature could transform the trans-lycopene to be cis-configuration and a reduction in carotenoids in gac fruit extract after spray drying at high temperature (200 °C) [23]. The radical scavenging ability of ETPE was evaluated since it is considered as antioxidant. The highest value was observed when spray dried at 160 °C and a reduction in this value was found by either lowest or highest drying temperature. A reduction in this value was expected upon increasing drying temperature since lycopene could be degraded/isomerized during drying at high temperatures. It is hypothesized that lycopene in the sample spray dried at 180 °C may not be in the active form [11]. In addition, antioxidants in the TP extract may not be relied on by only lycopene but also other bioactive compounds e. g. phenolic compounds [6]. Therefore, a reduction in radical scavenging ability might not be governed by only a reduction in lycopene content. Based on the results in this part, the encapsulated TP extract by MD at 160 °C was selected for further application as the natural colorant and antioxidant in order to reduce the nitrite content in sausage.

4.2. Effect of ETPE on Properties of Sausage

4.2.1. Technological Properties

To determine how adding MD to the recipe affected the sausage, some key technical parameters, specifically cooking yield and expressible moisture content, were evaluated. Our results showed that including MD had no significant effect on the cooking yield and expressible moisture content (Table 4). This was in agreement with our previous report in the chicken sausage model [11]. Thus, adding ETPE powder at 1.0% was selected. In addition, adding MD to the control sausages had no negative impact on the formation of the emulsion or its ability to gel properly during cooking. This suggested that encapsulated TP extract would be possible in emulsion sausage made from pork.

4.2.2. Textural Properties

Texture profiles of pork sausage were not affected significantly by addition of ETPE as the data shown in Table 5. This might be due to the addition of MD at equivalent

amounts in each sample, resulting in the compensated results. Based on our preliminary study, adding more encapsulated powder (>1.0%) affected the gelation of myofibrillar proteins resulting in a reduction in emulsion gel hardness. Therefore, selection of adding this ETPE at 1.0% was chosen to avoid the negative impact on textural properties. It has been reported that beef frankfurters containing 3–7% TP developed hardness and chewiness as compared to control [19]. Direct addition of TP in sausage resulting in improving the textural properties due to the action of proteins in tomato seen and presented in TP [24]. Application of ETPE at this condition in low-nitrite sausage would be feasible without affecting textural properties.

4.2.3. Color Values

Color is a critical attribute of sausage, as it governs the first impression of consumers. Beyond esthetics, the color, particularly from pigments like carotenoids, can also indicate nutritional quality. In this study, ETPE was used to improve or maintain the desirable color of sausage while using nitrite at a low amount. Since the lightness value of the ETPE samples was the lowest among all groups (Table 6), they were considered to have the brightest. This appeal demonstrated the effectiveness of adding pigment in the form of ingredient powder. However, ETPE significantly improved the color of the sausage, as evidenced by a noticeable increase in both yellowness and redness. The presence of lycopene in ETPE would be solubilized from the wall material (MD) to emulsify with other components during performing emulsion. This shows its potential as a natural colorant, suggesting it could effectively reduce the need for nitrite in sausage production. Adding a TP extract to sausage significantly improved its redness, even without the use of sodium nitrite. Remarkably, the redness of the ETPE-infused sausage was higher than that of the positive control, even though the latter contained 150 mg/kg of nitrite. This positive effect is a result of the lycopene from the extract interacting directly with the myoglobin, a pigment in meat. Interaction between pigments in tomato and nitrite, allowing the reduction in nitrite content in frankfurter, has been documented [25]. This suggests that ETPE can create a desirable color in sausages, even with reduced nitrite. This effect is likely due to the presence of encapsulated carotenoids, specifically lycopene, within a maltodextrin wall material. A further challenge to ensure the practical application would be the evaluation of consumer perception by sensory evaluation.

4.3. Effect of ETPE on Stability of Sausage

4.3.1. Color Stability

The high redness levels maintained over two weeks indicated that this encapsulation technology is an effective way to stabilize the pigment during storage (Figure 1). Our color measurements revealed that the addition of ETPE resulted in the highest yellowness values. This increase in yellowness was directly correlated with a reduction in lightness. The consistent values for yellowness, lightness, and redness throughout the experiment demonstrate a high degree of pigment stability in the encapsulated powder. Lycopene played a role in stabilizing meat color by reduce oxidative stress protecting myoglobin from oxidation [26]. These also suggested that interaction between lycopene and pigment in meat would be the key mechanism to stabilize the color appearance during storage. Thus, ETPE could serve as an effective natural colorant to reduce nitrite in sausage production. However, conducting longer storage time is still challenged for practical application. This not only offers a healthier alternative but also provides a sustainable strategy to convert by-products from tomato processing into a high-value ingredient.

4.3.2. Oxidative Stability

Rancidity in sausage is a result of lipid oxidation, a significant chemical reaction that generates undesirable characteristics. The process is initiated by the radical formation of unsaturated fatty acids, often sped up by factors like metal ions or light. As the reaction proceeds, it produces intermediate peroxides, which then degrade into volatile compounds such as aldehydes and ketones. Since this type of chemical deterioration is a major concern for high-fat food products, preventing it is essential for quality control [27]. The lipid oxidation can be monitored by detecting the secondary products of oxidation and this technique is suitable to follow the reaction during storage. The reaction between thiobarbituric acid and aldehyde are well known for this application. The TBARS values of sausage after storage for 0 days were not different ($p < 0.05$) and were found at such a low level. This is because the degradation of unsaturated fatty acids in all samples to be aldehyde were formed negligibly during fresh preparation of the sausage. However, this value gradually increased in the negative control sample during storage in the air package at 10 °C (Figure 2). A similar trend was observed in sausage produced with ETPE (1.0%), although a lower level was found. This suggested that low nitrite content was not enough to inhibit oxidation although it is enough for developing the desirable color. A reduction in TBARS value was clearly found in a sample with ETPE. This suggested that bioactive compounds presented in the powder would be able to inhibit the lipid oxidation. This also corresponded with the DPPH radical scavenging ability of ETPE presented in Table 2. Those compounds would likely be carotenoids (lycopene and carotene), which are mainly found in the aril part of gac fruit. Moreover, phenolic compounds and carotenoids were major components in TP extract [28]. These phenols could effectively scavenge the radical and would likely be able to terminate the oxidation during the propagation step. Therefore, the oxidation of lipids was finally inhibited. Phenolic compounds present in the hydrophilic part of TP extract exhibited a radical scavenging ability against DPPH and ferric-reducing antioxidant powder (FRAP) reactions [6]. The results suggested that radical scavenging ability based on in vitro assay was sufficient to evaluate the effectiveness of compounds for further application in the food system. This would be the alternative strategy to produce the image of meat product from carcinogenic food to be healthier.

4.3.3. Microbial Stability

To evaluate the microbial stability of sausage stored at 10 °C, the total microbial count was monitored. Initially, no microorganisms were detected due to the thermal pasteurization of the product at 80 °C for over 30 min. However, since this process did not achieve complete sterilization, the residual microbial population was able to proliferate during storage (Table 7). After two weeks of cold storage, the control sausage (containing only 25 mg/kg of nitrite) showed a total microbial count exceeding four log cycles. After adding ETPE, a reduction in microbial count for a log cycle was observed. This suggests that the ETPE likely carries an antimicrobial agent along with a natural colorant. Bioactive compounds in TP, including lycopene, β -carotene, polyphenols, and tetraterpenoids, likely play a dual function by retarding the oxidative degradation and microbial spoilage. It is reported that the extract from tomato seed had an antimicrobial effect against Gram-negative (*E. coli* ATCC25922 and *P. Aeruginosa* ATCC 27853) and Gram-positive (*S. aureus* and *S. pneumoniae*) bacteria [29]. The inhibitory effects were observed against *P. aeruginosa*, a prominent species known for spoiling foods with high moisture levels [29]. This would be beneficial for extending the shelf life of sausage although the ability may not be superior when compared with the high nitrite content at 150 mg/kg in a positive control sample. However, low nitrite content would be more preferable to the consumer rather than adding high amounts of nitrite. Extension shelf life of lamb meat for a week has been achieved by addition of organic TP extract [30]. Therefore, ETPE carries the antimicrobial activity

after spray drying and extending the shelf life of food products is one of the main advantages of using ETPE in food applications.

Table 7. Total plate count (log CFU/g) of low-nitrite pork sausage during storage for two weeks in air packages under chilling condition (10 °C).

Storage Time (Week)	Sausage Recipe		
	Negative Control Without ETPE	Treatment with ETPE 1%	Positive Control with Nitrite (125 mg/kg)
0	nd	nd	nd
1	3.03 ± 0.05	2.57 ± 0.01	nd
2	4.48 ± 0.04 a	3.70 ± 0.10 b	1.87 ± 0.06 c

Mean ± SD was averaged from two replications with three measurements/replication. Different letters indicate the statistical difference at $p < 0.05$, nd = not detected.

5. Conclusions

The bioactive powder rich in carotenoids was successfully produced from a tomato pomace extract through encapsulation via spray drying. Maltodextrin was chosen as the wall material, and a drying temperature of 160 °C was found to maximize the powder's radical scavenging ability. This encapsulated powder could improve the color of low-nitrite sausage and promote storage stability by reducing rancidity and preserving color during chilled storage, while maintaining the technological and textural properties of sausage.

Author Contributions: N.C.: Methodology, Investigation, Analysis, Writing—original draft. B.-O.H.: Conceptualization, Methodology, Investigation, Writing—original draft. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Basic Research Fund, Khon Kaen University.

Data Availability Statement: The original data presented in the study are openly available in Google Drive at [\[https://drive.google.com/drive/folders/15VnYqSLsAYHce00k_2v8nqhnKzk2IrDY?usp=drive_link\]](https://drive.google.com/drive/folders/15VnYqSLsAYHce00k_2v8nqhnKzk2IrDY?usp=drive_link).

Acknowledgments: The authors wish to thank the School of Applied Sciences, Faculty of Interdisciplinary Studies, Khon Kaen University for all facilities. Financial support from Basic Research Fund, Khon Kaen University, was gratefully acknowledged.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GA	Gum Arabic
ETPE	Encapsulated Tomato Pomace Extract
MD	Maltodextrin
TBARS	Thiobarbituric Acid Reactive Substance
TP	Tomato Pomace
TPC	Total Plate Count

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