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Comparative effect of different cooking methods on the physicochemical and sensory characteristics of high pressure processed marinated pork chops

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Abstract

The objective of this study was to assess the effect of griddle and steam cooking on the physicochemical and sensory characteristics of high pressure processed (HPP) piri-piri marinated pork chops (MPC). Raw MPC that were HPP at 400 MPa had higher (P<0.05) marinade absorption compared to untreated samples. After cooking, griddled MPC were significantly (P<0.05) darker, less red, less yellow, tougher and had higher cook loss compared to steam cooked samples. The appearance of the griddled MPC was preferred while the texture, tenderness, juiciness and overall sensory acceptability (OSA) were preferred in steam cooked MPC. The increased marinade absorption in MPC that were HPP modified the fatty acid composition resulting in increased (P<0.05) levels of oleic acid (C18:1c). Steam cooked MPC had a lower (P<0.05) n-6: n-3 PUFA ratio and were preferred by the sensory panel compared to griddled MPC. Overall, from the cooking methods assessed steam cooking was the best cooking method for untreated and MPC that were HPP.

Industrial Relevance

Processed meat manufacturers are constantly looking for new ways to increase yield, safety and shelf life of meat products. While high pressure processing (HPP) of raw meat has been shown to increase the safety and shelf life of these products; however, negative effects on the physicochemical characteristics of raw meat products have been reported. For example, HPP of raw meat products causes a whitening effect which may negatively affect consumers' acceptance of these products. In this study, we used a novel approach (a combination of HPP, marinade and a mix of organic acids Inbac^{TM}) which showed great potential not only for enhancing the yield of marinated pork chops but also enhancement of the sensory properties, safety and shelf life and particularly the piri-piri marinade masked the discoloration of raw pork meat caused by HPP. This study also provides consumers, retailers and caterers with information on how to best prepare HPP meat products and showed that steam cooked HPP marinated pork chops had the best physicochemical and sensory characteristics compared to griddled marinated pork chops.

1. Introduction

Pork is currently the most widely consumed meat in the world followed by poultry, beef, and mutton (Worldwatch Institute, 2018) and the global demand for pork meat continuing to rise (Bord Bia, 2018). The consumer demand for convenience is a driving force within the meat industry (Bord Bia, 2011) and an increase in the range of commercially available marinated products was reported (Hall, Marks, Campus and Booren., 2008; Yusop, O' Sullivan and Kerry., 2011). HPP is gaining importance in the food industry because of its advantage of inactivating microorganisms and enzymes at ambient or low temperatures without affecting the nutritional properties of food (Indrawati, Van Loey, Smout and Hendrickx, 2003). However, pressure levels applied at commercial levels in raw meat products have been reported to denature protein, increase lipid oxidation and induce colour and texture changes (Yagiz, Kristinson, Balaban, Welt, Ralat *et al.*, 2009). Our previous study (O' Neill, Cruz-Romero, Duffy and Kerry., 2018a), evaluated the ability of HPP to accelerate marinade absorption and improve flavour of MPC and the results showed that HPP at 400 and 500 MPa combined with Inbac^{TM} (0.3%) accelerated (P<0.05) the marinade absorption of raw piri-piri pork chops and enhanced the flavour acceptability while also extended the shelf life significantly; however, immediately after HPP at 500 MPa the MPC were tougher (P<0.05) than untreated control samples or MPC that were HPP at 300 or 400 MPa. HPP at 400MPa was apparently the best pressure level at which significantly lower changes on the physicochemical characteristics of MPC were obtained with an enhanced safety and shelf life. The piri-piri marinade also masked the whitening effect of HPP on the raw pork meat which can negatively affect consumers' acceptance of raw meat products.

As meat is usually cooked before consumption it is important to understand the physicochemical and sensorial characteristics of meat products that were HPP and cooked before consumption. Cooking of meat is essential to achieve a palatable and safe product (Tornberg, 2005) as it enhances flavour and tenderness, inactivates pathogenic microorganisms (Broncano, Petron, Parra and Timon., 2009; Rodríguez-Estrada, Penazzi, Caboni, Bertacco and Lercker., 1997), denature proteins and increases the digestibility and bioavailability of nutrients (Meade, Reid and Gerrard; 2005). The physical properties and quality of cooked meat are strongly affected by the degree of protein denaturation as a result of the type of heat treatment applied, the temperature and length of time of cooking (Ishiwatari, Fukuoka and Sakai, 2013). Many studies have shown that protein denaturation due to cooking causes structural changes in meat and affects its physical properties such as water-holding capacity, texture, and colour (Bendall and Restall, 1983; Palka and Daun, 1999; Tornberg, 2005; Garcia-Segovia, Andres-Bello and Martinez-Monzo., 2007) and as a result all sensory attributes can be influenced by changes in the cooking technique (Bejerholm & Aaslyng, 2004).

The most common methods of cooking meat includes roasting, boiling, grilling, broiling, frying, braising, steaming, griddling, poaching, microwaving, baking, poaching, barbequing, *sous*vide and *confit* (AMSA, 2018; Sobral, Cunha, Faria and Ferreira., 2018). The three main factors that differ among various cooking techniques are the temperature on the surface of the meat, the temperature profile through the meat and the method of heat transfer (convection or conduction by contact, air or steam) (Bejerholm & Aaslyng, 2004). Time also plays an important role in the characteristics of cooked muscle-based food products (Sobral *et al*. 2018). Steam cooking is a widely used, convenient and healthy cooking method as the typical characteristics of colour, flavour, texture, palatability and nutrients are retained (Kahlon, Chiu and Chapman, 2008). Steaming relies on cooking with steam heat resulting from boiling water. The meat has direct contact only with steam which contributes to the moist texture of steam cooked meat (Sobral *et al*. 2018). Air convection is often coupled with steam injection in the oven chamber to improve meat tenderness and to reduce cooking losses (Murphy, Johnson, Duncan, Claausen, Davis *et al*., 2001). Griddle cooking is gaining popularity in meat research, especially in industry settings. The griddle cooks meat through conduction heating as the heat is transferred directly from the hot griddle surface to the meat (Yancey, Wharton and Apple, 2011).

It is well known that different cooking techniques result in different eating qualities of meat products (Fjelkner-Modig, 1986; Heymann, Hedrick, Karrasch, Eggeman and Ellersieck, 1990; Wood, Nute, Fursey and Cuthbertson., 1995). Cooking method can also alter the fatty acid composition in meat products (Badiani, Montellato, Bochicchio, Anfossi, Zanardi *et al*., 2004; Maranesi, Bochicchio, Montellato, Zaghini, Pagliuca *et al*., 2005; Sarriés, Murray, Moloney, Troy and Beriain., 2009) due to increased cook loss or due to oxidation (Weber, Bochi, Ribeiro, Victorio and Emanuelli, 2008).

Dreeling, Allen and Butler (2000) examined the effect of various cooking methods (grilling, frying, griddling, roasting or deep fat frying) on the quality of low-fat beef burgers and found that the cooking method significantly affected the cook loss with deep fat frying and grilling resulted in the highest cooking losses and deep fat frying also resulted in beef burgers with the lowest moisture content. The sensory characteristics of overall sensory acceptability (OSA), tenderness, flavour, appearance, texture and juiciness were significantly affected by the cooking method and griddling was the most acceptable cooking method in terms of OSA. Latif (2010) concluded that the most suitable cooking methods for marinated chicken breast meats were roasting and boiling as they reduced the cook loss compared to microwaving and frying; however, griddling and steaming were not investigated in this study. Barbanti & Pasquini, (2005) reported that marination, followed by air-steam cooking is the best combination to obtain the most tender chicken breast slices.

Currently, very little attention has been given to the comparative physicochemical and sensory properties of cooked HPP meat products and as a result consumers do not have information available on how to best prepare HPP meat products to retain the maximum nutritional quality and physicochemical and sensory characteristics when cooking HPP meat products. Therefore, it is important to determine the physicochemical changes in MPC that were HPP and cooked using common cooking methods (e.g steam or griddle cooking). While there are studies that assessed the effects of various cooking methods on the physicochemical and sensory characteristics of marinated muscle-based food products (Barbanti & Pasquini, 2005; Latif, 2010; Kim, Jang, Jin, Lee and Jo., 2008; Dhanda, Pegg and Shand., 2006), to the best of our knowledge, there are no studies investigating the effects of different cooking methods (griddle and steam cooking) on the physicochemical characteristics of MPC that were HPP; therefore the objective of this study was to assess the effects of different cooking methods (e.g. griddle and steam cooking) on the physicochemical and sensory characteristics of MPC that were HPP.

2. Materials & Methods

2.1 Materials

Pork loins were obtained from a local meat processor (Ballyburden, Ballincollig, Cork). Piri-Piri marinade (Rapeseed oil 60%, Spices and flavourings 36% (chilli, garlic, jalapeno, black pepper, onion, paprika, lovage root, fenugreek seed, bird clover, onion leek, coriander, turmeric, ginger, cumin seed, fennel, sugar, grapefruit, passion fruit, papaya, mango, palm fat) and Salt 4%) was obtained from Oliver Carty (Athlone, Co. Roscommon, Ireland). A commercial antimicrobial mix of organic acids Inbac™ (a mix of Sodium acetate 43%, Malic acid 7%, emulsifier-mono and diglycerides of fatty acids and technological coadjuvants; anticaking agents, calcium phosphate, magnesium carbonate and silicon dioxide ~50%) was obtained from Chemital (Chemital Ltd, Barcelona, Spain).

2.2 Methods

2.2.1 Marination of pork chops

The pork loins were cut into 3cm chops including the fat ring, weighed and placed in a combivac vacuum pouch (20 polyamide/70 polyethylene bags (Alcom, Campogalliano, Italy) and piri-piri marinade which contained Inbac™ (0.3%) at a weight ratio 80:20 (Pork chop:marinade) was added and then vacuum packed using a Webomatic vacuum packaging system (Werner Bonk, type D463, Bochum, German). Marinated untreated control samples were stored in a chill room at 4 °C for 24 hrs before cooking. For samples requiring HPP (400 MPa), MPC were HPP (as outlined in section 2.2.2) before storage in a chill room at 4 °C for 24 hrs before cooking.

2.2.2 High Pressure Processing

Vacuum-packed pork chops that were marinated for 24 hr were HPP at 400 MPa using an industrial Hiperbaric 420 litre unit (Burgos, Spain) at the HPP Tolling facilities (HPP tolling, St. Margaret's, Dublin) using water as the pressure transmitting medium. The speed of pressurisation was 130 MPa per minute, the speed of depressurisation was instantaneous (~ 1 second) and the holding time was 3 minutes. The water inlet temperature was 10°C. Before HPP, the initial temperature of the surface of the vacuum packaged MPC was 3.6 °C and after HPP the temperature on the surface of the meat was ~6.5 °C and this was measured using a hand held temperature probe (Monika, United Kingdom).

2.2.3 Marinade absorption

The initial weight of raw unmarinated pork chops was recorded. Samples were then marinated as described in Section 2.2.1 and after 24 hrs storage at 4°C untreated and HPP samples were placed on an elevated stainless steel wire rack for 5 mins turned half way through and then re-weighed. Calculation for marinade absorption was as follows;

% marinade absorption = (weight after 24 hours marination – initial unmarinated weight) / (initial unmarinated weight) * 100.

Each value represents the average of 8 measurements (two independent trials x four samples).

2.2.4 Cooking

MPC were either steam cooked or griddled. For steam cooked, vacuum-packed MPC were cooked at full steam (90 °C) in a Zanussi oven (Zanussi Professional, Italy) and temperature monitored using a thermocouple data logger (Omega Engineering Ltd., Manchester, UK) inserted into the coldest point of the MPC until an internal temperature of 74 °C was reached (~ 8 mins). For griddling, MPC were removed from the vacuum pouch and placed on a Gico grill plate, Model 90185 (Gico, Italy), turned half way through and temperature monitored using the thermocouple data logger which was inserted into the coldest point of the MPC until an internal temperature of 74 °C was reached (~ 12 mins). The samples were then cooled down at room temperature before analysis was carried out.

2.2.5 Cook loss

The cook loss of both untreated MPC and MPC that were HPP was determined after griddle or steam cooking. Briefly, the initial weight of the raw MPC was recorded after samples had been placed on an elevated stainless steel wire rack for 5 mins. After cooking, the samples were re-weighed and calculated as follows:

% cook loss = (cooked weight – initial raw weight) / (initial raw weight) * 100

Each value represents the average of 8 measurements (two independent trials x four samples).

2.2.6 Proximate composition

To obtain a representative sample for proximal composition analysis of cooked MPC the outer layer of fat was removed and homogenised for 20 seconds in a Buchi™ mixer B-400 (Büchi Labortechnik, Switzerland). Proximate composition (fat, moisture, protein and ash) of cooked MPC was determined using the methods previously described by O'Neill, Cruz-Romero, Duffy and Kerry (2018b). Each value represents the average of 8 measurements (two independent trials x two samples x two readings).

2.2.7 pH

The pH of cooked untreated MPC and MPC that were HPP was measured using a digital pH metre (Mettler-Toledo GmbH, Schwerzenbach, Switzerland) by inserting the glass probe directly into the sample. Each value represents the average of 8 measurements (two independent trials x two samples x two readings).

2.2.8 Warner-Bratzler Shear force

Warner-Bratzler Shear force (WBSF) was measured according to the method outlined by Shackelford, Koohmaraie, Whipple, Wheeler, Miller *et al.* (1991). Briefly, the 3 cm thick

MPC were cooked as described in Section 2.2.3 to an internal temperature of 74 °C and then cooled at room temperature (20 °C). Four cylinders of a 1.27 cm diameter were obtained from each cooked pork chop parallel to the muscle fibre direction using a corer. The pork steak cylinders were sheared using a Texture Analyser TA-XT2 (Stable Micro Systems, Surrey, UK) attached with a Warner Bratzler V-shaped shearing device at a crosshead speed of 4 mm/s. Each value represents the average of 8 measurements (two independent trials x four samples).

2.2.9 Colour of cooked marinated pork chops

The colour of the surface of the cooked MPC was measured as described by O' Neill *et al*. (2018b). CIE L*, a* and b* values (Lightness, redness and yellowness, respectively) are reported and each value represents the average of 12 measurements (two independent trials x two samples x three readings).

2.2.10 Fatty acid analysis

2.2.10.1 Lipid extraction, Transesterification to fatty acid methyl esters and Gas chromatography

Total lipids for fatty acid analysis were extracted using the method described by Bligh and Dyer (1959). Briefly, 1.5g of MPC was homogenised in methanol and lipid was extracted from 0.6g of homogenate using water, methanol and chloroform as the extracting solvents. Following phase separation, the lower chloroform layers were dried under nitrogen prior to transesterification. The lipid fractions were trans-esterified to fatty acid methyl esters (FAME's) according to the procedure described by Slover and Lanza (1979). FAME's were separated using a Varian 3800 gas chromatograph (Varian, Walnut Creek, CA, USA) using a WCOT fused silica capillary column (Varian CP-SIL 88 Tailor Made FAME, 60 m x 0.25 mm i.d x 0.20 µm film thickness) and a flame ionisation detector. Helium was used as the carrier gas at a pressure of 30 psi. The injection volumes and split ratios for FAME's were 1 µl and 1:2 split, respectively. Individual fatty acids were identified by comparing relative retention times with pure FAME standards (Supleco 37 component FAME mix, Sigma-Aldrich Ireland Ltd., Vale Road, Arklow, Wicklow, Ireland). Each value is the average of 8 measurements (two independent trials x four samples).

2.2.11 Sensory evaluation

A 25 member semi-trained taste panel was used to evaluate the cooked untreated MPC and MPC that were HPP over two separate sessions using a 9-point hedonic scale. The panellists were recruited from staff and postgraduate students at the School of Food and Nutritional Sciences, University College Cork and chosen based on their experience in the sensory analysis of meat products and on their availability. The panellists are described as semi trained as they have partaken in sensory analysis of meat products over an extensive period of time and were familiar with the sensory terminology.

Samples were labelled with a three digit random number, steam or griddled cooked as described in Section 2.2.3 and served warm (50 °C) on labelled polystyrene plates. The tested attributes were: Liking of Appearance (1=Extremely dislike, 9=Extremely like), Liking of Texture (1=Extremely dislike, 9=Extremely like), Liking of Flavour (1=Extremely dislike, 9=Extremely like), Juiciness (1=Very dry, 9=Very juicy), Tenderness (1-Extremely tough, 9= Extremely tender), Off-flavour (1= Imperceptible, 9=Extremely pronounced) and Overall sensory acceptability (OSA) (1=Extremely dislike, 9=Extremely like).

2.2.12 Statistical analysis

Colour, texture, cook loss, marinade absorption, proximate composition, pH, fatty acid composition and sensory data were tested using one way ANOVA and significance assessed using Tukey's test at 5% significance level using SPSS software package (SPSS for Windows, version 21 IBM Corp., Armonk, NY, USA. Principle component analysis (PCA) was carried out using the Unscrambler software package version 10.3 (CAMO ASA, Trondheim, Norway).

3. Results & Discussion

3.1 Marinade absorption & Cook loss

The results showed that marinade absorption/yield of the pork chops increased (*P*<0.05) when MPC were HPP at 400 MPa compared to untreated MPC samples (Table 1). It was reported that marinades diffuse from the meat surface into the interior of the meat due to the gradient formed from the higher concentration of marinade to the lower concentration of fluid in the interior of the meat (Yusop *et al*. 2011) and apparently HPP may have accelerated this process.

The cook loss was significantly higher (*P*<0.05) in griddled MPC compared to steam cooked MPC independent of whether HPP was applied or not (Table 1). The higher cook loss in samples that were cooked using the griddle may be due to the longer cooking time as this cooking method is by contact between the hot surface and the MPC and the main method of heat transfer is *via* conduction. It was reported that different cooking methods have significant effects on the physicochemical changes due to the cook loss of meat products that affect the cooking times, temperatures and methods of heat transfer (Ishiwatari *et al*. 2013; Bejerholm & Aaslyng, 2004). Alfaia, Alves, Lopes, Fernandes, Costa *et al.* (2010) and Utama, Baek, Jeong, Yoon, Joo *et al.* (2018) reported increased cook loss when beef was oven roasted rather than boiled due to prolonged heat exposure duration.

3.2 Proximate composition & pH

The results for proximate composition of untreated MPC or MPC that were HPP and cooked using griddle or steam cooking are shown in Table 1. The results indicated that the cooking method did not affect significantly the fat, protein and ash content of untreated MPC or MPC that were HPP; however, the moisture content was significantly lower (*P*<0.05) when MPC were cooked using the griddle method compared to steam cooked MPC independent of whether HPP was applied or not and this may be attributed to the significantly (*P*<0.05) higher cook loss in samples that were cooked using the griddle (Table 1). Similarly, Dreeling *et al.* (2000) reported that cooking method (griddling, grilling, frying, deep fat frying or roasting) did not significantly affect the protein or fat content in beef burgers. Conversely, the authors reported that griddled burgers had the lowest cook loss and highest moisture content.

The results also showed that independent of the cooking method used no significant differences in the pH were observed on untreated MPC or MPC that were HPP (Table 1). It was reported that HPP causes an increase in pH in raw meat (Rodriguez-Calleja *et al*. 2012; Wang, Yao and Ganzle. 2015; Cruz-Romero, Kelly and Kerry., 2007) which usually occurs due to the decrease in available acidic groups in the meat as a result of conformational changes associated with protein denaturation (McArdle, Marcos, Kerry and Mullen, 2011) while the increase in pH due to cooking may be due to decreases in the number of acidic groups in muscle proteins as proteins unfold (Hamm & Deatherage, 1960). Regarding the increase of pH on cooked MPC that were HPP, apparently the combined effects of cooking (heat treatment) and HPP were not additive as the pH was not significantly different compared to the pH of cooked untreated MPC. This may be due to the increased severity of the cooking processes in comparison to the milder non-thermal process (HPP). A similar effect on pH in cooked beef muscle was reported by Ma & Ledward, (2004) as the combined effects of cooking and HPP were not additive and the pH of the HPP beef meat was not significantly different compared to the pH of cooked untreated beef.

3.3 Colour of cooked marinated pork chops

The results showed that the untreated MPC or MPC that were HPP and steam cooked were significantly (P<0.05) redder and yellower compared to untreated MPC or MPC that were HPP and cooked using the griddle method. This may be due to the presence of the highly pigmented piri-piri marinade (CIE L*, a* and b* values of 26.86, 17.68 and 54.28, respectively) on the surface of the meat (Table 2). In regards to lightness, griddle cooked MPC (untreated and HPP) were significantly darker (P<0.05) than steam cooked MPC (untreated and HPP) (Table 2). This increased darkness may be due to the fact that the in griddled MPC, Maillard reaction, a nonenzymatic chemical reaction between amino acids and reducing sugars which causes browning (Tamana & Mahood, 2015) has taken place. This reaction occur upon heating meat because meat, a proteinaceous material also contains a small amount of carbohydrates, primarily those originating from glycogen and nucleotides (Schmidt, 1988). Humidity/moist head methods (e.g steam cooking) has been reported to influence colour development of cooked meat as high humidity will prevent Maillard reactions from taking place (Bejerholm & Aaslyng, 2004) and this may be the reason why steam cooked MPC were significantly lighter compared to griddled MPC. These results found in this study are in agreement with the findings of Chao, Hsu and Yin (2009), Delgado-Andrade, Seiquer, Haro, Castellano and Navarro. (2010) and Hull, Woodside, Ames and Cuskelly. (2012) who reported that dry heat cooking methods such as frying and grilling increased Maillard reaction compared to moist heat methods such as boiling. Colour changes due to cooking may be due to the denaturation of myoglobin as the cooked pigment is denatured metmyoglobin which is darker in colour (Boles & Pegg, 1999). Colour changes in muscle-based food products after HPP have been reported that may be related to the denaturation of the myofibrillar and sarcoplasmic proteins (Zhou, Xu and Liu, 2010; Ma & Ledward, 2013; Bak *et al*., 2017).

Interestingly, MPC that were HPP at 400 MPa and steam cooked resulted in lighter (P<0.05) MPC compared to steam cooked untreated MPC samples; however, this effect was not observed in the griddled MPC and no significant differences between griddled MPC that were HPP and griddled untreated MPC were found. This effect in steam cooked MPC may be due to the fact that when MPC were HPP, it may have increased lightness due to the denaturation of proteins before cooking. The cooking process may have resulted in further protein denaturation compared to untreated MPC that were cooked but not HPP. This apparently resulted in lesser degree of protein denaturation and therefore a lesser lightness change. The reason this effect was not evident in griddled MPC may be due to the severity of the griddling cooking process which employs direct contact heat at higher temperature (150 - 200 ºC) for a longer duration (~ 12 mins) to reach the required internal temperature inducing Maillard reaction, compared to a milder treatment such as steam cooking (100 ºC for ~8 mins). The higher temperature on the surface of the dry heat cooked (griddled) MPC may also have induced the colour changes (increased darkness) due to Maillard reaction.

3.4 Texture

The results for WBSF showed that griddled MPC were significantly harder (P<0.05) than steam cooked samples (Table 2) regardless of whether samples were HPP or not. Myofibrillar and connective tissue proteins (collagen and elastin) affect the toughness of muscle tissues and during heating, these proteins are denatured, causing destruction of cell membranes, shrinkage of fibres, aggregation, and gelling of myofibrillar and sarcoplasmic proteins, and shrinkage and solubilisation of connective tissue (Tornberg 2005; Yu, Morton, Clerens and Dyer, 2017). Higher WBSF values for griddled MPC may be due to the higher cook loss (Table 1) or the severe heat treatment on the surface of the MPC which may have resulted in more protein denaturation and aggregation into much larger protein aggregates and therefore increasing meat toughness. Similarly, Yancey *et al.* (2011) reported that beef steaks which were griddle cooked were tougher compared to beef steaks which were grilled or oven cooked.

It was reported that HPP increased the hardness of muscle foods (Kruk, Yun, Rutley, Lee, Kim *et al*, 2011; Zamri, Ledward and Frazier, 2006; Rodrigues, Trindade, Caramit, Candogan, Pokhrel *et al*. 2016; Macfarlane, McKenzie and Turner., 1980). The increased toughness with pressure has been attributed to an increasing incidence of sarcomeres, in which thick filaments have been compressed onto the Z-line, thus removing the I-band as a zone of weakness (Macfarlane *et al*., 1980). However, in this study the significant differences (P<0.05) on hardness were observed in the cooking methods applied and the application of HPP apparently did not have an additive effect in terms of increasing hardness of the MPC. This may be due to the severity of the thermal cooking process and its increased ability to denature proteins compared to HPP which is a milder non-thermal process.

3.5 Fatty acid composition of marinated pork chops

Fatty acid composition of meat is of major importance for consumers due to their importance for meat quality and nutritional value (Wood, Nute, Fisher, Campo, Kasapidou *et al*. 2004). The fatty acid composition of the untreated MPC, MPC that were HPP and the piri-piri marinade is presented in Table 4. The results showed that in the piri-piri marinade 15 fatty acid were present and in the untreated and MPC that were HPP 28 fatty acids were present. The main fatty acids detected in marinade were C16 (Palmitic acid- SFA), C18:1c (Oleic acid- MUFA) and C18:2c (Linoleic acid- PUFA) which accounted for 83% of the total fatty acid composition. In the MPC, the main fatty acids present were typical for pork and consisted of C16 (Palmitic acid- SFA), C18 (Stearic acid - SFA), C18:1 (Oleic acid - MUFA), C18:2 (Linoleic acid- PUFA) which accounted for ~85% of the total fatty acids in all MPC. According to Enser *et al*. 1996 the values typical for the main fatty acids for pork are: C16 - Palmitic acid (23.9%), C18 -Stearic acid (12.8%), C18:1 - Oleic acid (35.8%), C18:2 - Linoleic acid (14.3%) which are extremely close to the results found in this study (Table 4).

HPP is a very mild process in terms of its effect on fatty acids (Yagiz *et al*. 2009). Independent of the cooking methods used, the results showed that in general, there were no significant differences in SFA, MUFA and PUFA in MPC that were HPP compared to untreated marinated samples; however, the MPC that were HPP had significantly (P<0.05) higher C18:1c (Oleic acid – MUFA) which may be due to the higher marinade absorption by the pork chops as Oleic acid is the main fatty acid present in the piri-piri marinade. Similarly, previous studies have indicated that HPP of salmon, beef, goat and oysters up to 800 MPa had no significant effect on their overall fatty acid composition (Cruz-Romero, Kerry and Kelly, 2008; McArdle, Marcos, Kerry and Mullen. 2010; Mc Ardle *et al*. 2011; Yagiz *et al*. 2009; He, Huang, Li, Qin, Wang *et al*. 2012); however, these studies did not include the addition of marinade. Kruk, Kim, Kim, Rutley, Jung *et al*. (2014) reported that HPP at 300 MPa did not affect the fatty acid composition of chicken breast meat; however, the addition of olive oil and soya sauce in combination with HPP at 300 MPa significantly changed the fatty acid composition which may be due to composition of these marinades. Interestingly, when olive oil was added to chicken breast fillets and HPP at 600 MPa, the fatty acid composition was modified further and increased MUFA's obtained which may have been due to the ability of HPP to increase marinade absorption; however, the authors did not determine marinade absorption nor did they determine the fatty acid composition of the marinades.

It was reported that cooking methods such as frying or deep fat frying can affect the fatty acid composition due to the addition of oils or fats (Broncano *et al*., 2009). The cooking methods applied in this study did not change significantly the fatty acid composition; however, the MPC that were steam cooked had a lower (P<0.05) n-6/n-3 ratio compared to griddled samples. Typical n-6:n-3 PUFA ratios in pork meat were reported to be 6.30 (Shortle, 2016) which is similar to the results found for griddled MPC. A lower n-6/n-3 ratio was reported to increase ration of these group of fatty acids and have increased health benefits including the prevention of cardiovascular, cardiometabolic, and other chronic diseases as well as the reduction of inflammation (Siscovick, Barringer, Fretts, Wu, Lichtenstein *et al*., 2017; Chen, Yu, Shao *et al*., 2015; Sanders (2014). The health attributes of n-3 PUFA is due to the direct effects of α-linolenic acid (ALA), which cannot be synthesized by humans, or the conversion of ALA to eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) and/or the decrease in the n-6:n-3 PUFA ratio (Domenichiello, Kitson and Bazinet. 2015).

3.6 Sensory analysis

The sensory analysis results are shown in Table 3. Griddled MPC were significantly (*P*<0.05) more acceptable in terms of appearance compared to steam cooked samples which may be due to chargrilled effect and darker colour on the surface of the meat as a result of Maillard reaction. Similarly, Dreeling *et al* (2000) reported that grilling and griddling were the most preferred cooking method in terms of appearance compared to roasting and frying.

Steam cooked MPC (untreated and HPP) were preferred (*P*<0.05) in regards to texture, tenderness, juiciness and OSA compared to griddled MPC (untreated and HPP) which may be attributed to the lower cook loss and subsequent higher fat and moisture content. The results of the sensory analysis are also in agreement with the instrumental texture results (Table 2) which showed that steam cooked MPC (untreated or HPP) were tenderer (*P*<0.05) than griddled MPC (untreated or HPP). Barbanti & Pasquini (2005) suggested that marination process followed by air-steam cooking was the best combination to obtain the most tender chicken breast slices. Similar to our results, Dreeling *et al* (2000) concluded that the sensory characteristics of OSA, tenderness, appearance, texture and juiciness were significantly affected by the cooking method applied (grilling, frying, griddling, roasting or deep fat frying) and griddling was the most acceptable cooking method in terms of OSA; however, steam cooking was not investigated in this study.

HPP can increase the toughness of post rigor meat (Ma and Ledward, 2004; Del Olmo, Morales, Avila, Caldaza and Nunez., 2010; Jung, Ghoul and de Lemballerie-Anton., 2000; Grossi, Bolumar, Soltoft-Jensen and Orlien, 2014); however, our results indicated that cooking method of the MPC had a more significant effect on the textural and sensory characteristics of MPC than HPP which may be due to the severity of the cooking process compared to HPP which is a non-thermal and milder process. Furthermore, the sensory results showed that steam cooking resulted in a more acceptable MPC in terms of texture and OSA compared to griddled MPC. Steam cooked MPC were also cooked in their final packaging resulting in a more convenient product for consumer use compared to griddled MPC.

The effect of HPP on oxidative stability of lipids in pork meat depends on the applied pressure, with a value between 300 and 400 MPa constituting the critical pressure to induce catalysis (Cheah & Ledward, 1996, 1997, Ma et al., 2007, Kruk et al., 2011). From a sensory point of view, lipid oxidation can impair quality and cause rancidity problems which are considered unpleasant by consumers (Jeremiah, 2001; Guyon et al., 2016). However, the results in this study show no significant differences in off-flavour between samples suggesting that a significant increase in lipid oxidation has not occurred at this pressure level (400 MPa).

The PCA plot (Fig 1) is a graphical representation of the degree of existing correlations between the MPC samples and the significant physicochemical and sensory responses. The plots showed that the 0.1 MPa/ steam cooked MPC and the 400 MPa/ steam cooked MPC were closely related to each other and were also correlated with the physicochemical characteristics of lightness, redness, yellowness and moisture and the sensory attributes of texture liking, juiciness, tenderness and OSA. These results correspond with the descriptive results presented in Tables 1, 2 and 3 as steam cooked MPC were lighter, redder, more yellow, had a higher moisture content and were also preferred in terms of texture liking, juiciness, tenderness and OSA.

The griddle cooked MPC (0.1 MPa and 400 MPa) were related to each other and to the physicochemical attributes cook loss and WBSF and to the sensory attribute of appearance. These results also correspond with the descriptive results presented in Tables 1 & 3 as griddle cooked MPC had higher cook loss, WBSF and liking of appearance compared to steam cooked MPC.

Based on their location the plot, the responses of appearance, cook loss and WBSF were shown to be negatively correlated with the responses of lightness, redness, yellowness, texture, moisture, juiciness, tenderness and OSA.

The plot also shows that marinade absorption was related to HPP as the 400 MPa/griddle and 400 MPa/steam samples were located in the top half of the plot and closer to the physicochemical characteristic of marinade absorption. The data shown in Table 1 confirms this as HPP at 400 MPa increased the marinade absorption significantly.

Overall, the cooking methods applied (steam or griddle) had the most significant effect on all physicochemical and sensory responses in comparison to HPP.

4. Conclusion

While HPP at 400 MPa accelerated ($P<0.05$) marinade absorption in raw MPC, it had minimal effects on the quality of the cooked MPC. The acceleration of marinade absorption on the pork chops by HPP apparently modified the fatty acid composition of the MPC and significantly ($P<0.05$) increased the level of oleic acid which was the main fatty acid present in the piri-piri marinade.

The cooking methods applied (Steam or griddle cooking) had a significant effect on the physicochemical and sensory quality of cooked MPC. Griddled MPC were preferred in terms of appearance; however, steam cooking resulted in better quality MPC in terms of physicochemical (cook loss, moisture content, WBSF and n-6: n-3 PUFA ratio) and sensory (texture, tenderness, juiciness and OSA) characteristics.

Overall, the results showed that from the cooking methods assessed steam cooking was the best cooking method for MPC that were HPP and provided an advantage as it can be cooked vacuum-packed resulting in a convenient product for consumer use and extended shelf life of the MPC due to the hurdle approach used (combined effect of HPP and antimicrobial Inbac^{TM}) was also found in our previous study.

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TABLE 1 Physicochemical characteristics of untreated and high pressure processed marinated pork chops cooked using steam cooking or griddle*

Treatment Pressure (MPa)/cooking method	Cook Loss (%)	Marinade absorption** (%)	Moisture (%)	Protein (%)	Fat (%)	Ash (%)	pH
0.1/steam	16.93 ± 0.97 [a]	1.88 ± 0.14 [a]	64.11 ± 1.80 [a]	29.08 ± 1.57 [a]	4.73 ± 0.66 [a]	1.39 ± 0.04 [a]	5.86 ± 0.11 [a]
0.1/griddle	19.73 ± 0.94 [b]	1.95 ± 0.19 [a]	61.87 ± 1.54 [b]	29.37 ± 0.80 [a]	4.13 ± 0.20 [a]	1.43 ± 0.08 [a]	5.87 ± 0.05 [a]
400/steam	16.67 ± 1.07 [a]	2.68 ± 0.23 [b]	65.23 ± 1.13 [a]	30.31 ± 1.52 [a]	4.63 ± 0.56 [a]	1.46 ± 0.08 [a]	5.91 ± 0.06 [a]
400/griddle	18.88 ± 1.28 [b]	2.65 ± 0.27 [b]	61.90 ± 1.13 [b]	30.18 ± 1.36 [a]	4.07 ± 0.12 [a]	1.47 ± 0.06 [a]	5.90 ± 0.07 [a]

*Values are Mean ± standard deviation. [a,b] Different superscripts in the same column indicate significant difference ($P < 0.05$) between treatments. **Analysis carried out before cooking.

TABLE 2 Colour and textural analysis of untreated and high pressure processed marinated pork chops cooked using steam cooking or griddle*

Treatment Pressure (MPa)/cooking method	**L*** (L)	**a*** (a)	**b*** (b)	**WBSF** (N)
0.1/steam	52.41 ± 2.77 [a]	9.30 ± 0.92 [a]	33.78 ± 2.16 [a]	15.93 ± 1.87 [a]
0.1/griddle	45.58 ± 2.58 [c]	7.45 ± 0.84 [b]	29.07 ± 1.88 [b]	21.52 ± 2.35 [b]
400/steam	59.34 ± 3.43 [b]	9.33 ± 1.50 [a]	35.80 ± 3.59 [a]	16.44 ± 2.06 [a]
400/griddle	47.64 ± 2.06 [c]	7.93 ± 0.59 [b]	29.74 ± 2.35 [b]	21.83 ± 2.51 [b]

*Values are Mean ± standard deviation. [a,b,c] Different superscripts in the same column indicate significant difference ($P < 0.05$) between treatments.

TABLE 3 Sensory analysis of untreated and high pressure processed marinated pork chops cooked by steam cooking or griddle*

Treatment	**Sensory Attributes**						
Pressure (MPa)/cooking method	Appearance	Texture	Flavour	Tenderness	Juiciness	Off-flavour	OSA
0.1/steam	5.93 ± 1.88 [a]	6.68 ± 1.47 [a]	6.31 ± 1.56 [a]	5.90 ± 1.28 [a]	5.93 ± 1.88 [a]	1.96 ± 1.78 [a]	7.05 ± 1.34 [a]
0.1/griddle	6.68 ± 1.23 [b]	5.13 ± 1.27 [b]	6.68 ± 1.40 [a]	4.41 ± 0.94 [b]	4.87 ± 1.23 [b]	2.23 ± 1.84 [a]	6.12 ± 1.09 [b]
400/steam	5.65 ± 1.07 [a]	6.41 ± 1.29 [a]	6.83 ± 1.14 [a]	5.82 ± 1.44 [a]	5.94 ± 1.52 [a]	1.73 ± 1.30 [a]	6.99 ± 1.02 [a]
400/griddle	7.14 ± 1.17 [b]	5.67 ± 1.32 [b]	7.03 ± 1.45 [a]	4.17 ± 1.12 [b]	5.00 ± 1.19 [b]	2.43 ± 1.89 [a]	6.02 ± 1.25 [b]

*Values are Mean ± standard deviation. [a, b]. Different superscripts in the same column indicate significant difference ($P < 0.05$) between treatments.

Appearance, Texture, Flavour, OSA (1=Extremely dislike, 9=Extremely like), Juiciness (1=Very dry, 9=Very juicy), Tenderness (1-Extremely tough, 9= Extremely tender), Off-flavour (1= Imperceptible, 9=Extremely pronounced).

TABLE 4 Fatty acid composition of untreated and high pressure processed marinated pork chops cooked by steam cooking or griddle*

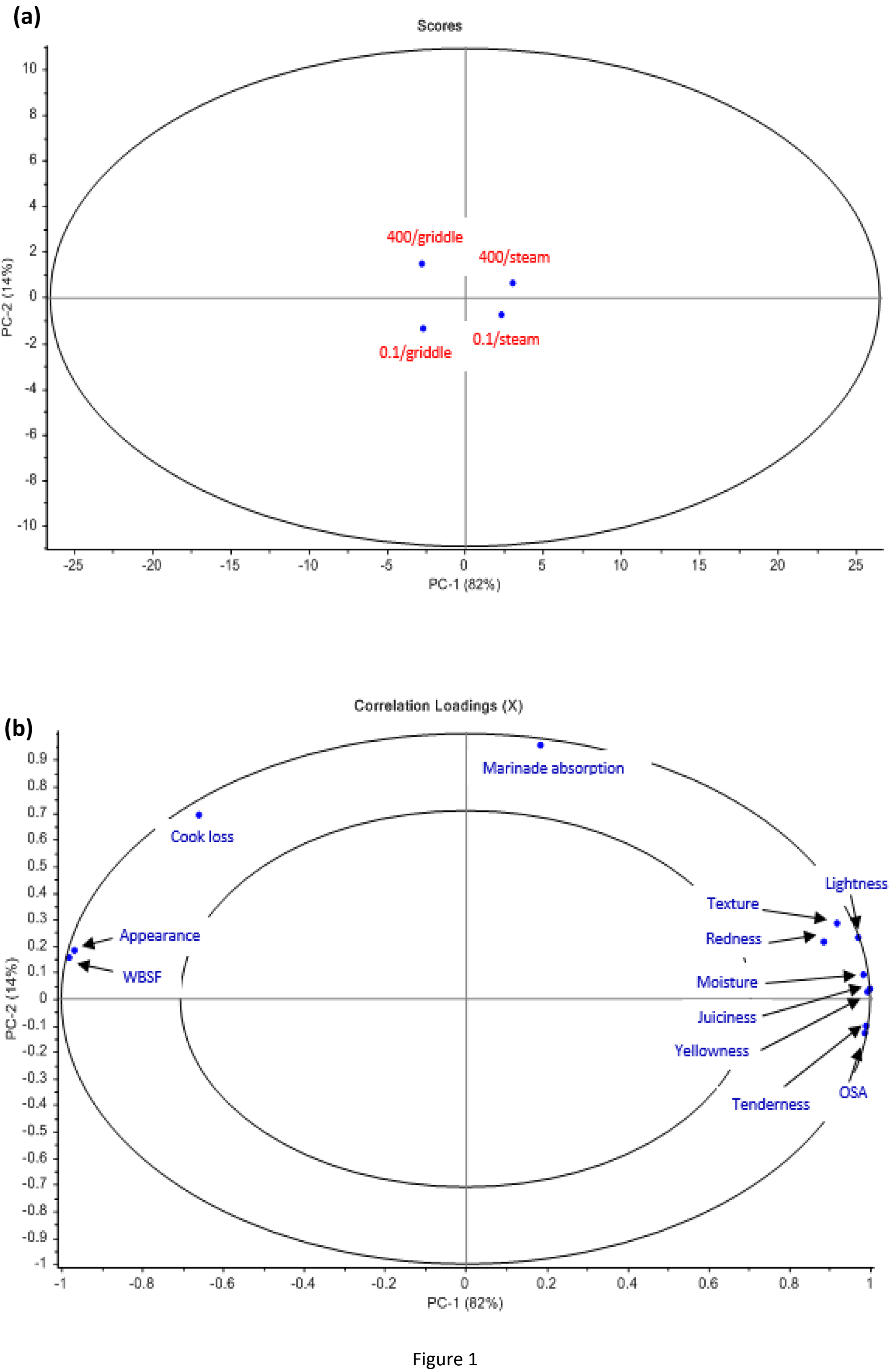
Fatty acid	Piri-piri Marinade	0.1 MPa/griddle	0.1 MPa/steam	400 MPa /griddle	400 MPa/ steam
Lauric acid (C12:0)	ND	0.14 ± 0.02 [a]	0.16 ± 0.03 [a]	0.12 ± 0.04 [a]	0.10 ± 0.00 [a]
Myristic acid (C14:0)	0.14 ± 0.01	1.36 ± 0.03 [ab]	1.57 ± 0.24 [b]	1.08 ± 0.07 [a]	1.14 ± 0.04 [a]
Palmitic acid (C16:0)	6.73 ± 0.16	24.54 ± 0.66 [a]	25.30 ± 3.33 [a]	23.34 ± 0.69 [a]	22.31± 0.49 [a]
Heptadecanoic acid (C17:0)	ND	0.32 ± 0.01 [a]	0.45 ± 0.11 [a]	0.34 ± 0.02 [a]	0.31 ± 0.02 [a]
Stearic acid (C18:0)	1.07 ± 0.37	13.05 ± 0.92 [a]	13.27 ± 2.33 [a]	12.62 ± 0.97 [a]	12.73 ± 0.67 [a]
Arachidic acid (C20:0)	0.50 ± 0.02	ND	ND	ND	ND
Heneicosanoic acid (C21:0)	ND	0.17 ± 0.03 [a]	0.18 ± 0.06 [a]	0.28 ± 0.03 [b]	0.19 ± 0.02 [ab]
Behenic acid (C22:0)	ND	0.68 ± 0.26 [a]	0.59 ± 0.22 [a]	0.35 ± 0.02 [a]	0.78 ± 0.08 [a]
Tricosanoic acid (C23:0)	ND	0.55 ± 0.31 [a]	0.42 ± 0.20 [a]	0.46 ± 0.03 [a]	0.63 ± 0.14 [a]
Lignoceric acid (C24:0)	ND	0.81 ± 0.08 [a]	0.50 ± 0.22 [a]	0.34 ± 0.03 [a]	0.62 ± 0.32 [a]
Palmitoleic acid (C16:1 (n-7))	0.25 ± 0.02	1.42 ± 0.10 [a]	1.70 ± 0.26 [a]	1.38 ± 0.13 [a]	1.16 ± 0.31 [a]
Cis-10 Heptadecenoic acid (C17:1c (n-7))	ND	0.13 ± 0.01 [a]	0.19 ± 0.02 [b]	0.15 ± 0.03 [ab]	0.12 ± 0.03 [a]
Elaidic acid (C18:1t (n-7))	0.16 ± 0.05	3.38 ± 1.10 [a]	1.18 ± 1.12 [b]	1.46 ± 0.11 [b]	2.24 ± 0.08 [ab]
Oleic acid (C18:1c (n-9))	56.32 ± 0.94	29.58 ± 0.38 [a]	31.00 ± 2.12 [ab]	34.85 ± 1.20 [c]	33.20 ± 0.75 [bc]
Cis-11 Eicosenoic acid (C20:1c (n-9))	8.27 ± 0.20	1.51 ± 0.05 [a]	1.49 ± 0.05 [a]	1.29 ± 0.34 [a]	0.99 ± 0.29 [a]
Erucic acid (C22:1c (n-9))	0.26 ± 0.09	0.34 ± 0.03 [a]	0.32 ± 0.07 [a]	0.40 ± 0.08 [a]	0.35 ± 0.04 [a]
Nervonic acid (C24:1c (n-9))	ND	0.27 ± 0.02 [a]	0.41 ± 0.17 [a]	0.44 ± 0.11 [a]	0.46 ± 0.15 [a]
Linoelaidic acid (C18:2t (n-6))	ND	1.00 ± 0.07 [a]	1.27 ± 0.40 [a]	1.11 ± 0.02 [a]	1.10 ± 0.28 [a]
Linoleic acid (C18:2c (n-6))	19.15 ± 0.56	14.94 ± 0.50 [a]	13.93 ± 3.04 [a]	15.58 ± 0.63 [a]	15.14 ± 1.01 [a]
G - Linolenic acid (C18:3c (n-3))	1.25 ± 0.07	0.60 ± 0.02 [a]	0.55 ± 0.03 [a]	0.61 ± 0.08 [a]	0.47 ± 0.09 [a]
A - Linolenic acid (C18:3c (n-6))	0.39 ± 0.07	0.36 ± 0.02 [a]	0.34 ± 0.04 [a]	0.30 ± 0.02 [a]	0.32 ± 0.01 [a]

Cis-11,14 Eicosenoic acid (C20:2 (n-6))	0.09 ± 0.01	0.68 ± 0.06 [a]	0.63 ± 0.10 [a]	0.87 ± 0.10 [a]	0.64 ± 0.18 [a]
Cis-8,11,14 Eicosatrienoic acid (C20:3c (n-3))	0.13 ± 0.03	1.70 ± 0.47 [a]	2.38 ± 1.07 [a]	1.75 ± 0.60 [a]	1.72 ± 0.18 [a]
Cis-11,14,17 Eicosatrienoic acid (C20:3c (n-6))	0.31 ± 0.02	0.63 ± 0.19 [a]	0.51 ± 0.28 [a]	0.57 ± 0.02 [a]	0.71 ± 0.18 [a]
Arachidonic acid (C20:4 (n-6))	ND	0.43 ± 0.12 [a]	0.36 ± 0.13 [a]	0.34 ± 0.03 [a]	0.36 ± 0.16 [a]
Eicosapentaenoic acid (C20:5 (n-3))	ND	0.19 ± 0.10 [a]	0.24 ± 0.04 [a]	0.15 ± 0.11 [a]	0.42 ± 0.18 [a]
Cis-13,16 Docosadienoic acid (C22:2 (n-6))	ND	0.45 ± 0.20 [a]	0.45 ± 0.18 [a]	0.41 ± 0.10 [a]	0.50 ± 0.07 [a]
Docosahexaenoic acid (C22:6 (n-3))	ND	0.50 ± 0.19 [a]	0.42 ± 0.13 [a]	0.43 ± 0.10 [a]	0.78 ± 0.18 [a]
ΣSFA	**8.44**	**41.62 ± 1.49 [a]**	**42.61 ± 2.64 [a]**	**38.73 ± 1.09 [a]**	**39.31 ± 1.87 [a]**
ΣMUFA	**65.26**	**36.63 ± 3.16 [a]**	**36.29 ± 1.71 [a]**	**39.97 ± 2.87 [a]**	**38.52 ± 2.14 [a]**
ΣPUFA	**21.32**	**21.48 ± 1.36 [a]**	**21.08 ± 1.35 [a]**	**22.12 ± 1.27 [a]**	**22.16 ± 1.84 [a]**
Σn-3	**1.38**	**2.99 ± 1.07 [ab]**	**3.59 ± 0.44 [a]**	**2.77 ± 0.64 [b]**	**3.39 ± 0.49 [a]**
Σn-6	**19.94**	**18.49 ± 0.80 [a]**	**17.49 ± 0.78 [b]**	**19.18 ± 1.25 [a]**	**17.44 ± 1.24 [b]**
n-6/n-3	**14.45**	**6.18 ± 0.82 [a]**	**4.87 ± 1.12 [b]**	**6.92 ± 1.34 [a]**	**5.14 ± 0.74 [b]**

*Values are mean ± standard deviation [a, b, c]. Different superscripts in the same row indicate significant difference ($P < 0.05$) between treatments. Fatty acids are % of total. ND = Not detected.

Highlights

- High pressure processing (HPP) increased marinade flavour absorption in pork chops
- Enhanced marinade absorption modified the fatty acid composition of marinated pork chops (MPC)
- Cooking methods (Steam or Griddle) affected the physicochemical & sensory characteristics of MPC
- Steam cooked MPC that were HPP had better physicochemical characteristics compared to griddled MPC
- Steam cooked MPC that were HPP had the best sensory characteristics compared to griddled MPC



(a)
Scores
400/griddle
400/steam
0.1/griddle
0.1/steam
PC-2 (14%)
PC-1 (82%)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-25
-20
-15
-10
-5
0
5
10
15
20
25
(b)
Correlation Loadings (X)
Marinade absorption
Cook loss
Lightness
Texture
Redness
Appearance
WBSF
Moisture
Juiciness
Yellowness
Tenderness
OSA
PC-2 (14%)
PC-1 (82%)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

Figure 1