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Enhancing health-oriented Chashu pork: Effects of transglutaminase and omega-3 enriched pork belly with improved sliceability and fatty acid profile

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Abstract Results from the first experiment indicated that powdered transglutaminase (TG) at 1% w/w resulted in the highest slicing yield, hardness, and gumminess of the fat portion compared with the control and dissolved TG treatments ($P<0.05$). Sensory evaluation also showed significantly higher scores for binding, taste, texture, and overall acceptability than the other treatments ($P<0.05$). The second experiment further investigated Chashu pork produced from omega-3 enriched pork in comparison with pork obtained from animals fed a standard diet (control). Analysis of composition showed that omega-3 pork and its Chashu contained lower fat but higher protein and moisture contents as well as significantly greater omega-3 fatty acids compared with control pork ($P<0.05$). In addition, these samples demonstrated a higher polyunsaturated fatty acids/saturated fatty acids (PUFA/SFA) ratio ($P<0.05$), indicating improved lipid nutritional quality. Notably, Chashu from omega-3 pork had approximately 3.8-fold higher omega-3 fatty acids than control Chashu and achieved an omega-6/omega-3 ratio below 4.0, compared with about 19.3 in the control group. Sensory evaluation revealed no significant differences in all tested attributes between treatments ($P>0.05$). These findings demonstrated that the use of powdered TG improved the sliceability and sensory quality of Chashu pork, while omega-3 pork provided additional nutritional benefits by improving the PUFA/SFA ratio and enhancing omega-3 fatty acids. This approach not only helps to reduce product loss caused by separation during slicing, but also enhances the value of pork belly with adding health benefits.

Keywords: Braised pork belly, TGase, Omega-3 pork, Linolenic acid, Functional meat products

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Introduction

Chashu pork, commonly prepared from braised pork belly, is widely recognized as a popular part of East Asian cuisine, especially as a topping for ramen dishes (Ura, 2020). It is typically distinguished by its alternating layers of lean meat and fat, tender texture, and rich savory flavor (Ura, 2020). However, from a processing perspective, Chashu pork poses several technical challenges. The layered structure often results in fragmentation during thin slicing because the meat and fat layers tend to separate leading to reduce product yield and uniformity. In addition, pork belly which is the primary raw material contains higher fat and lower protein compared to other cuts results in raising health concerns among consumers (Davidson, 2022). These limitations indicate a need for approaches that can improve both product structure and nutritional quality.

One potential solution to improve binding and slicing performance in meat products is the application of transglutaminase (TG). This enzyme facilitates covalent bonding between glutamine and lysine residues in proteins, forming ε-(γ-glutamyl) lysine linkages. As a result, protein networks become stronger and more stable, leading to improved gel formation, elasticity, and water retention. These effects contribute to better texture and structural integrity of restructured meat products (Motoki and Seguro, 1998; Sorapukdee and Tangwatcharin, 2018). Previous studies have demonstrated that TG can enhance cohesiveness and sliceability, as well as overall consumer acceptance, in a variety of products such as low-fat sausages, restructured hams, and poultry-based items (Chin and Chung, 2003; Dos Santos *et al.*, 2023; Erdem *et al.*, 2020).

In terms of nutrition, consumer preferences have increasingly shifted toward meat products containing beneficial fatty acids, particularly omega-3 polyunsaturated fatty acids (PUFAs). Enriching pork with omega-3 fatty acids through dietary strategies has been shown to increase levels of α-linolenic acid (ALA), as well as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These changes also improve the ratio of polyunsaturated to saturated fatty acids (PUFA/SFA) and reduce the omega-6 to omega-3 (n-6/n-3) ratio (Corino *et al.*, 2014; Enser *et al.*, 2000; Kouba and Mourot, 2011). These improvements are associated with cardiovascular benefits, including reduced intake of saturated fats and increased availability of anti-inflammatory compounds (Hunter *et al.*, 2010; Simopoulos, 2002).

Among the sources of omega-3 for pig diets, linseed (flaxseed) has gained attention as a practical and effective option. Compared with marine-based sources such as fish oil, linseed is more cost-efficient, readily available, and less likely to negatively affect sensory attributes (Hoz *et al.*, 2003). It is particularly rich in ALA (C18:3n3) with approximately 55.75% of its fatty acid composition

(Upadhaya *et al.*, 2016). Previous research has shown that supplementation of pig diets with 5% ground linseed during the growing–finishing phase significantly increased omega-3 levels in pork around 2.6–3.2 times compared to control groups (Theeraphapsombut *et al*., 2021).

This enrichment effect of linseed supplementation has been observed across various pork cuts, including high-fat portions such as belly and backfat, as well as retail cuts like ham, boston butt, and leg (Theeraphapsombut *et al.*, 2021). The increase is mainly due to higher ALA content. Because pig is monogastric animal, it has a limited ability to convert ALA into long-chain omega-3 fatty acids such as EPA and DHA (Dugan *et al.*, 2015). However, the higher ALA content remains nutritionally valuable, as it serves as a precursor to other omega-3 fatty acids and contributes to anti-inflammatory effects.

Importantly, previous studies have indicated that omega-3 enrichment does not adversely affect the sensory properties of pork (Hong, 2022; Hui *et al.*, 2025). This suggests that omega-3–enriched pork can be used as a raw material for functional Chashu products. Therefore, this study aimed to improve the structural integrity and slicing quality of Chashu pork using transglutaminase and to enhance nutritional profile by utilizing omega-3–enriched pork belly derived from linseed-supplemented pigs.

Materials and methods

Experiment I: Effect of TG on improving Chashu pork quality

Chashu pork production

Fresh pork belly was used as the primary raw material for Chashu production. Each pork belly was separated into layered sheets of lean and fat, each measuring approximately 20 cm wide × 30 cm long, with a combined weight of about 1200 g. Prior to treatment, these sheets were marinated in a standard Chashu seasoning solution to enhance flavor and taste. After marination, TG was applied to both lean and fat sheets according to the designated treatments: (i) Control (without TG), (ii) Powdered TG, in which enzyme was directly sprinkled at 1% (w/w) of meat weight, and (iii) Dissolved TG, in which TG at 1% (w/w) was dissolved in 4% (w/w) water before application.

Following enzyme application, the lean and fat sheets were rolled together, tightly bound with elastic netting, wrapped with food-grade film, and vacuum-packed. Samples were stored at 4 °C overnight to allow TG activity. The rolls were then oven-cooked at 150 °C for 1 h, followed by braising in a prepared Chashu broth for 30 min. After cooking, the Chashu rolls were chilled and sliced into thin pieces using an automatic slicing machine (Slicer). The overall production process is illustrated in Figure 1. The entire Chashu production process was repeated in three independent processing batches to ensure reproducibility. From each batch, representative samples were randomly collected and subjected to subsequent analyses, including physical properties, and sensory evaluation as described below.

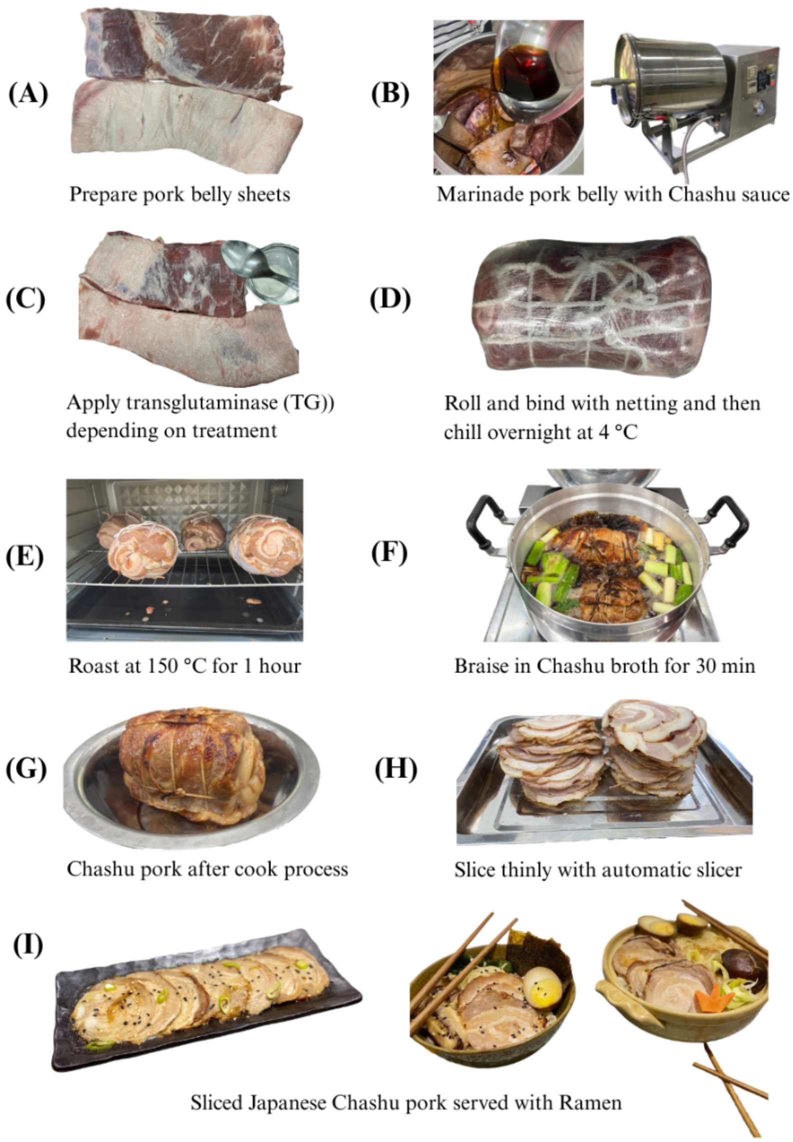

Figure 1. Overview of the processing steps for Chashu pork prepared from pork belly including marination, TG treatment, cooking, and slicing

Sliceability index

Sliceability index was evaluated to determine the integrity of Chashu pork after slicing. For each treatment, three Chashu rolls were weighed and sliced into as many uniform slices as possible using a mechanical slicer. The weights of intact slices (W_i), broken slices (W_b), and residual portions (W_l) were recorded and used to calculate the sliceability index according to the following equation:

$$\text{Sliceability index (\%)} = \frac{Wi}{Wi+Wb+Wl} \; x \; 100$$

Color measurement

The internal color of Chashu pork was determined using a colorimeter (Hunter Associates Laboratory Inc., Reston, VA, USA). Color values were expressed in the CIE L* (lightness), a* (redness), and b* (yellowness).

Texture profile analysis (TPA)

Textural properties of both lean and fat portions were assessed using a texture analyzer (Instron Model 3344, Illinois Tool Works Inc., USA) equipped with a cylindrical probe. Seven samples (15 × 15 × 15 mm) from each treatment were analyzed. Parameters such as hardness, cohesiveness, gumminess, springiness, and chewiness were calculated from the results of force and time curves. All data were processed using Bluehill 2 software.

Sensory evaluation

Sensory evaluation was conducted according to the hedonic test described by Stone *et al.* (2020). Cooked Chashu samples were labeled with random three-digit codes and presented to 30 semi-trained panelists under control conditions. Panelists evaluated binding, color, flavor, taste, texture, and overall acceptability using a nine-point hedonic scale (1 = dislike extremely, 9 = like extremely).

Experiment II: Effect of omega-3 enriched pork belly on the nutritional quality of fresh pork and Chashu products

Animals and sample collection

Two groups of pigs were reared on a private farm in Prachinburi Province, Thailand. Gilts in the control group were fed a standard commercial diet and slaughtered at a live weight of 100–105 kg. The omega-3 group (gilts of the same breed) received a diet supplemented with 5% ground linseed during the growing–finishing phase and were slaughtered at 105–110 kg live weight. All pigs were raised for approximately six months. Following slaughter, carcasses were chilled overnight at 0–4 °C. Pork belly cuts were transported to the laboratory for analysis of proximate and fatty acid compositions, as well as Chashu processing. Chashu pork was prepared using the same method as in experimental I.

Proximate composition and energy value

Moisture, crude protein, crude fat, carbohydrate, and ash contents of fresh pork belly and Chashu products were determined in triplicate using AOAC (2012) standard methods. Energy values were calculated as 9 kcal/g fat, 4 kcal/g protein, and 4 kcal/g carbohydrate, and expressed as kcal/100 g. The percentage of calories derived from fat and reductions in total fat and energy content were also calculated.

Fatty acid composition and lipid quality indices

Fatty acid composition of fresh pork belly and Chashu products was determined using the AOAC (2019) method. Results were expressed as g/100 g of sample. In addition, total *n*-3, *n*-6, and *n*-9 fatty acid contents were quantified and reported as mg/100 g. Nutritional lipid quality indices, including PUFA/SFA and *n*-6/*n*-3 ratios, were calculated.

Sensory evaluation

Sensory characteristics of omega-3 Chashu were assessed following the methodology described in Experiment I. Binding, color, flavor, taste, texture, and overall acceptability were assessed by a panel of 30 semi-trained assessors using a nine-point hedonic scale.

Statistical analysis

A randomized complete block design (RCBD) was used in Experiment I, with three independent processing batches was setted as blocks. The effects of TG treatments were analyzed using one-way ANOVA, followed by Duncan's multiple range test for mean comparisons ($P<0.05$). In Experiment II, differences between control and omega-3–enriched pork were analyzed using independent *t*-tests for both fresh and processed (Chashu) samples. Statistical analyses were performed using SPSS (Version 28, IBM SPSS Inc., Chicago, IL, USA).

Results

Experiment I: Effect of TG on improving Chashu pork quality

The effects of TG application on the physical properties of Chashu pork are summarized in Table 1. The use of powdered TG had the highest value of sliceability of the product, followed by the dissolved TG and the control group, respectively (P<0.05). This indicates that powdered TG enhanced product cohesion during slicing more effectively than the other treatments. Regarding color parameters, no significant differences were observed in lightness (L*), redness (a*), and yellowness (b*) values among treatments (P>0.05).

Table 1. Effect of TG on physical property of Chashu pork

Items	Treatment group[1]		
	Control	Powdered TG	Dissolved TG
Sliceability (%)	75.2 ± 1.52[c/2]	86.7 ± 2.56[a]	82.9 ± 2.27[b]
Color			
- Lightness (L*)	59.55 ± 3.50	60.65 ± 2.15	64.22 ± 1.52
- Redness (a*)	3.68 ± 0.93	3.90 ± 1.29	4.00 ± 0.74
- Yellowness (b*)	17.80 ± 1.47	17.31 ± 0.19	16.52 ± 1.08
Texture profile analysis of lean portion			
- Hardness (N)	7.97 ± 2.27	7.73 ± 1.98	6.42 ± 2.26
- Cohesiveness (ratio)	0.57 ± 0.10[b]	0.67± 0.10[a]	0.70 ± 0.11[a]
- Gumminess (N)	4.53 ± 1.43	5.24 ± 1.58	4.38 ± 1.27
- Springiness (ratio)	0.73 ± 0.15	0.78 ± 0.07	0.87 ± 0.09
- Chewiness (N)	3.47 ± 1.55	4.13 ± 1.50	3.88 ± 1.05
Texture profile analysis of fat portion			
- Hardness (N)	5.48 ± 1.43[b]	7.69 ± 1.54[a]	4.90 ± 0.63[b]
- Cohesiveness (ratio)	0.79 ± 0.04	0.77 ± 0.06	0.72 ± 0.10
- Gumminess (N)	4.35 ±1.06[b]	5.74 ± 0.75[a]	4.61 ± 0.63[b]
- Springiness (ratio)	0.95±0.03	0.92 ± 0.08	0.91 ± 0.11
- Chewiness (N)	4.13 ±0.95	5.19 ± 0.70	4.19 ± 0.80

[abc]: Means with different superscript in the same row differed significantly (P<0.05).
[1]/: Control = sample without transglutaminase; Powdered TG = transglutaminase applied as a powdered form at 1% w/w; Dissolved TG = 1% w/w of transglutaminase dissolved in 4 % w/w of water
[2]/: Values are given as means±standard deviation of each processing batch (n = 3).

For the texture profile of the meat portion, the application of both powdered and dissolved TG significantly increased cohesiveness compared to the control (P<0.05). Other parameters including hardness, gumminess, springiness, and chewiness of the meat part did not differ significantly among treatments (P>0.05). Morevoer, in the fat portion, hardness and gumminess were significantly greater in the powdered TG group than both control and dissolved TG (P<0.05). No significant differences were observed in cohesiveness, springiness, and chewiness among treatments (P>0.05).

The results of the sensory evaluation of Chashu pork are presented in Table 2. The use of powdered TG significantly improved several sensory attributes compared with the control. Binding scores were highest in the powdered TG treatment (P<0.05). This suggested that powdered TG improved adhesion between the meat and fat layers, resulting in a more cohesive structure as perceived by the panelists. In the same trend, flavor, taste, and overall acceptability were also significantly higher in the powdered TG group compared with the control (P<0.05). The texture scores followed a similar pattern, with the powdered TG treatment providing the highest ratings among all groups (P<0.05), indicating an improvement in mouthfeel and structural integrity. No significant differences in color were observed among treatments (P>0.05). It was noted that the dissolved TG group generally showed intermediate values across most attributes and did not demonstrate clear improvements compared with the powdered TG treatment.

Table 2. Impact of tranglutaminase on sensory property of Chashu pork

Items	Treatment group[/1]		
	Control	Powdered TG	Dissolved TG
Binding	4.85 ± 1.97[c/2]	7.67 ± 1.42[a]	6.11 ± 1.69[b]
Color	5.78 ± 1.56	6.22 ± 1.16	6.17 ± 1.56
Flavor	6.30 ± 1.63[b]	7.13 ± 1.34[a]	6.80 ± 1.32[ab]
Taste	6.91 ±1.54[b]	7.59 ± 1.32[a]	6.81 ± 1.48[b]
Texture	6.65 ± 1.38[c]	7.76 ± 1.11[a]	7.22 ± 1.19[b]
Overall acceptability	6.81 ± 1.18[c]	8.07 ± 0.94[a]	7.22 ± 1.02[b]

[abc:] Means with different superscript in the same row differed significantly (P<0.05).

[1]/: Control = sample without transglutaminase; Powdered TG = transglutaminase applied as a powdered form at 1% w/w; Dissolved TG = 1% w/w of transglutaminase dissolved in 4 % w/w of water

[2]/: Values are given as means±standard deviation of each processing batch (n = 3).

Experiment II: Effect of omega-3 enriched pork belly on the nutritional quality of fresh pork and Chashu products

Proximate composition analysis indicated that pork from animals fed an omega-3–enriched diet showed improved nutritional characteristics compared with pork from those fed a standard diet (Table 3). Fresh omega-3 pork contained significantly higher levels of moisture and protein, while its fat content was significantly lower than that of the control (P<0.05). As a result, the total energy value was reduced (195.87 kcal/100 g), along with a lower proportion of energy derived from fat (57.48%). Overall, these results suggested that dietary strategies can be used to produce pork with improved nutritional value and reduced fat content.

A similar trend was observed after processing into Chashu products. Omega-3 Chashu contained significantly higher moisture and protein with lower fat compared with control Chashu (P<0.05). As a result, the energy value and energy from fat were markedly reduced in omega-3 Chashu (277.99 kcal/100 g and 64.98% from fat) compared with the control product (384.15 kcal/100 g and 79.63% from fat).

Table 3. Proximate composition and energy value of fresh meat and Chashu product obtained from omega-3 enriched pork belly compared with control pork

Items	Fresh Pork/1		Chashu Product/1	
	Control	Omega-3	Control	Omega-3
Moisture (%)	49.70 ± 2.74[b/2]	68.13 ± 5.42[a]	45.24 ± 0.15[b]	54.24 ± 2.25[a]
Protein (%)	15.20 ± 2.16[b]	20.82 ± 4.15[a]	16.70 ± 0.60[b]	22.09 ± 1.43[a]
Fat (%)	40.67 ± 5.12[a]	12.51 ± 3.78[b]	33.99 ± 1.03[a]	20.07 ± 2.56[b]
Ash (%)	0.63 ± 0.05[b]	0.83 ± 0.15[a]	1.20 ± 0.04[a]	1.32 ± 0.10[b]
Carbohydrate (%)	<0.01	<0.01	2.86 ± 1.59[a]	2.27 ± 1.37[a]
Total energy value (kcal/100 g)	426.83 ± 45.13[a]	195.87 ± 38.21[b]	384.15 ± 31.72[a]	277.99 ± 27.16[b]
Energy from fat (kcal/100 g)	366.03 ± 35.14[a]	112.59 ± 10.57[b]	305.91 ± 27.21[a]	180.63 ± 30.78[b]
Energy from fat (%)	85.76 ± 9.27[a]	57.48 ± 7.16[b]	79.63 ± 6.25[a]	64.98 ± 4.02[b]

[abc]: Means with different superscript in the same row differed significantly (P<0.05).

1/: Control = pork from animals fed a standard diet ; Omega-3 = pork from animals fed a omega-3 enriched diet.

2/: Values are given as means±standard deviation of each processing batch (n = 3).

Analysis of fatty acid composition revealed pronounced nutritional advantages in omega-3 enriched pork and its derived Chashu products compared with control samples are shown in Table 4. Fresh omega-3 pork exhibited markedly lower concentrations of major SFA, including palmitic acid (C16:0), stearic acid (C18:0) and myristic acid (C14:0), resulting in a significantly reduced total SFA level (4.34 g/100 g) compared with control pork (14.02 g/100 g) (P<0.05).

A similar trend was observed after processing into Chashu, where omega-3 Chashu also contained lower SFA (7.39 g/100 g) than control Chashu (12.23 g/100 g). Control pork contained a significantly higher monounsaturated fatty acids (MUFA) content (especially oleic acid and palmitoleic acid) compared with omega-3 pork. Although the total MUFA was lower in omega-3 pork (P<0.05), improvements were evident in the PUFA profile. Notably, omega-3 pork showed significantly higher ALA (C18:3*n*3) and eicosatrienoic acid (C20:3*n*3) (P<0.05), as well as the presence of EPA (C20:5*n*3) in omega-3 Chashu, which was absent in control samples. This resulted in substantially elevated total omega-3 fatty acids: 564.56 mg/100 g in fresh omega-3 pork versus 302.74 mg/100 g in control pork, and 931.24 mg/100 g in omega-3 Chashu compared with 245.03 mg/100 g in control Chashu (P<0.05).

Table 4. Fatty acid composition and nutritional index of lipid in fresh meat and Chashu product obtained from omega-3 enriched pork belly compared with control pork

Items	Fresh Pork[/1]		Chashu Product[/1]	
	Control	Omega-3	Control	Omega-3
Fatty aid content (g/100 g)				
Saturated Fatty Acid (SFA)				
- Capric acid, C10:0	0.03 ± 0.02[/2]	0.01 ± 0.00	0.03 ± 0.02	0.02 ± 0.01
- Lauric acid, C12:0	0.07 ± 0.02[a]	0.03 ± 0.01[b]	0.06 ± 0.02	0.05 ± 0.01
- Myristic acid, C14:0	0.64 ± 0.03[a]	0.21 ± 0.01[b]	0.58 ± 0.02[a]	0.31 ± 0.01[b]
- Pentadecanoic acid, C15:0	0.02 ± 0.01	ND	0.01 ± 0.00	ND
- Palmitic acid, C16:0	9.38 ± 1.15[a]	2.79 ± 0.08[b]	8.13 ± 1.36[a]	4.34 ± 0.74[b]
- Heptadecanoic acid, C17:0	0.08 ± 0.02[a]	0.02 ± 0.00[b]	0.07 ± 0.02[a]	0.04 ± 0.01[b]
- Stearic acid, C18:0	3.7 ± 0.07[a]	1.25 ± 0.05[b]	3.28 ± 0.74	2.58 ± 0.32
- Arachidic acid, C20:0	0.09 ± 0.02[a]	0.03 ± 0.01[b]	0.07 ± 0.02[a]	0.05 ± 0.01[b]
Total SFA	14.02 ± 0.78[a]	4.34 ± 0.06[b]	12.23 ± 0.75[a]	7.39 ± 0.68[b]
Monounsaturated Fatty Acid (MUFA)				
- Plamitolecid acid, C16:1*n*7	1.12 ± 0.64[a]	0.26 ± 0.04[b]	0.99 ± 0.31[a]	0.29 ± 0.07[b]
- Eladidic acid, C18:1*n*9t	0.05 ± 0.02	ND	0.04 ± 0.02	ND
- Oleic acid, C18:1*n*9	17.03 ± 3.51[a]	4.33 ± 1.23[b]	13.85 ± 4.62[a]	6.6 ± 1.47[b]
- Eicosenoic acid, C20:1*n*9	0.32 ± 0.25[a]	0.08 ± 0.04[b]	0.24 ± 0.07[a]	0.13 ± 0.06[b]
Total MUFA	18.54 ± 2.78[a]	4.67 ± 0.84[b]	15.12 ± 3.74[a]	7.03 ± 1.39[b]
Polyunsaturated Fatty Acid (PUFA)				
- Linoleic acid, C18:2*n*6c	5.51 ± 1.21a	2.18 ± 0.35[b]	4.45 ± 1.47[a]	3.48 ± 0.78[b]
- gamma-Linolenic acid, C18:3*n*6	0.01 ± 0.01	ND	0.01 ± 0.01	ND
- alpha-Linolenic acid, C18:3*n*3	0.27 ± 0.06[b]	0.5 ± 0.02[a]	0.22 ± 0.02[b]	0.82 ± 0.03[a]
- Eicosadieonic acid, C20:2*n*6	0.19 ± 0.01[a]	0.07 ± 0.01[b]	0.14 ± 0.02	0.12 ± 0.01
- Eicosatrieonic acid, C20:3*n*6	0.04 ± 0.01	0.02 ± 0.01	0.03 ± 0.01	0.02 ± 0.00
- Eicosatrieonic acid, C20:3*n*3	0.03 ± 0.01[b]	0.05 ± 0.01[a]	0.02 ± 0.00[b]	0.09 ± 0.02[a]
- Arachidonic acid, C20:4*n*6	0.09 ± 0.02[a]	0.05 ± 0.01[b]	0.09± 0.02	0.09 ± 0.03
- Eicosapentaenoic acid, C20:5*n*3	ND	ND	ND	0.02 ± 0.01
Total PUFA	6.14 ± 0.57[a]	2.87 ± 0.13[b]	4.96 ± 0.71	4.64 ± 0.53
Total UFA	24.68 ± 4.75[a]	7.54 ± 1.67[b]	20.08 ± 3.54[a]	11.67 ± 1.08[b]
Nutritional quality index of lipid				
- MUFA/SFA ratio	1.32 ± 0.04[a]	1.08 ± 0.02[b]	1.24 ± 0.07[a]	0.95 ± 0.06[b]
- PUFA/SFA ratio	0.44 ± 0.05[b]	0.66 ± 0.03[a]	0.41 ± 0.06[b]	0.63 ± 0.03[a]
- Trans fat content (g/100 g)	0.05 ± 0.01	ND	0.04 ± 0.01	ND
Omega-3, 6, 9 contents (mg/100g)				
- Total Omega-3 (*n*-3)	302.74 ± 70.15[b]	564.56 ± 31.04[a]	245.03 ± 24.54[b]	931.24 ± 47.13[a]
- Total Omega-6 (*n*-6)	5841.24 ± 987.47[a]	2323.13 ± 472.11[l]	4721.42 ± 851.73[a]	3713.99 ± 527.42[b]
- Total Omega-9 (*n*-9)	17351.44 ± 2541.62[a]	4411.05 ± 1232.94[b]	14082.47 ± 1756.12[a]	6733.94 ± 872.14[b]
***n*-6/*n*-3 ratio**	19.29 ± 2.41[a]	4.11 ± 0.54[b]	19.27 ± 1.24[a]	3.99 ± 0.67[b]

[abc:] Means with different superscript in the same row differed significantly (P<0.05).
[1]/: Control = pork from animals fed a standard diet ; Omega-3 = pork from animals fed a omega-3 enriched diet.
[2]/: Values are given as means±standard deviation of each processing batch (n = 3).

Importantly, the ratio of *n*-6/*n*-3 was dramatically improved in omega-3 pork (4.11) and omega-3 Chashu (3.99), compared with approximately 19 in the control groups. Furthermore, the PUFA/SFA ratio, an indicator of desirable lipid balance, was significantly higher in omega-3 pork (0.66) and omega-3 Chashu (0.63) compared with the control groups (0.44 and 0.41, respectively) (P<0.05). Trans fatty acids were not detected in omega-3 enriched pork, further strengthening its nutritional value.

The sensory evaluation of Chashu pork prepared from omega-3 enriched pork belly compared with the control group is shown in Table 5. No significant differences were observed between treatments for all sensory attributes, including binding, color, flavor, taste, texture, and overall acceptability (P>0.05).

Table 5. Sensory liking scores of Chashu product obtained from omega-3 enriched pork belly compared with control pork

Items	Treatment group[1]	
	Control Chashu	Omega-3 Chashu
Binding	7.30 ± 0.95[a/2]	7.20 ± 0.92[a]
Color	5.80 ± 1.48[a]	5.60 ± 1.35[a]
Flavor	6.80 ± 1.55[a]	7.30 ± 1.64[a]
Taste	7.70 ± 1.16[a]	7.00 ± 1.33[a]
Texture	7.10 ± 1.85[a]	7.00 ± 1.41[a]
Overall acceptability	7.00 ± 0.82[a]	7.10 ± 0.88[a]

[abc]: Means with different superscript in the same row differed significantly (P<0.05).
[1]/: Control = pork from animals fed a standard diet ; Omega-3 = pork from animals fed a omega-3 enriched diet.
[2]/: Values are given as means±standard deviation of each processing batch (n = 3).

Discussion

The present study demonstrated that the application of TG, particularly in powdered form, significantly improved both the physical and sensory quality attributes of Chashu pork. In terms of physical properties, powdered TG treatment exhibited the highest sliceability index with the highest hardness, and gumminess values of fat portion compared with the control and dissolved TG groups. These improvements are consistent with the enzymatic mechanism of TG, which catalyzes the formation of ε-(γ-glutamyl)lysine cross-links between muscle proteins, thereby enhancing protein network density and strengthening structural integrity (Motoki and Nio, 1983; Motoki and Seguro, 1998; Muguruma *et al.*, 1990; Sakamoto *et al.*, 1995). The increase in sliceability index in the powdered TG group reflected a more cohesive and compact structure, which contributed to reduced breakage during slicing and improved yield.

Results from sensory evaluation supported these findings, where the powdered TG treatment showed clear advantages in binding, texture, taste, and overall acceptability compared with the control. The improvements can be attributed to the cross-linking action of TG, which enhances protein interactions, leading to a firmer texture and better moisture retention. Comparable findings have been reported in TG-treated meat products such as restructured beef and sausages (Kaić *et al.*, 2021; Li *et al.*, 2018; Sorapukdee and Tangwatcharin, 2018; Zhang *et al.*, 2025). However, color preference did not differ significantly among treatments, suggesting that the effect of TG is more pronounced in structural and textural attributes than in appearance.

Overall, these findings indicated that powdered TG is more effective than its dissolved form in enhancing both the structural integrity and sensory quality of Chashu pork. The development of a stable protein matrix helped minimize processing losses, such as breakage during slicing, while also improving consumer acceptance through better binding, texture, and taste. These results suggested that powdered TG could serve as a useful functional ingredient in the production of value-added pork products with improved quality and market potential.

In addition, the second part of the study showed that using omega-3–enriched pork belly, together with TG application, can improve the nutritional profile of Chashu products without compromising sensory quality. Omega-3 pork contained less fat and higher protein and moisture levels than the control, both before and after processing. These findings are in agreement with earlier studies reporting that omega-3 supplementation can reduce fat accumulation and increase lean tissue in pork (Kouba and Mourot, 2011; Wood *et al*., 2008). The reduction in total fat and energy content, together with the increase in protein concentration, further supports the potential of omega-3–enriched pork as a healthier raw material for processed meat products.

Fatty acid analysis showed that omega-3 pork contained lower levels of saturated fatty acids (SFA), particularly palmitic (C16:0) and myristic acids (C14:0), which are commonly associated with increased LDL cholesterol and a higher risk of cardiovascular disease (Grundy, 1997). Stearic acid (C18:0) was also reduced in omega-3 pork compared with the control. Although stearic acid is classified as an SFA, it has been reported to have a neutral or less adverse effect on blood cholesterol than palmitic and myristic acids, and its lower level may further support cardiovascular health (Hunter *et al.*, 2010).

In contrast, control pork showed higher levels of monounsaturated fatty acids (MUFA), especially oleic and palmitoleic acids, which are known for their beneficial effects on lipid profiles (Grundy, 1997; Kris-Etherton *et al*., 1999). However, the overall fatty acid composition of omega-3 pork was more favorable from a nutritional standpoint. The increased content of omega-3 polyunsaturated fatty acids (PUFA), together with an improved PUFA/SFA ratio and a significantly lower n-6/n-3 ratio, suggests a greater potential benefit for long-term cardiovascular health. Previous studies have also indicated that, although MUFA plays a positive role in lipid metabolism, increasing omega-3 intake may offer additional advantages in reducing inflammation and lowering the risk of chronic diseases (Simopoulos, 2002; Wood *et al.*, 2008).

As compared with the control, omega-3 pork contained higher levels of ALA (C18:3*n*3) and eicosatrienoic acid (C20:3*n*3), and EPA (C20:5*n*3) was detectable only in omega-3 Chashu. These differences resulted in a higher total omega-3 content approximately 3.8-fold greater in omega-3 Chashu than in the control with improvement of the *n*-6/*n*-3 ratio (approximately 4 in omega-3 pork and Chashu compared with around 19 in the control). Ratios below 4 are generally considered favorable for reducing the risk of chronic inflammation and cardiovascular disease (Simopoulos, 2002). In addition, the PUFA/SFA ratio was higher in the omega-3 group, further indicating an improved lipid profile. These findings are consistent with previous reports showing that omega-3 supplementation in pigs enhances PUFA deposition and improves lipid-related nutritional indices (Corino *et al.*, 2014; Enser *et al.*, 2000). Interestingly, these changes did not affect sensory perception. No significant differences were found between the two groups for any of the evaluated attributes. Similar outcomes have been reported in earlier studies, where omega-3 enrichment did not compromise product quality (Hong, 2022; Hui *et al.*, 2025). This suggests that nutritional improvements can be achieved without negatively influencing consumer acceptance.

In summary, the combination of omega-3 pork and TG in Chashu production resulted in a product with improved nutritional properties while maintaining desirable sensory characteristics, making it a promising option for the development of functional meat products.

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Conflicts of interest

The authors declare no conflict of interest.

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