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Correlation between muscle fiber type, muscle-to-fat ratio, and physicochemical properties in pork belly and mokshim (neck)

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Abstract (up to 350 words)

The purpose of this study is to measure the muscle and fat ratio of mokshim (neck, Boston butt equivalent) and pork belly using computed tomography (CT) and magnetic resonance imaging (MRI), and to provide basic data that can be used for quality evaluation by comparing it to the traditional pork quality assessment indicator, the physicochemical properties. A total of 115 pork mokshim and pork belly were scanned by CT, while 30% (33 samples of pork) of them were imaged by MRI. The ratios of muscle-to-fat were estimated using Vitrea workstation version 7. The muscle-to-fat ratio of mokshim measured by CT and MRI showed comparable values of 1:0350 and 1:0.325, respectively. The correlations between physicochemical properties and non-destructive assessment methods, including CT, MRI, and histochemical staining, were evaluated using GraphPad Prism version 8. The muscle-to-fat ratio in the mokshim measured by CT showed a significant negative correlation with cooking loss ($r = -0.226$, $p < 0.05$), and positive correlations with moisture content ($r = 0.203$, $p < 0.05$) and yellowness (b*) ($r = 0.220$, $p < 0.05$). In the pork belly, the muscle-to-fat ratio also showed a significant positive correlation with b* ($r = 0.411$, $p < 0.001$). In contrast, no significant correlation was observed between the muscle-to-fat ratio measured by MRI and any of the physicochemical properties. Similarly, no significant correlations were found between muscle fiber type I and physicochemical properties across all belly regions. However, significant associations were observed between muscle fiber types and meat color in the pork belly. Type IIA Fibers showed negative correlations with lightness and yellowness, whereas Type IIB fibers showed positive correlations with these color traits. These results suggest a potential relationship between muscle fiber composition, muscle-to-fat ratio, and pork quality traits. However, further studies with larger sample sizes are needed to confirm these findings.

Keywords (3 to 6): Computed tomography, Magnetic resonance imaging, mATPase staining, Muscle fiber type, Pork quality, Physicochemical properties

Introduction

Pork is one of the most widely consumed meat products worldwide [1], and in addition to taste and nutrition, increasing attention is being paid to its functionality, safety, and quality. Accordingly, the evaluation of pork quality has become an important issue for both consumers and producers [2–4]. Pork carcasses consist of various cuts, each with different taste and texture characteristics, and their demand and economic value vary depending on consumer preference. Recently, as consumers show decreasing preference for excessively fatty meat, there has been growing demand for the labeling of muscle-to-fat content and quality in specific cuts such as pork belly and mokshim (neck, Boston butt equivalent), rather than relying solely on the overall carcass grade [5].

In Korea, pork quality grading is conducted in two stages based on the standard of the Korea Institute for Animal Product Quality Evaluation [6]. The grading system consists of two stages: carcass yield is evaluated based on hot carcass weight and backfat thickness, while meat quality is assessed based on the visual and textual characteristics—such as marbling, meat and fat color, and texture—of the *longissimus dorsi* muscle exposed between the last rib and the first lumbar vertebra; the final grade is determined by the lower of the two [7,8]. However, this grading system, which is based on how carcass evaluation, primarily reflects meat quantity rather than quality. However, such grading system relying visual assessment of the exposed loin surface, has inherent limitations in representing the overall carcass quality [8,9]. While physicochemical analyses are commonly used to evaluate pork quality, they are limited in providing direct information on muscle fat content—an attribute of growing importance to consumers.

Many previous studies have emphasized the importance of an appropriate muscle-to-fat ratio in determining meat taste and texture [10–12]. According to Monziols et al. [11] muscle contributes to elasticity and quality, while fat enhances tenderness and flavor; thus muscle-to-fat ratio is a critical factor in determining meat quality [7]. Furthermore, the distribution of muscle fiber types has been shown to significantly affect meat quality characteristics such as color, tenderness, and water-holding capacity [13–15]. In previous studies, muscle an characteristics have consistently been identified as key factors influencing meat quality [3,16–18].

With recent advances in technology, a variety of non-invasive and non-destructive methods–such as spectroscopy, radiography, computed tomography (CT), and magnetic resonance imaging (MRI)—have been introduced to quantitatively analyze the composition of carcasses and animal tissues [19–22]. However, these imaging technologies are limited in their ability to distinguish muscle fiber types. To date, the most reliable method for classifying muscle fiber types remains histochemical staining, particularly myofibrillar adenosine triphosphatase (mATPase) staining [23].

Although several studies have explored the relationship between carcass traits and pork quality, most have focused on the loin [24,25]. There is notable lack of research on the correlation between the muscle-to-fat ratio and quality characteristics of consumer-preferred cuts such as pork belly and mokshim. In Korea, these two cuts account for a large proportion of total pork consumption and play a decisive role in determining carcass value and consumer preference, underscoring their industrial importance [25]. In particular, the relationship between muscle fiber composition and physicochemical properties in these cuts remain largely unexplored.

CT and MRI non-destructively visualize tissue structure and fat distribution, whereas mATPase staining identifies muscle fiber types that affect physicochemical and sensory properties. Integrating CT and MRI with mATPase staining enables a comprehensive evaluation of both structural and histochemical characteristics, leading to a more precise understanding of the relationship between tissue composition and meat quality. Therefore, the objective of this study was to evaluate the muscle-to-fat ratio and muscle fiber type composition of pork belly and mokshim using CT, MRI, and mATPase staining, and to investigate their relationship with physicochemical characteristics. This study aims to provide baseline data for establishing a more accurate quality assessment system for pork cuts preferred by consumers.

Materials and Methods

Mokshim (pork neck) and pork belly preparation

This study was conducted using pig carcasses from 115 crossbred sows [Duroc × (Landrace × Large White)] with an average body weight 115kg and a grade of 1+, which were obtained from a commercial slaughterhouse approved for human animal management and use, according to the standard procedure of the Korea Livestock Products Quality Evaluation Institute.

At 24 hours postmortem, the right half of each carcass was used for physicochemical property analysis, while the left half was scanned using CT and MRI. Prior to scanning, the mokshim, from the 1st cervical vertebra to between the 4th thoracic vertebrae (TV), and non-trimmed whole belly, from between the 4th TV to the 6th lumbar vertebra, were dissected from the left half in accordance with the Korean pork carcass cutting and fabrication standards established by the Korea Institute for Animal Products Quality Evaluation [6]. After scanning, samples measuring 1cm in thickness were collected for muscle fiber type classification: from the mokshim at a point 2 cm distal to the capitulum region, and from the pork belly at the 6th and 11th TV. All samples were stored at −80℃ until staining.

Computed tomography and Magnetic resonance imaging

CT and MRI were used as complementary imaging techniques (CT = high-precision, MRI = high-contrast) to improve the reliability and interpretability of quantitative and qualitative evaluation of tissue composition. CT was used to estimate tissue density and the muscle-to-fat ratio based on Hounsfield units (HU), whereas MRI was used to distinguish fat distribution and structural morphology with high soft-tissue contrast, thereby enabling the evaluation of overall tissue composition. Imaging was performed using optimized sequences and parameters (slice thickness, spacing, and program settings), determined through preliminary examinations to ensure accurate evaluation of fat and muscle mass. Mokshim and pork belly samples were scanned using a 32-detector row CT scanner (Alexion™, Thoshiba, Japan) with the following settings [9,26] : 120kVp, 150 mAs, 1 mm slice thickness, 0.75 s rotation time, and a beam pitch of 0.938. CT images were extracted using the soft tissue window [window level: 40 Hounsfield units (HU); window width: 400 HU] and processed with Xelis software (INFINITT Healthcare, Korea).

Subsequently, MRI scans were performed on mokshim and pork belly samples using a 1.5 Tesla MRI system (Vantage Elan™, Canon Medical Systems, Japan) equipped with an Atlas SPEEDER 1.5T body coil. The following scan parameters were applied [27]: 3D T1-weighted fast field eco sequence (TR/TE = 6.2/3.2) in the sagittal plane; field of view, 20 × 20 cm and 40 × 40 cm; and matrix size, 256 × 256 and

512 × 256, for mokshim and pork belly, respectively. Slice thickness was set to 2mm with no inter-slice gap for both samples. All CT and MRI images were reviewed using a picture archiving and communication (PACS). The muscle and fat volumes from the cross-sectional images were estimated using the Vitrea workstation version 7 (Vital Images, Minnetonka, Minnesota, USA) and reconstructed in 3D as shown in Fig. 1. Volume measurements were expressed in milliliters (mL).

Histochemical analysis for muscle fiber classification

Serial transverse muscle sections were cut at a thickness of 10 ㎛ using a cryostat microtome at -20℃ and mounted onto glass slides for histochemical analysis. To classify muscle fiber types, the sections were stained for mATPase following acid (pH 4.6) and alkaline (pH 10.4) preincubation at room temperature, according to modified version of the method by Brooke and Kaiser [28], as applied in an previous study [29]. Fiber types were identified based on differences in ATPase activity and visualized using an ATP substrate solution. According to distinct histochemical reaction patterns, muscle fibers were classified as type I(dark black, high activity), type IIA(light white, low activity), and type IIB (gray, intermediate activity) [30,31]. The stained sections were examined under a light microscope, and the proportion of each type of fiber was calculated as a percentage of the total number of fibers using ImageJ software (National Institutes of Health, Bethesda, MD, USA). The analysis was performed in five replicates for each sample region (mokshim, pork belly at TV6 and TV11). For pork belly samples, histochemical analysis was conducted on three muscle regions each at TV6 and TV11*: cutaneous trunci* muscle (TV6-1), *latissimus dorsi* muscle (TV6-2), *external intercostal* muscle (TV6-3), *external abdominal oblique* muscle (TV11-1), *cutaneous trunci* muscle (TV11-2), and *transversus thoracis* muscle (TV11-3).

Physicochemical properties

The physicochemical properties were analyzed as previously described by Jo et al. [32] and Jeong et al. [33]. In brief, moisture (Mo) and crude protein (Pro) were determined using AOAC methods (2010), while pH, cooking loss (CL), shear force (SF), and meat color (CIE L*, a*, b*) were measured following the standard procedures described in those studies. The physicochemical data were adopted from the studies of Jo et al. [32] and Jeong et al. [33], which analyzed the same animals used in this experiment. Specifically, the left half of each carcass was used for imaging and histochemical evaluation, and the right half was used for physicochemical analyses, ensuring one-to-one correspondence between datasets according to carcass batch and identification.

Correlation and statistical analysis

The physicochemical properties of pork used in the correlation analysis were obtained from previously published data [32,33] and were reused in the present study with permission. Pearson correlation coefficients were calculated to evaluate the relationship between non-destructive evaluation methods (CT, MRI, and histochemical staining) and physicochemical properties of the same pork cuts. Statistical analyses were performed using GraphPad Prism version 8.

Results

Muscle-to-fat ratio and physicochemical properties

The muscle-to-fat ratio of mokshim measured by CT and MRI showed comparable values of 1:0.278 and 1:0.318, respectively (Table 1). As shown in Fig. 2, the muscle-to-fat ratio in the mokshim measured by CT showed a significant correlations with CL (r = −0.226) and Pro (r = −0.206) in a negative direction, and with Mo (r = 0.203), redness (*a**, r = 0.162), and yellowness (*b**, r = 0.220) in a positive direction ($p < 0.05$ for all variables). Similar to the results above, the muscle-to-fat ratio of pork belly measured by CT showed significant positive correlations with the *a** and *b** values, with correlation coefficients of r = 0.274 ($p < 0.01$) and r = 0.411 ($p < 0.0001$), respectively. In contrast, the muscle-to-fat ratio measured by MRI was not significantly correlated with any physicochemical properties of pork.

Muscle fiber type and physicochemical properties

The correlation between muscle fiber type composition and physicochemical properties of the mokshim is shown in Table 2. No significant correlations were observed between muscle fiber type I (Type I) and any physicochemical properties in the mokshim. For muscle fiber type IIA (Type IIA), a significant negative correlation was found with the *a** value (r = −0.491, $p < 0.001$) and the *b** value (r = −0.298, $p < 0.05$), while a significant positive correlation was observed with the lightness (*L**, r = 0.381, $p < 0.01$). In contrast, muscle fiber type IIB (Type IIB) fibers showed a positive correlation with *a** (r = 0.450, $p < 0.01$) and *b** (r = 0.326, $p < 0.05$).

A correlation analysis was performed to examine the relationship between muscle fiber type and physicochemical properties, including CL, shear force (SF), and CIE color parameters (*L**, *a**, *b**) in pork belly. These relationships were assessed separately at the 6th and 11th TV, and the results are presented in Table 3 and Table 4, respectively. No significant correlations were observed between Type 1 and physicochemical properties at both TV6 and TV11. Type IIB in TV11-2 showed a significant positive correlation with CL (r = 0.358, $p < 0.05$), but no other significant correlations were found except for meat color values (*L** and *b**). In TV6-1, Type IIA showed significant negative correlations with *L** (r = −0.451, $p < 0.01$) and *b** (r = −0.375, $p < 0.05$), whereas Type IIB showed significant positive correlation with *L** (r = 0.430, $p < 0.01$) and *b** (r = 0.382, $p < 0.05$). In TV6-2, Type IIB showed significant positive correlations with both *L** (r = 0.469, $p < 0.01$) and *b** (r = 0.361, $p < 0.05$). In TV6-3, Type IIA showed significant negative correlations with *L** (r = −0.458, $p < 0.01$) and *b** (r = −0.376, $p < 0.05$), while Type IIB showed significant positive correlations with *L** (r = 0.418, p < 0.05) and *b** (r = 0.468, $p < 0.01$). In TV11-1, Type IIA showed significant negative correlations with *L** (r = −0.355, $p < 0.05$) and *b** (r = −0.352, $p < 0.05$), whereas Type IIB showed significant positive correlations with *L** (r = 0.348, $p < 0.05$) and *b** (r = 0.358, $p < 0.05$). In TV11-2, Type IIA showed a significant negative correlation with *L** (r = −0.439, $p < 0.01$), while Type IIB showed significant positive correlations with *L** (r = 0.379, $p < 0.05$) and *b** (r = 0.346, $p < 0.05$). In TV11-3, Type IIA showed a significant negative correlation with both *L** (r = −0.353, $p < 0.01$), whereas Type IIB showed a significant positive correlation with *L** (r = 0.394, $p < 0.05$).

Discussion (optional)

Unlike previous studies that independently analyzed imaging or histochemical data [24,34][35], this study integrated CT, MRI, and mATPase-based analyses within the same samples to identify correlations between muscle-to-fat ratio and muscle fiber composition, providing a more comprehensive understanding of pork quality properties. Several studies have investigated the effects of muscle and fat content on the physicochemical properties of pork [36–39]. According to Hoa et al. [8], an increase in fat content is associated with reductions in collagen content, Mo and CL, whereas a decrease in fat content tends to result in higher values for these traits. Generally, in pork, overall fat content shows an inverse relationship with Pro because of the dilution effect, while moderate fat levels can help reduce CL by limiting water release during heating [38,40]. The CT-derived muscle-to-fat ratio exhibited in this study a negative correlation with CL and Pro, and a positive correlation with Mo, which is consistent with these established relationships, confirming the reliability of CT as a quantitative indicator of pork composition. CT has also been reported to provide high quantitative accuracy and reproducibility for estimating tissue density and fat/lean mass in pig carcasses, with reports of near-perfect explained variance ($R^2 \approx 0.999$) [11,41]. Although MRI yielded fewer significant associations, the directional trends were consistent with those observed from CT—samples with higher fat ratios measured by CT also showed higher relative intensity values in MRI. Despite similar coefficient values between the two modalities, the MRI-derived muscle-to-fat ratio did not reach statistical significance, likely due to limited sample size and the number of repetitions but also to fundamental technical differences between imaging modalities [42,43]. Previous studies have indicated that even when the effect size is constant, a small sample size can reduce statistical power, making it difficult to detect significant differences [44–46]. MRI detects water-fat proton relaxation signals, whereas CT measures X-ray attenuation based on tissue density. Differences in voxel resolution and image-reconstruction algorithms may also influence quantitative results [11,22]. In addition, it is noteworthy that the muscle-to-fat ratio measured by CT showed a positive correlation with the *a** and *b** values, which are meat color indicators. This suggests that intramuscular fat content may influence meat color [40,47]. The muscle-to-fat ratio is an important determinant of pork quality, as it reflects the relative contribution of lean tissue and intramuscular fat to physicochemical properties such as color, water-holding capacity, and tenderness [24,38]. A balanced proportion of muscle and fat contributes to desirable quality characteristics, supporting its used as a key indicator for assessing pork quality. Similar findings have been reported in previous study, where pork with higher fat content was associated with better meat quality and sensory characteristics [8,39]. Therefore, the muscle-to-fat ratio could serve as a useful indicator for predicting the visual quality of pork. Given the significant correlations between CT-derived values and quality traits, CT has potential for application in automated carcass grading and precision quality control systems. Nevertheless, high equipment cost, scanning throughput, and data processing time remain practical challenges for large-scale industry adoption [22, 35].

In the study, we analyzed the correlations between muscle fiber type composition and the physicochemical properties of pork, with a focus on the mokshim and pork belly regions. No significant correlations were observed for Type I, which may reflect either a weaker association with physicochemical properties or greater variability across samples, compared to Type IIA or IIB fibers [48]. Type I fibers are oxidative and slow-twitch, supporting aerobic metabolism and endurance-related energy production, whereas Type II fibers—particularly Type IIB—are glycolytic and fast-twitch, contributing to larger fiber diameter and lower water holding capacity. These intrinsic metabolic and structural differences may explain the absence of correlation between Type I fibers and physicochemical properties, while Type II fibers showed more pronounced relationship with color and moisture traits [41-43]. Notably, muscle fiber type IIB exhibited significant positive correlations with meat color parameters ($L*$ and $b*$) and CL in several anatomical regions, particularly at TV6 and TV11. These findings are consistent with previous studies suggesting that muscle fiber composition influences quality parameters such as water-holding capacity, drip loss, and meat color [25,49–51].

As shown in this study, Type IIB fibers were positively correlated with CL and b* values, while Type IIA fibers showed negative correlations with $L*$ and $b*$. These relationships suggest that muscles with a higher proportion of glycolytic fibers (Type IIB) may retain less moisture and exhibit greater lightness and yellowness, potentially due to their larger fiber diameter and lower water-holding capacity [50–52].

The results of this study are consistent with previous observations by Schober el al. [48] reporting that Type IIB fibers are associated with increased drip loss. Similarly, Lebedová et al. [53] showed that the area proportion of Type IIB fibers—identified via ATPase staining—was positively correlated with drip loss and negatively with SF, further supporting the link between fiber type and physicochemical traits.

Interestingly, they also noted that the correlation between fiber types and quality parameters varied across muscle regions, with Type I fibers generally showing negative correlations with drip loss. In addition, this study demonstrates moderate and statistically significant correlations between glycolytic fiber types (especially Type IIB) and meat color parameters (L^* and b^*) in specific regions such as TV6-1, TV6-2 and TV11-2. Although the strength of these correlations varied, the repeated appearance of similar trends across multiple regions suggests a possible broader pattern that warrants further investigation. However, previous study by Chang et al. [54] reported no significant correlations between drip loss and myosin heavy chain isoforms in certain muscles (e.g., *longissimus dorsi* and *psoas*), emphasizing that breed, muscle region, and staining methodology (e.g., mATPase vs. immunohistochemistry) can all influence the strength and direction of these correlations.

Based on these findings, it appears that muscle fiber composition, particularly the proportions of Type IIA and IIB fibers, plays a role in determining key pork quality parameters such as color and water-holding capacity. Further research involving multiple muscle types and comparative analyses of different staining techniques may help clarify the complex interactions between fiber type distribution and meat quality.

Conclusion

In pork belly and mokshim, this study evaluated the correlation between muscle-based structural data —obtained through CT, MRI, and histochemical staining—and physicochemical properties. The muscle-to-fat ratio measured by CT in both cuts showed significant correlations with several quality traits, particularly Mo, Pro, and meat color parameters such as a^* and b^*. In contrast, the muscle-to-fat ratio measured by MRI did not exhibit significant associations with physicochemical properties. Regarding muscle fiber composition, Type IIA and IIB exhibited distinct associations with meat color in mokshim, while Type I showed no significant correlations with the evaluated traits. These findings suggest that CT-based assessment of muscle-to-fat ratio and histochemical analysis of muscle fiber types may be correlated with pork quality characteristics, and that applying these approaches could offer valuable indicators for evaluating the quality of consumer-preferred pork cuts. However, further studies with larger sample sizes and additional pork cuts are necessary to improve the applicability of these methods in meat quality grading systems. Also, research on the development and standardization of CT image-analysis algorithms is required for practical application in the meat industry.

Declarations

Ethics approval and consent to participate

This article does not require IRB/IACUC approval because there are no human and animal participants.

Competing interests

No potential conflict of interest relevant to this article was reported.

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Tables and Figures

Table 1. Muscle and fat composition in mokshim and pork belly.

Items	Mokshim (neck)	Pork belly
Computed tomography		
Muscle (ml)	1536.9	3856.7
Fat (ml)	537.2	2321.3
Muscle : fat ratio	1 : 0.35	1 : 0.60
Magnetic resonance imaging		
Muscle (ml)	1589.5	2155.7
Fat (ml)	517.0	1143.7
Muscle : fat ratio	1 : 0.33	1 : 0.53

Table 2. Muscle fiber type composition and correlations with physicochemical properties in mokshim.

Items	Type I	Type IIA	Type IIB
Composition (%)	37.45	28.26	34.37
Correlation (r)			
pH	0.029	0.028	-0.038
Cooking loss	0.198	-0.275	0.159
Meat color			
*L** value	-0.134	0.381**	-0.282
*a** value	-0.022	-0.491***	0.450**
*b** value	-0.132	-0.298*	0.326*

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 3. Muscle fiber type composition and correlations with physicochemical traits in pork belly at the 6th thoracic vertebrae.

Items	TV6-1			TV6-2			TV6-3		
	Type I	Type IIA	Type IIB	Type I	Type IIA	Type IIB	Type I	Type IIA	Type IIB
Composition (%)	10.84	24.03	65.76	17.55	23.54	60.04	35.11	25.1	39.37
Correlation (r)									
Cooking loss	-0.247	-0.162	0.194	-0.194	-0.006	0.160	-0.244	-0.065	0.175
Shear force	0.104	-0.045	0.032	0.089	0.061	-0.005	0.075	0.018	-0.052
Meat color									
*L** value	0.212	-0.451**	0.430**	-0.130	-0.333	0.469**	0.072	-0.458**	0.418*
*a** value	-0.009	0.005	-0.004	0.310	0.050	-0.085	-0.277	0.039	0.103
*b** value	-0.035	-0.375*	0.382*	0.020	-0.228	0.361*	-0.186	-0.376*	0.468**

* $p < 0.05$, ** $p < 0.01$.

Table 4. Muscle fiber type composition and correlations with physicochemical traits in pork belly at the 11th thoracic vertebrae.

Items	TV11-1			TV11-2			TV11-3		
	Type I	Type	Type	Type I	Type	Type	Type I	Type	Type
Composition (%)	9.91	25.68	64.51	32.77	23.73	43.86	27.53	29.98	42.39
Correlation (r)									
Cooking loss	-0.088	-0.259	0.260	-0.249	-0.276	0.358*	-0.089	-0.190	0.215
Shear force	-0.113	-0.039	0.050	-0.175	-0.026	0.098	-0.192	-0.071	0.148
Meat color									
*L** value	-0.059	-0.355*	0.348*	0.086	-0.439**	0.379*	-0.203	-0.353**	0.394*
*a** value	-0.061	-0.031	0.037	-0.149	0.059	0.003	0.302	0.022	-0.141
*b** value	-0.174	-0.352*	0.358*	-0.093	-0.329	0.346*	0.001	-0.312	0.276

* $p < 0.05$, ** $p < 0.01$

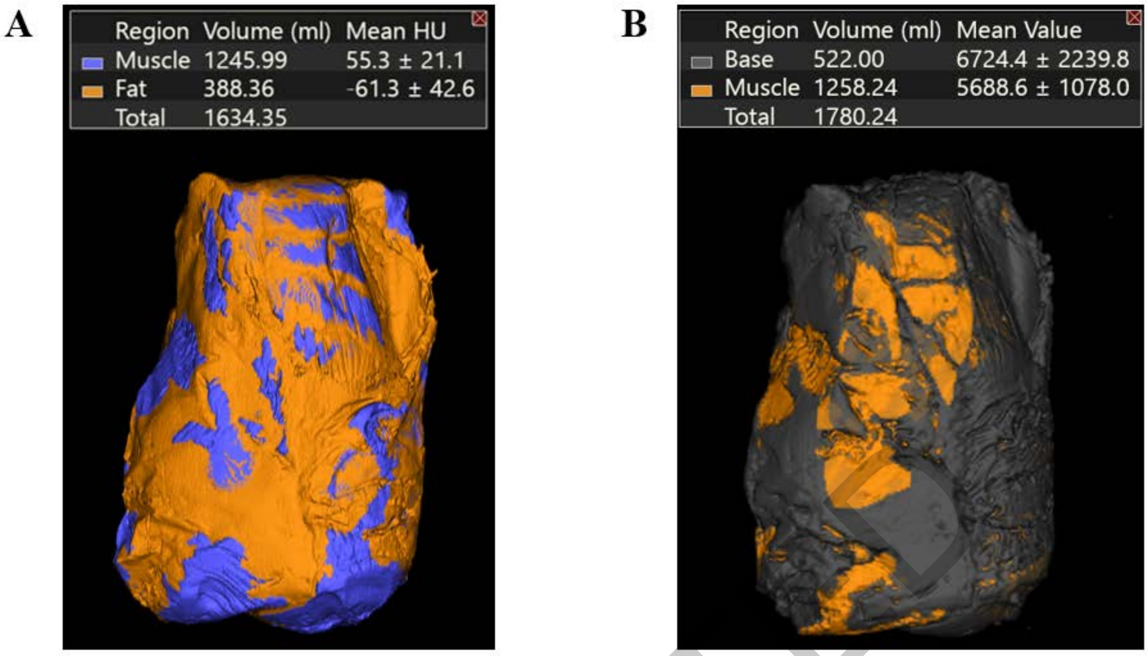

Fig. 1. Representative images showing muscle and fat volumes in mokshim (neck), reconstructed in 3D using (A) CT and (B) MRI data with Vitrea Workstation version 7.

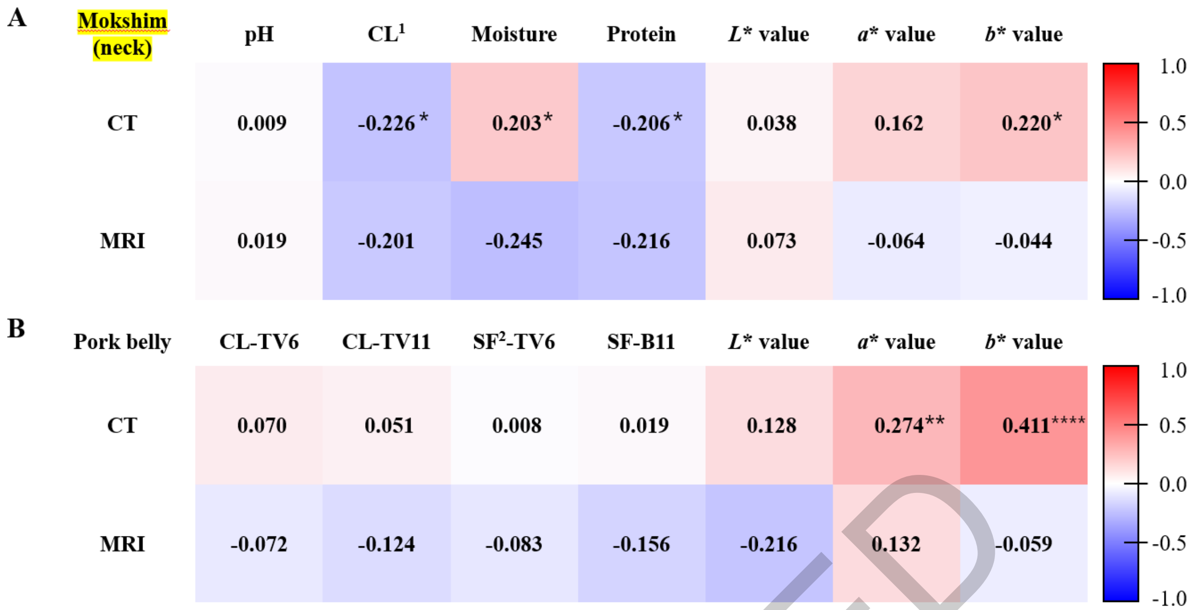

Fig. 2. Heatmap of correlation coefficients between CT and MRI parameters and physicochemical properties in (a) mokshim (neck) and (b) pork belly. Color intensity represents the strength of correlation (Pearson's r), with red indicating positive and blue indicating negative correlations.

[1]CL Cooking loss, [2]SF Shear force, * p <0.05, ** p <0.01, **** p <0.0001