Meat Science 173 (2021) 108381

Contents lists available at ScienceDirect

Meat Science

journal homepage: www.elsevier.com/locate/meatsci

Fatty acid composition, shelf-life and eating quality of beef from steers fed corn or wheat dried distillers' grains with solubles in a concentrate supplement to grass silage

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ARTICLE INFO

Keywords:
Distillers' grains
Beef
Oxidation
Fatty acids
Sensory attributes

ABSTRACT

Thirty-six steers were randomly assigned to one of three dietary treatments fed *ad libitum* grass silage and concentrate supplements containing either barley/soybean meal (CON), 80% DM corn (CDGS)- or 80% DM wheat (WDGS)-dried distillers' grains with solubles for 124 days pre-slaughter. Chemical and fatty acid composition, shelf-life, and eating quality of *longissimus thoracis* muscle were determined. Dietary CDGS and WDGS increased the proportion of conjugated linoleic acids ($P < 0.05$) and tended to increase C18:3*n*-3 ($P = 0.075$) and total polyunsaturated fatty acids ($P = 0.060$) relative to the CON. Feeding diets containing distillers' grains reduced the lipid and colour stability of fresh beef patties stored in modified atmosphere packs (MAP), with CDGS exhibiting an intermediate effect between CON and WDGS. Diet did not negatively influence the texture profile parameters and eating quality attributes of beef stored in MAP. The inclusion of CDGS or WDGS in supplementary concentrates may improve the fatty acid profile but decreased the shelf-life of beef.

1. Introduction

The rapid expansion of the global bioethanol industry has resulted in an increased biomass availability of co-products such as distillers' grains, obtained after the removal of starch from the grains. Distillers' grains are often dehydrated to enhance storage and handling characteristics for utilization in livestock diets. Dried distillers' grains have been extensively studied as a valuable source of energy, protein and fibre in cattle feed (Klopfenstein, Erickson, & Bremer, 2008). Typically, winter-finishing of beef cattle in temperate countries like Ireland is accomplished by feeding medium to high-quality grass silage supplemented with concentrate rations (McGee, 2005). The inclusion of starch-rich grains in concentrate rations fed with forages increases the susceptibility of diets to rapid ruminal fermentation that may impair fibre digestion and negatively affect animal performance (Dixon & Stockdale, 1999). The lower starch and higher fibre content in distillers' grains represent an ideal replacement for high-starch grains in concentrate rations fed with forage-based diets (Schoonmaker, Trenkle, & Beitz, 2010).

Previous studies have examined the effect of distillers' grains in concentrate-based feedlot rations on quality indices in beef (Buttrey et al., 2013; De Mello et al., 2018; Domenech-Pérez et al., 2017). The interaction of dietary distillers' grains with forages may exert a contrasting digestion pattern and carcass composition (Schoonmaker et al., 2010); however, limited information exists on subsequent effects on beef quality. Schoonmaker et al. (2010) demonstrated that replacing corn/soybean meal with up to 40% DM of wet distillers' grains in a low-forage (12% DM hay) diet increased the polyunsaturated fatty acids (PUFA) content in the *longissimus* muscle of steers but not in those fed a high-forage (50% DM hay) diet. Therefore, it is proposed that the impact of distillers' grains and grass silage on nutrient metabolism might contribute to variation in the physicochemical and metabolic traits of muscle that could influence beef quality attributes.

Furthermore, dietary distillers' grains may exhibit varied effects on meat quality attributes, particularly the fatty acid composition, depending on the fermentation substrate. Corn and wheat are the major

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https://doi.org/10.1016/j.meatsci.2020.108381
Received 23 August 2020; Received in revised form 21 November 2020; Accepted 23 November 2020
Available online 27 November 2020

grains used as fermentation substrates for bioethanol production depending on their relative availability in different countries (Klopfenstein et al., 2008; Yang & Li, 2017). Few studies have examined a direct comparison of the effect of corn (CDGS)- and wheat (WDGS)-distillers' grains with solubles on ruminant meat quality. Aldai et al. (2010b) reported that beef from steers fed 40% DM of WDGS exhibited a healthier *trans*-fatty acid profile compared to animals fed 40% DM of CDGS. However, there was no difference in the fatty acid profile of lamb meat when 20% DM of CDGS or WDGS was substituted for barley grain and canola meal in a total mixed ration (McKeown et al., 2010). Additionally, feeding up to 40% DM of CDGS may improve the tenderness and palatability of beef compared to a barley-based diet while meat from steers fed WDGS possessed intermediate sensory characteristics (Aldai et al., 2010a). Therefore, the objective of the current study was to examine the chemical composition, fatty acid profile, shelf-life stability, and sensory eating quality of beef from steers fed grass silage and supplementary concentrates containing CDGS or WDGS compared to a barley/soybean meal-based concentrate.

2. Materials and methods

2.1. Animals, diets and experimental design

The Teagasc animal ethics committee approved the experimental procedures used in this study and the study was conducted under license from the Irish Government Department of Health and Children. Trained personnel managed the animals according to the European Union legislation for the protection of animals used for scientific purposes (2010/63/EU Directive). A total of thirty-six weaned, spring-born Charolais and Limousin-sired suckler bulls were purchased directly from suckler farms at ~7 months of age and brought together at Teagasc Animal & Grassland Research and Innovation Centre, Grange, Ireland. The bulls were castrated and offered grass silage *ad libitum* plus 2 kg of a barley-based concentrate and 60 g of a mineral-vitamin supplement per head daily for a 187-d back-grounding period. All animals had *ad libitum* access to clean water.

Steers were subsequently blocked by breed and live weight (421.9 ± 38.9 kg) and, from within each block, randomly assigned to one of three concentrate rations (n = 12 steers/treatment) offered separately as a supplement to *ad libitum* grass (*Lolium perenne*) silage. The concentrate portion of the ration contained either barley/soybean meal (control, CON), 80% dry matter (DM) CDGS or 80% DM WDGS as a replacement for the barley/soybean meal. The inclusion of CDGS or WDGS is equivalent to 35% DM distillers' grains in the total diet (grass silage + concentrate). The ingredient and chemical composition (DM basis) of the concentrate rations are presented in Table 1. Representative samples of the concentrate rations were obtained twice weekly and stored at −20 °C before chemical analysis. The steers were housed in a slatted-floor building in groups of five or six animals per pen with a Calan gate feeding system (American Calan Inc., Northwood, NH, USA). Steers were individually offered the grass silage and 4.0 kg dry matter (DM) (2 kg DM in the morning and afternoon feeding sessions) of their respective supplementary concentrates for 124 days pre-slaughter. Animals were slaughtered in a commercial abattoir on two consecutive weeks (balanced for treatment) to facilitate sample collection and measurements. Samples of *longissimus thoracis* muscle (LT) were removed from the left side of the carcass at 48 h post-mortem, vacuum-packed and aged for 14 days at 4 °C, and subsequently stored at −20 °C before further analysis. Information relating to production performance and carcass characteristics has been presented elsewhere (McGee, Kelly, Kelly, & Moloney, 2019).

2.2. Feed analyses

Representative samples of concentrate rations were analysed for dry matter (DM), crude protein, ash, fibre fractions and starch as described by O'Kiely (2011), while extraction with a Soxtec instrument (Tecator, Höganäs, Sweden) was used for analysing total fat concentration or Oil-B (acid hydrolysis/ether extract).

Sequential extraction with methanol (50:50, *v*/v) and acetone (70:30, v/v) was used to extract phenolic compounds from the experimental diets (Jiménez-Escrig, Jiménez-Jiménez, Pulido, & Saura-Calixto, 2001). The concentration of total phenol in the extracts was measured spectrophotometrically after reaction with the Folin-Ciocalteu reagent, as described by Singleton, Orthofer, and Lamuela-Raventós (1999). The results were expressed as g of gallic acid equivalents (GAE)/kg of DM feed.

As described by Cherif et al. (2018), the fatty acid profile was determined in freeze-dried samples of concentrate rations by a one-step extraction–transesterification procedure using chloroform and 2% (*v*/v) sulfuric acid in methanol, with C19:0 (Larodan, Solna, Sweden) added as an internal standard. Gas chromatographic analysis was performed using a GC 8000 Top ThermoQuest (Milan, Italy) gas-chromatograph equipped with a flame ionization detector and a high polar column (WCOT-fused silica CP-Select CB for FAME Varian, Middelburg, the Netherlands; 100 m × 0.25 mm i.d.; film thickness 0.25 μm). Helium was used as the carrier gas at a constant flow of 1 mL/min. Total fatty acid methyl esters (FAME) profile in a 2 μL sample volume (split ratio 1:80) was determined using the following conditions: the oven temperature was programmed at 40 °C and held for 4 min, then increased to 120 °C at 10 °C/min, held for 1 min, then increased up to 180 °C at 5 °C/min, held for 18 min, then increased up to 200 °C at 2 °C/min, held for 15 min, and then increased up to 230 °C at 2 °C/min, held for 19 min. The injector and detector temperatures were set at 270 °C and 300 °C, respectively. FAME identification was based on a standard mixture of 52 Component FAME Mix (Nu-Chek Prep Inc., Elysian, MN, USA) and individual FAME standards (Larodan Fine Chemicals, Malmo, Sweden). Individual fatty acids were expressed as g/kg of DM feed.

Table 1
Ingredient and chemical composition of experimental concentrate diets containing corn or wheat dried distillers' grains with solubles.

Item	CON	CDGS	WDGS
Ingredient (% dry matter (DM))			
Rolled barley	86.2	12.7	12.7
Soybean meal	6.0	–	–
Dried corn distillers' grains	–	80.0	–
Dried wheat distillers' grains	–	–	80.0
Cane molasses	5.0	5.0	5.0
Minerals and vitamins	2.8	2.3	2.3
Chemical composition			
DM (%)	80.1	84.4	85.6
Crude protein[1]	13.1	24.1	29.5
Ash[1]	5.8	7.7	8.2
Total fat[1]	2.8	8.1	7.5
Neutral detergent fibre[1]	20.1	32.8	35.2
Acid detergent fibre[1]	6.2	11.2	12.5
Starch[1]	50.2	12.7	10.0
Total phenol content[2]	6.55	10.61	9.52
Fatty acid (g/kg DM)			
C12:0	0.10	0.20	0.10
C14:0	0.10	0.10	0.10
C16:0	3.30	1.90	8.40
C18:0	0.20	1.40	0.80
c-9 C18:1	1.90	13.90	7.40
c-9,12 C18:2	6.50	31.5	21.0
c-9,12,15 C18:3	0.60	1.10	1.10

[1]Expressed as % DM.
[2]Expressed as gram gallic acid equivalents/kg DM.
CON: control; CDGS: corn distillers' grains with solubles; WDGS: wheat distillers' grains with solubles.

2.3. Measurement of muscle pH, proximate composition, vitamin E and fatty acids

As described by Salami et al. (2020), the LT muscle was homogenised in distilled water and the pH of the homogenates was measured at 20 °C using a pH meter (Seven Easy portable, Mettler-Toledo GmbH, Schweizenbach, Switzerland). A SMART Trac rapid analyser (CEM Corporation, Matthews, NC, USA) was used for the determination of moisture and fat contents in LT, while protein was determined by the Kjeldahl method (AOAC, 1996) and ash content was determined using a muffle furnace set at 550 °C for 3 h.

The procedure of Buttriss and Diplock (1984) was used to extract vitamin E from LT sample. As described in detail by Salami et al. (2020), the α-tocopherol content was determined by high-performance liquid chromatography (HPLC) on a ProStar liquid chromatograph (Varian Analytical Instruments, Palo Alto, CA, USA) equipped with a ProStar autosampler (Model 410, Varian Instruments). Briefly, the α-tocopherol was separated on a 250 × 4.6 mm Polaris C18-A 5u column (Metachem, Ansys® Technologies, CA, USA) using methanol/water (97:3) as a mobile phase and isocratic elution (2 mL/min). The analyte was detected at 292 nm using a ProStar UV/Vis detector (Varian Instruments). Standard solutions of α-tocopherol were used to generate a standard curve, while the percentage recovery was calculated by the comparison of peak areas of vitamin E recovered through the extraction procedure with those obtained by direct injection of the vitamin E standard. The concentration of α-tocopherol in beef was expressed as μg/g of beef muscle.

For the analysis of the fatty acid composition, lipids were extracted from LT samples as described by Bligh and Dyer (1959) and fatty acids were converted to methyl esters (FAME) using boron trifluoride in methanol (Park & Goins, 1994) and finally dissolved in isooctane. The gas-chromatographic analysis was conducted following the injection, pressure and temperature conditions described in detail by Salami et al. (2020). In brief, FAME 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 × 0.25 mm i.d. x 0.20 μm film thickness) and a flame ionization detector. The column oven temperature was held at 150 °C for 25 min and programmed to increase from 150 °C to 240 °C at 4 °C/min and held for 2 min. The injector and detector temperatures were 270 °C and 260 °C respectively. Helium was used as the carrier gas at a pressure of 30 psi. The injection was carried out using a Combi PAL (CTC Analytics AG, Zwingen, Switzerland) auto-injector. The injection volumes and split ratios for FAME were 1 μL and 1:2 split, respectively. Individual compounds were identified using FAME standards (a mixture of Supleco 37 component FAME mix, trans-11 vaccenic acid methyl ester and conjugated linoleic acid methyl ester; Sigma-Aldrich Ireland Ltd., Vale Road, Arklow, Wicklow, Ireland) and results were reported as g/100 g of the total fatty acids. Indices of atherogenicity and thrombogenicity were calculated according to Ulbricht and Southgate (1991).

2.4. Measurement of total phenol content and in vitro antioxidant activity

Antioxidant capacity was determined in beef homogenates (10% *w/v*) prepared in phosphate buffer following the method of Qwele et al. (2013). As described by Salami et al. (2020), an aliquot of the homogenates was centrifuged and filtered and the supernatants were used for measuring the ferric reducing antioxidant power (FRAP) and the ferric ion chelating activity (FICA). For the analysis of total phenol content (TPC) and 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging activity, another aliquot of the homogenates was previously mixed with 10% trichloroacetic acid and subsequently centrifuged and filtered. Muscle extracts were analysed for TPC using an adaptation of the spectrophotometric the Folin-Ciocalteu assay, as described in detail by Salami et al. (2020) and results are expressed as mg of gallic acid equivalents (GAE)/g of muscle. A modification of the DPPH assay described by Yen and Wu (1999) was used for measuring the radical scavenging activity in muscle. As detailed by Salami et al. (2020), methanolic DPPH was added to the muscle extract diluted with distilled water and the mixture was incubated in the dark for 1 h at room temperature. Absorbance was measured at 517 nm on a UV–vis spectrophotometer (Cary 300 Bio) against a methanol blank. Additionally, another assay blank composed of distilled water methanolic DPPH was used for calculation purposes. Standard solutions of Trolox in methanol were used to calibrate the assay and results were expressed as mg of Trolox equivalents (TE)/g of muscle.

As described by Salami et al. (2020), the antioxidant activity in muscle was also measured in terms of reducing capacity, using an adaptation of the FRAP assay described by Benzie and Strain (1999). Briefly, freshly prepared FRAP reagent (30 mM acetate buffer (pH 3.6), 10 mM 2,4,6–Tris (2-pyridyl)-*s*-triazine in 40 mM HCl and 20 mM $FeCl_3.6H_2O$ in distilled water in the ratio 10:1:1 was mixed with the muscle extract. After incubation in the dark for 30 min, the absorbance was recorded at 593 nm on a UV–vis spectrophotometer (Cary 300 Bio) against a blank containing all reagents. Methanolic solutions of Trolox were used as standards and results were expressed as mg TE/g of muscle.

Finally, as described in detail by Salami et al. (2020), the antioxidant capacity of muscle was measured as the iron-chelating activity using a modification of the FICA assay described by Yen and Wu (1999). Briefly, muscle extract was mixed with distilled water and aqueous solutions of $FeCl_2$ and Ferrozine. The mixture was incubated for 1 h in the dark at room temperature and absorbance measurements were recorded at 562 nm against a water blank and a control blank (containing all the reagents except the muscle extract) on a UV–vis spectrophotometer (Cary 300 Bio). The chelating activity was calculated as follows:

Chelating activity (%) = [1 − (absorbance of sample)/(absorbance of control)] × 100.

2.5. Analysis of shelf-life and sensory attributes of beef

2.5.1. Determination of lipid oxidation and oxymyoglobin in muscle homogenates

As described by Salami et al. (2020), muscle homogenates (25%) were prepared in KCl/histidine buffer (pH 5.5) and lipid oxidation was initiated by the addition of $FeCl_3$ and sodium ascorbate at an equimolar concentration (45 μM, final concentration). Lipid oxidation (2-thiobarbituric acid reactive substances, TBARS) and oxymyoglobin (OxyMb) content in muscle homogenate were measured after 1 and 4 h of storage at 4 °C as described by Hayes et al. (2009).

2.5.2. Preparation of beef patties, colour and lipid oxidation analyses

The LT muscles were thawed, minced and formed into beef patties (100 g portions) for further storage in modified atmosphere packs (MAP) and aerobic packs, as described in detail by Salami et al. (2020). Briefly, fresh beef patties were individually placed in low-oxygen permeable polystyrene/ethyl-vinyl alcohol/polyethylene (PE) trays and flushed with 80% O_2:20% CO_2 MAP using a vacuum-sealing unit equipped with a gas mixer. Trays were covered and heat-sealed using a low-oxygen permeable (3 cm^3/m^2/24 h at STP) laminated barrier film with a polyolefin heat-sealable layer. Fresh beef patties in MAP were stored for up to 14 days under fluorescent lighting (660 lx) at 4 °C. The average gas composition in MAP was 79.94 ± 0.97% O_2 and 20.67 ± 0.19% CO_2 on the first day of storage and 73.41 ± 1.33% O_2 and 26.53 ± 1.27% CO_2 on day 14 of storage. For aerobic storage study, beef patties were cooked at 180 °C for 20 min in a fan-assisted convection oven until an internal temperature of 72 °C was reached. Cooked beef patties were placed in PE trays over-wrapped with oxygen-permeable film and stored for up to 6 days at 4 °C.

Lipid oxidation was measured in fresh beef patties stored in MAP (n = 12/treatment) on days 1, 4, 7, 11, and 14 of storage and days 1, 3, and 6 in cooked beef patties. Lipid oxidation measurements were carried out following the method described by Siu and Draper (1978). Results were expressed as TBARS in mg malondialdehyde (MDA)/kg meat. The

surface colour of fresh beef patties ($n = 12$/treatment) was measured on days 1, 4, 7, 11, and 14 of storage using a Konica Minolta CR-400 Chroma-Meter (Minolta Camera Co., Osaka, Japan). The Chroma-Meter consisted of a measuring head (CR-400), with an 8 mm diameter measuring area, illuminant D65, a 2° standard observer, and a data processor (DP-400). The Chroma-Meter was calibrated on the CIE LAB colour space system using a white tile (D_c: L = 97.79, a = −0.11, b = 2.69). The 'L^*', 'a^*' and 'b^*' values represent lightness, redness and yellowness, respectively. Surface colour measurements were taken from four different locations on the beef patties and readings were averaged. Chroma (C^*) and hue angle (H^*) were calculated as $[(a^{*2} + b^{*2})^{1/2}]$ and $[\tan^{-1}b^*/a^*]$, respectively.

2.5.3. Sensory analysis of beef patties

Texture profile analysis (TPA) was measured in fresh beef patties ($n = 12$/treatment) stored in MAP on storage days 2 and 7. As described by Moroney, O'Grady, O'Doherty, and Kerry (2013), a texture analyser (TA.XT2i Texture Analyser, Stable Micro Systems, UK) was used to measure the TPA parameters (hardness (N), springiness (mm), cohesiveness (dimensionless), chewiness (N × mm), adhesiveness (N)).

Forty untrained panellists were used to conduct sensory evaluations on fresh beef patties ($n = 8$/treatment) stored in MAP on days 2 and 7 of storage following the method described by O'Sullivan, Byrne, and Martens (2003). As described in detail by Salami et al. (2020), beef patties were cooked and served to panellists over two separate sessions. Sensory analysis was performed according to international standard regulations (ISO, 2007) using the individual panel booths at the university's sensory laboratory. Each panellist received beef samples presented in a randomised order and panellists were provided with water to cleanse their palates between samples to prevent any flavour carryover effects (MacFie, Bratchell, Greenhoff, & Vallis, 1989). Panellists were requested to indicate their degree of liking for appearance, odour, texture, juiciness, flavour and overall acceptability on a 10 cm line scale ranging from 0 (extremely dislike) to 10 (extremely like).

2.6. Statistical analysis

A general linear model was used to assess the effect of the dietary treatment on the proximate composition, antioxidant potential and fatty acid profile of meat, with the block being included as a random factor. Data on lipid and colour stability, and the sensory attributes were analysed using a mixed model to test the effect of diet and storage/incubation time as fixed factors and their interaction. The effects of panellist and session were included as random terms in the model used for the analysis of eating quality attributes. The effect of slaughter day was included as a covariate term in all models but was removed from the models due to non-significance ($P > 0.05$). The Tukey's HSD adjustment for multiple comparisons was used when a significant effect of the fixed factors was found at $P \leq 0.05$. Trends toward significance were considered when $0.05 < P \leq 0.10$. All data analysis was performed using SPSS statistical software (IBM Statistics version 22).

3. Results and discussion

In the scientific literature, limited information exists on the quality of meat from cattle finished on a grass silage-based diet in a combination with a supplementary concentrate containing distillers' grains. Feeding distillers' grains with a forage-based diet may influence ruminal and post-ruminal digestion due to a lower starch level and, higher PUFA and fibre contents, compared to grains (Schoonmaker et al., 2010). The variation in nutrient metabolism profile might contribute to differences in the physicochemical and metabolic traits of muscle that could influence meat quality attributes (Salami et al., 2019). Current evidence suggests that dietary CDGS and WDGS markedly influence beef quality parameters, in particular, fatty acid profiles (Aldai, Aalhus, et al., 2010a). Thus, the current study examined the quality traits of beef from steers offered grass silage and concentrate supplements containing 80% CDGS or WDGS as substitutes for barley/soybean meal.

3.1. Chemical composition and antioxidant potential of LT muscle

The pH and proximate composition of LT muscle are shown in Table 2. Beef from cattle fed CDGS had greater pH ($P < 0.05$) compared to those of CON whereas beef pH of cattle fed WDGS was not different ($P > 0.05$) from those of CDGS and CON. In general, the beef pH values (5.47–5.54) measured in all treatments are in agreement with the normal pH range (5.4–5.8) for *post-mortem* muscle (Faustman & Cassens, 1990), suggesting that feeding distillers' grains did not exert a negative impact on beef pH. The moisture and intramuscular fat contents were not influenced ($P > 0.05$) by dietary treatments. In comparison to WDGS, dietary CDGS increased ($P < 0.05$) the protein content and decreased the ash content in LT. In contrast to our observation, Aldai, Aalhus, et al. (2010a) reported a decrease in the protein content of LT of steers fed WDGS compared to a barley-based control diet while that of CDGS was intermediate. In general, the present results agreed with previous studies indicating that inclusion of CDGS or WDGS in concentrate-based feedlot rations had little or no impact on the chemical composition of *longissimus* muscle (Aldai, Aalhus, et al., 2010a; De Mello et al., 2018; Domenech-Pérez et al., 2017; Koger et al., 2010).

The concentration of α-tocopherol (vitamin E) and phenolic compounds in muscle tissues is dependent on dietary intakes (Salami et al., 2016). Dried distillers' grains, compared to the corresponding cereal, contains a considerably higher amount of α-tocopherol (Nade, Uchida, Omori, & Kimura, 2013) and phenolic compounds such as vallinic, caffeic, *p*-coumaric, ferulic and sinapic acids, with potent antioxidant activity (Luthria, Liu, & Memon, 2012). However, there is limited data on the effect of feeding distillers' grains on the concentration of these compounds in beef. Despite higher TPC levels in CDGS and WDGS diets compared to CON (Table 1), feeding distillers' grains did not influence ($P > 0.05$) the TPC in LT muscle (Table 2). This observation suggests that phenolic compounds from dietary distillers' grains were not deposited in the muscle possibly due to factors such as molecular complexity and microbial metabolism in the rumen, limiting their bioavailability and absorption into muscle tissues (Vasta & Luciano, 2011). Similarly,

Table 2
Effect of including corn or wheat dried distillers' grains with solubles in supplementary concentrate diets of steers on the pH, proximate composition, antioxidant status and antioxidant activity of *longissimus thoracis* muscle.

Item	Dietary treatment			SEM	*P*-value
	CON	CDGS	WDGS		
Muscle pH	5.47[b]	5.54[a]	5.52[ab]	0.011	0.009
Proximate composition (g/100 g wet weight)					
Protein	23.67[ab]	24.34[a]	22.60[b]	0.234	0.006
Intramuscular fat	2.57	2.76	2.76	0.142	0.828
Moisture	73.12	72.52	72.42	0.150	0.122
Ash	1.11[a]	1.05[b]	1.13[a]	0.009	0.001
Antioxidant status					
α-tocopherol (μg/g muscle)	2.38	2.62	2.70	0.072	0.180
TPC (mg GAE/g muscle)	0.94	0.85	0.76	0.032	0.074
Antioxidant activity					
DPPH (mg TE/g muscle)	0.25	0.25	0.25	0.002	0.720
FRAP (mg TE/g muscle)	0.38	0.41	0.41	0.007	0.110
FICA (%)	55.22	60.26	61.23	1.410	0.176

[a,b]Means within the same row bearing different superscripts are significantly different ($P < 0.05$).
SEM: Standard error of mean.
CON: Control; CDG: Corn distillers' grains with solubles; WDG: Wheat distillers' grains with solubles.
TPC: Total phenol content DPPH: 1,1-diphenyl-2-picrylhydrazyl; FRAP: Ferric reducing antioxidant power; FICA: Ferric ion chelating activity.
GAE: Gallic acid equivalent; TE: Trolox equivalent.

dietary treatment did not influence ($P > 0.05$) the α-tocopherol concentration in LT muscle. Previous research has also shown that feeding 15–30% wet or dried corn distillers grains to steers did not significantly influence the α-tocopherol concentration in plasma (Nade et al., 2013) and *longissimus* muscle (Chao, Domenech-Pérez, Voegele, Kunze, & Calkins, 2018). Moreover, the antioxidant capacity of LT muscle (DPPH, FRAP and FICA assays) was not influenced ($P > 0.05$) by dietary treatment. Similarly, the inclusion of up to 25% CDGS as a replacement for corn/soybean meal in broiler diets did not enhance antioxidant enzyme activities and the total antioxidant capacity of breast muscle and liver tissues (Min et al., 2012). Results from the present study suggest that feeding distillers' grains did not enhance the antioxidant potential of beef.

3.2. Fatty acid profiles of LT muscle

The protection of dietary PUFA from ruminal biohydrogenation is a significant strategy for improving the fatty acid composition of ruminant meat and milk (Bessa, Alves, & Santos-Silva, 2015). There is evidence that dietary distillers' grains may increase dietary fat digestibility and increase the amount of unsaturated fatty acids reaching the distal gut, indicative of decreased susceptibility of dietary PUFA to ruminal biohydrogenation (Vander Pol, Luebbe, Crawford, Erickson, & Klopfenstein, 2007; Xu et al., 2014). Previous studies have examined the fatty acid profile of beef from cattle fed distillers' grains included in concentrate-based feedlot rations whereas limited data exists on the inclusion of distillers' grains in concentrate rations fed in combination with a forage-based diet.

The inclusion of CDGS or WDGS in supplementary concentrates did not affect ($P > 0.05$) the percentage of total saturated fatty acids (SFA); however, few changes were observed for individual SFA (Table 3). Feeding WDGS decreased ($P < 0.05$) the proportion of C14:0 (myristic acid) and increased C20:0 (arachidic acid) compared to CON. Notably, the effect of WDGS may be nutritionally desirable because dietary myristic acid increases low-density lipoprotein cholesterol associated with an increased incidence of cardiovascular diseases (Mensink, 2005). However, feeding distillers grains did not influence ($P > 0.05$) the proportion of two major SFA (C16:0 and C18:0) associated with beef. Previous studies have also shown that C16:0 and C18:0 were unaffected by distillers' grains fed in a concentrate-based ration (De Mello et al., 2018; Depenbusch, Coleman, Higgins, & Drouillard, 2009) or forage-based diets (Schoonmaker et al., 2010). Stearic acid (C18:0) is the main end-product of microbial hydrogenation of dietary PUFA in the rumen (Bessa et al., 2015), and results (non-significance of C18:0) suggest that complete inhibition of ruminal biohydrogenation was not altered by diet.

The proportion of total monounsaturated fatty acids (MUFA) and *trans* fatty acids did not differ ($P > 0.05$) between dietary treatments. Accordingly, the percentage of the most abundant MUFA in beef, oleic acid (*c*-9 C18:1), was not affected ($P > 0.05$) by diet even though this fatty acid was predominant in the distillers' grains diets (Table 1). This observation may be attributed to the susceptibility of oleic acid to rapid hydrogenation to form stearic acid usually *via* a *trans*-vaccenic acid (*t*-11 C18:1) pathway (Jenkins, Wallace, Moate, & Mosley, 2008). Feeding distillers grains in beef cattle diets have been shown to alter the ruminal outflow of *trans* 18:1 isomers, particularly increasing *t*-11 C18:1 (Vander Pol et al., 2007; Xu et al., 2014), which may increase the concentration of this fatty acid in ruminant tissues. In this study, the proportion of *t*-9 + 10 18:1 and *t*-11 C18:1 were not different ($P > 0.05$) between dietary treatments. In agreement with our observation, feeding wet or dried distillers' grains had no effect on the concentration of *t*-11 C18:1 in *longissimus* muscles of beef cattle (Domenech-Pérez et al., 2017; Gill, VanOverbeke, Depenbusch, Drouillard, & DiCostanzo, 2008). On the contrary, previous studies indicated that the inclusion of CDGS or WDGS in concentrate-based feedlot rations increased the *t*-11 C18:1 measured in backfat tissue (Aldai, Dugan, et al., 2010b) as well as brisket fat and diaphragm (Dugan et al., 2010). Considering that the effects of diet on ruminal biohydrogenation was not measured in the present study, it is difficult to conclude if feeding distillers' grains resulted in a greater ruminal outflow of *t*-11 C18:1. Nonetheless, the discrepancy in the effects of distillers' grains on the accumulation of *t*-11 C18:1 in ruminant tissues may be partly due to the differences in the tissue of measurement and possible endogenous conversion to *c*-9, *t*-11 CLA (Palmquist, Lock, Shingfield, & Bauman, 2005). Furthermore, a higher proportion ($P < 0.05$) of C16:1 and *c*-10 17:1 were found in the muscle of CON-fed steers compared to those fed CDGS or WDGS. The substitution of grains with distillers' grains in a forage-based diet may result in a lower amount of ruminal volatile fatty acids (Schoonmaker et al., 2010) which could influence *de novo* fatty acid synthesis (Smith et al., 2009) which might explain the lower proportion of C16:1 and *c*-10 17:1 produced from the desaturation of their SFA equivalents (C16:0 and C17:0).

Furthermore, total PUFA in the LT muscle tended to be higher ($P = 0.06$) in steers fed CDGS or WDGS compared to CON. The increase in muscle PUFA of steers fed distillers' grains was primarily driven by a significantly greater ($P < 0.05$) proportion of CLA (*c*-9, *t*-11 18:2 + *t*-9, *c*-

Table 3
Effect of including corn or wheat dried distillers' grains with solubles in supplementary concentrate diets of steers on the fatty acid composition of *longissimus thoracis* muscle.

Fatty acids (% of total fatty acids)	Dietary treatment			SEM	*P*-value
	CON	CDGS	WDGS		
C12:0	0.07	0.05	0.06	0.008	0.670
C14:0	2.51[a]	2.09[ab]	2.02[b]	0.085	0.036
c-9 C14:1	0.44	0.37	0.39	0.032	0.680
C15:0	0.39[b]	0.36[b]	0.71[a]	0.053	0.009
C16:0	22.99	21.35	22.15	1.321	0.886
C16:1	1.85[a]	0.50[b]	0.47[b]	0.133	<0.001
C17:0	0.86	0.67	0.80	0.034	0.068
c-9 C17:1	0.50[b]	0.30[a]	0.30[a]	0.036	0.031
C18:0	13.32	13.77	12.67	0.320	0.381
t-9 + 10 18:1	2.07	1.57	1.58	0.136	0.233
t-11 C18:1	0.95	0.90	0.91	0.035	0.836
c-9 C18:1	29.11	27.83	28.98	0.970	0.847
t-9, *t*-12 C18:2	0.28	0.35	0.30	0.033	0.710
c-9, *c*-12 C18:2	2.29	3.95	3.69	0.384	0.167
C20:0	0.02[b]	0.08[ab]	0.12[a]	0.013	0.006
c-11 C20:1	0.46	0.39	0.45	0.504	0.319
c-9, *c*-12, *c*-15 C18:3	0.35	0.43	0.48	0.025	0.075
[1]CLA	0.14[a]	0.27[b]	0.27[b]	0.026	0.042
C22:0	0.52	0.69	0.61	0.034	0.130
C20:4 *n*-6	1.10	1.02	0.97	0.027	0.152
C20:5 *n*-3	0.18	0.24	0.24	0.032	0.640
C22:5 *n*-3	0.44	0.52	0.53	0.046	0.713
Summary					
∑SFA	41.15	39.33	39.39	1.448	0.850
∑MUFA	36.98	31.87	33.08	1.015	0.117
∑PUFA	4.97	7.18	6.89	0.474	0.062
Total *trans*	3.02	2.47	2.49	0.127	0.132
∑n-6 PUFA	3.87	5.71	5.36	0.468	0.126
∑n-3 PUFA	0.96	1.19	1.26	0.053	0.149
n-6:*n*-3	4.03	4.80	4.25	0.746	0.572
PUFA:SFA	0.12	0.18	0.17	0.013	0.418
[2]Atherogenicity index	0.82	0.83	0.82	0.049	0.992
[3]Thrombogenicity index	1.78	1.87	1.78	0.089	0.897

[a,b]Means in the same row bearing different superscripts are significantly different ($P \leq 0.05$).
SEM: Standard error of mean.
CON: control; CDGS: corn distillers' grains with solubles; WDGS: wheat distillers' grains with solubles.
[1]CLA: *c*-9 *t*-11 18:2 + *t*-9 *c*-11 18:2 + *t*-7 *c*-9 18:2.
[2]Atherogenic index: (C12:0 + [4 × C14:0] + C16:0)/(*n*-3 PUFA + *n*-6 PUFA + MUFA).
[3]Thrombogenic index: (C14:0 + C16:0 + C18:0)/([0.5 × MUFA] + [0.5 × *n*-6 PUFA] + [3 × *n*-3 PUFA] + [*n*-3/*n*-6 PUFA]).
CLA: conjugated linoleic acid; SFA: saturated fatty acids; MUFA: monounsaturated fatty acids; PUFA: poly-unsaturated fatty acids

11 18:2 + *t*-7, *c*-9 18:2) and a tendency for higher α-linolenic acid (C18:3 *n*-3; $P = 0.08$) and docosadienoic acid (C22:2 *n*-6). It is well-established that dietary consumption of PUFA is associated with numerous health benefits in humans and strategies that enhance PUFA accumulation in the muscle can improve the nutritional image of beef (Bessa et al., 2015). In particular, *c*-9, *t*-11 CLA is a bioactive fatty acid with physiological effects that may prevent cardiovascular diseases, obesity, cancers, bone density loss, and diabetes in humans (Dilzer & Park, 2012). In the present study, it is noteworthy that *c*-9, *t*-11 CLA co-eluted with *t*-9, *c*-11 and *t*-7, *c*-9 CLA as a single GC peak. The quantitative ratio of *c*-9, *t*-11 18:2 to *t*-9, *c*-11 18:2 was estimated to be approximately 32:1 in beef fat from steers (Fritsche & Fritsche, 1998). Indeed, *c*-9, *t*-11 18:2 is the major CLA isomer present in ruminant edible fat, accounting for 75–90% of the total CLA (Palmquist et al., 2005). Thus, the CLA peak identified in our study is expected to be predominantly *c-9, t*-11 CLA isomer.

In agreement with our study, dietary CDGS or WDGS (up to 60% DM) as substitutes for corn or barley in concentrate-based rations have been shown to increase the concentration of *c*-9, *t*-11 CLA in beef (Dugan et al., 2010; Mello et al., 2012). In contrast, other studies have shown no changes in the *c*-9, *t*-11 CLA content in beef (Depenbusch et al., 2009). The ability of distillers' grains to increase the content of *c*-9, *t*-11 CLA in beef may be attributed to its higher fibre content, compared to grains, which could modify the growth and activity of the bacteria (*Butyrivibrio fibrisolvens*) linked to the synthesis of this fatty acid in the rumen (Mello et al., 2012). Moreover, a higher proportion of intramuscular CLA in this study may be attributed to the abundance (3 to 5-fold) of linoleic acid (C18:2 *n*-6) in the CDGS and WDGS diets. This could be related to the fact that *c*-9, *t*-11 CLA is the major fatty acid intermediate synthesised from the isomerisation of linoleic acid during ruminal biohydrogenation (Jenkins et al., 2008). Moreover, *c*-9, *t*-11 CLA may also be synthesised endogenously *via* desaturation of *t*-11 18:1 (Corl et al., 2001). However, the lack of dietary effect on *t*-11 18:1 suggests that *de novo* synthesis might not play a major role in accounting for the differences in the accumulation of muscle CLA in this study. Finally, measures of nutritional indices of muscle fatty acid profiles indicated that feeding distillers' grains did not influence ($P > 0.05$) the ratios of PUFA:SFA, *n*-6:*n*-3, and the indices of atherogenicity and thrombogenicity.

The present study demonstrated that feeding distillers' grains with grass silage resulted in changes that may improve the fatty acid composition of beef. However, this effect is limited when compared to previous studies that reported a significant increase in the content of health-promoting fatty acid (linoleic and α-linoleic acids, and CLA and total PUFA) in beef from cattle fed CDGS or WDGS included in concentrate-based feedlot rations (Buttrey et al., 2013; De Mello et al., 2018; Domenech-Pérez et al., 2017; He et al., 2012). Moreover, the current study showed that dietary CDGS and WDGS had a comparable effect on muscle fatty acid composition. On the contrary, the inclusion of CDGS or WDGS in concentrate-based diets results in differences in the *trans*-18:1 isomers and *n*-3 PUFA profiles of backfat tissue in steers (Aldai, Dugan, et al., 2010b). Indeed, a dietary effect of distillers' grains on muscle fatty acid profiles may depend on the proportion of forages fed in the ration. Schoonmaker et al. (2010) reported that feeding up to 40% DM of wet distillers' grains in a low-forage (12% DM bromegrass hay) diet increased the PUFA content in the *longissimus* muscle of steers but not in those fed a high-forage diet (50% DM bromegrass hay). A high-forage diet (50% DM bromegrass hay) may increase fibre intake similar to the *ad libitum* grass silage offered in the present study, which could also explain why CDGS and WDGS did not significantly increase the total PUFA of muscle in our study. Though feed fatty acid profile was not reported by Schoonmaker et al. (2010), the present study indicated that inclusion of CDGS and WDGS increased dietary PUFA (oleic and linoleic acids) which might have contributed to the alteration of ruminal biohydrogenation as observed with a significantly higher percentage of CLA in the muscle. This result emphasised the need for future studies to report the feed fatty acid composition when examining the effect of distillers' grains on meat fatty acid profiles.

3.3. Shelf-life of beef patties

3.3.1. Lipid and colour stability in fresh beef patties

There was a significant interaction between diet and storage time on the lipid oxidation of fresh beef patties stored in MAP (Fig. 1a). On day 4 of storage, the interactive effects showed that lipid oxidation was lower ($P < 0.05$) in CON beef patties compared to CDGS and WDGS (Fig. 1a). However, the extent of lipid oxidation was similar ($P > 0.05$) between CDGS and CON from days 7 to 14 of storage. On days 7 to 14 of storage, fresh beef patties of WDGS had a higher level ($P < 0.05$) of lipid oxidation compared to CON but similar ($P > 0.05$) to that of CDGS. The increase in lipid oxidation may be partly attributed to the tendency for a greater amount of PUFA in LT muscle from steers fed CDGS or WDGS. An elevated level of PUFA content increases the susceptibility of meat to oxidation, resulting in the development of rancid off-flavours over time (Faustman, Sun, Mancini, & Suman, 2010). Lipid oxidation (TBARS) value of 2.28 MDA mg/kg of meat has been reported as the threshold for perceivable rancidity that may negatively influence consumer acceptability of oxidized beef (Campo et al., 2006). Thus, the retail shelf-life of beef patties from CDGS or WDGS may be limited to 7 days compared to CON that may extend to 10 days under the experimental conditions employed in the present study.

Meat colour is an important sensory attribute that contributes to quality perception and the purchasing decision of consumers during the shelf-life of fresh meat. Oxidative deterioration of meat colour is associated with the conversion of oxymyoglobin to metmyoglobin resulting in a change from a bright red colour to a brownish appearance (Faustman et al., 2010). The present results indicated that there was no effect of diet on the lightness (L^*) of MAP-stored fresh beef patties whereas MAP-stored beef patties from animals fed CDGS were yellower (b^*) than those from animals fed WDGS (Table 4). Moreover, the L^*values increased throughout storage while b^* values decreased over the storage time (Table 4). The interactive effects between diet and storage time influenced ($P < 0.01$) the redness (a^*), chroma (C^*) and hue angle values (H^*) of fresh beef patties stored in MAP (Fig. 1b, c, d, respectively). On day 1 of storage, beef patties of CDGS were redder (a^*) relative to those fed CON. Beef patties of CON exhibited higher a^* values compared to those of WDGS between days 7 and 14, while CON was redder than CDGS only at day 10 (Fig. 1b). The decrease in C^* over the storage period indicated that the redness of beef from WDGS-fed steers was lower relative to those of CON and CDGS on day 7, whereas CON was redder than CDGS and WDGS on day 10 (Fig. 1c). The H^* values also showed that beef patties from steers fed WDGS had a decreased red appearance compared to CON from 7 to 14 days of storage (Fig. 1d). It is noteworthy that on day 10 of storage, only the C^*value measured in beef from WDGS was less than 18, which represents the critical threshold for consumer rejection of discoloured fresh beef during the retail purchase (Hood & Riordan, 1973). Overall, instrumental colour profiles indicated that feeding distillers' grains increased the extent of discolouration of beef patties stored in MAP, with CDGS exhibiting an intermediate effect between CON and WDGS.

Lipid peroxidation and myoglobin oxidation are interactive processes that could reciprocally influence each other through chemical reactivity of their primary and secondary products (Faustman et al., 2010). This could explain the consistency in lipid oxidation and discolouration of fresh beef from steers fed distillers' grains, particularly WDGS. However, the mechanistic effect of dietary distillers' grains on beef oxidation has been controversial. In agreement our study, it has been shown that simulated retail display (≤ 7 days) increased lipid oxidation and discolouration of fresh beef from cattle fed ≥30% DM of distillers' grains in concentrate-based rations (Buttrey et al., 2013; De Mello et al., 2018). However, other studies reported that increased colour deterioration of beef was not accompanied by changes in lipid oxidation (Depenbusch et al., 2009; Segers et al., 2011).

Feeding distillers' grains preferentially increases the PUFA content in the sarcoplasmic membrane which may enhance its instability and

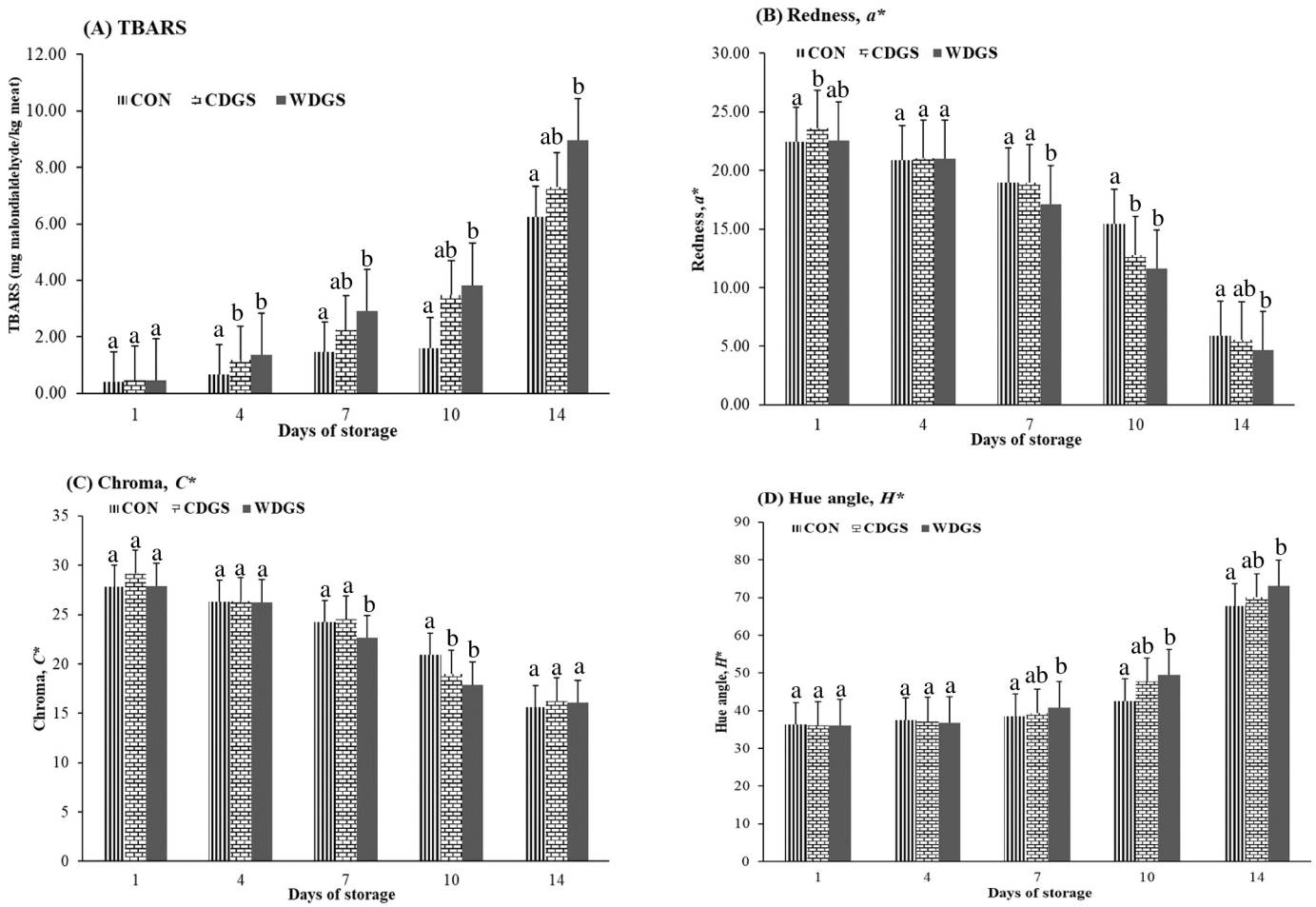

Fig. 1. Interactive effect of the diet and storage time (D × T) on the: (A) lipid oxidation (TBARS, mg malondialdehyde/kg meat) (B) Redness, a^* (C) Chroma, C^* (colour vividness; higher values indicate greater saturation of red) (D) Hue angle, H^* (trueness of red; lower values indicate a redder colour) measured in fresh beef patties stored in modified atmosphere packs (80% O_2:20% CO_2) at 4 °C for up to 14 days. Diets were: CON (control diet), CDGS (corn distillers' grains with solubles diet) and WDGS (wheat distillers' grains with solubles diet). Values are presented as means with standard error bars. [a,b]Within a storage time, values with different letters are significantly different ($P < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Effect of including corn or wheat dried distillers' grains with solubles in supplementary concentrate diets of steers on the shelf-life of beef.

Parameter	Diet (D)			Storage/incubation time (T)[1]					SEM	*P*-value[2]		
	CON	CDGS	WDGS	1	2	3	4	5		D	T	D x T
Fresh beef patties												
Lightness, L^*	49.24	49.89	49.80	48.03^{a}	48.56^{a}	49.41^{a}	49.37^{a}	52.85^{b}	0.337	0.525	<0.001	0.879
Yellowness, b^*	15.24^{xy}	15.58^{y}	15.17^{x}	16.69^{a}	15.89^{b}	15.14^{c}	15.02^{c}	13.91^{d}	0.157	0.027	<0.001	0.110
Cooked beef patties												
TBARS[3]	2.29^{xy}	1.74^{x}	2.65^{y}	1.59^{a}	2.27^{b}	2.83^{b}			0.151	0.002	<0.001	0.267
Muscle homogenates												
TBARS[3]	4.21	4.05	4.31	2.24^{a}	6.14^{b}				0.254	0.623	<0.001	0.966
OxyMb[4] (%)	65.31	68.13	65.57	86.61^{a}	46.06^{b}				2.604	0.450	<0.001	0.266

[x,y,z]Within row, different superscript letters indicate differences ($P < 0.05$) between dietary treatment.
[a,b,c,d,e]Within row, different superscript letters indicate differences ($P < 0.05$) between storage/incubation time.
CON: control; CDGS: corn distillers' grains with solubles; WDGS: wheat distillers' grains with solubles; SEM: Standard error of mean.
[1]Times 1, 2, 3, 4, 5 correspond to: 1, 4, 7, 10 and 14 days (fresh beef patties stored at 4 °C in modified atmosphere packs); 1, 3, 6 days (cooked beef patties stored at 4 °C in aerobic packs); 1 and 4 h (muscle homogenates incubated with Fe/Ascorbate at 4 °C)
[2]*P*-values for the effects of the dietary treatment (D), time of storage or incubation (T) and D × T interaction.
[3]TBARS: 2-thiobarbituric acid reactive substances expressed as mg malondialdehyde/kg meat.
[4]OxyMb: Oxymyoglobin, % of total myoglobin.

increases the susceptibility of muscle tissues to rapid oxidation (Chao, Domenech-Pérez, & Calkins, 2017). Therefore, the mincing of beef in the present study contributed to the disruption of the muscle cell structure exposing labile lipid components to oxygen (O'Grady, Monahan, Burke, & Allen, 2000), resulting in rapid lipid oxidation in LT beef patties from cattle fed distillers' grains. Another contributing factor may be the peroxidizable nature of the PUFA content relative to the antioxidant potential of the muscle. In this study, it was observed that dietary distillers' grains did not enhance the antioxidant potential of muscle which may partly explain why a tendency for increased PUFA content resulted in greater lipid oxidation and discolouration in fresh beef stored in MAP. In particular, vitamin E is a very important membrane-bound antioxidant and a concentration of 3.0–3.5 μg/g of muscle may be required to maintain cellular integrity and enhance the oxidative stability of beef (Liu, Scheller, Arp, Schaefer, & Williams, 1996). Lower vitamin E concentrations (2.38–2.70 μg/g muscle) were reported in the present study (Table 2) and dietary supplementation of vitamin E may be an effective strategy to improve the lipid and colour stability of fresh beef from cattle fed distillers' grains (Chao et al., 2018).

3.3.2. Oxidative stability of cooked beef patties and muscle homogenates

The susceptibility of meat to oxidative deterioration can be increased by storage and processing conditions such as catalysts, light and temperature (Bekhit, Hopkins, Fahri, & Ponnampalam, 2013). The effect of feeding CDGS or WDGS on the oxidative stability of beef was further examined under intense oxidative conditions such as cooking or subjecting fresh LT muscle homogenates to iron/ascorbate-induced lipid oxidation. Aerobically stored cooked beef patties of WDGS exhibited higher ($P < 0.05$) lipid oxidation (TBARS) than those of CDGS over the 6-day storage period (Table 4). Lipid oxidation increased ($P < 0.05$) over the storage duration but there was no interactive effect ($P > 0.05$) between diet and storage time (Table 4). Furthermore, lipid and myoglobin oxidation were examined in muscle homogenates subjected to induced oxidation by incubating with iron/ascorbate pro-oxidants for 4 h at 4 °C. Results indicated that both lipid and oxymyoglobin oxidation increased as a function of time but there was no effect ($P > 0.05$) of dietary treatment (Table 4). These results suggest that effect of feeding distillers' grains on the susceptibility of beef to lipid peroxidation was more pronounced under moderate oxidative conditions as shown with the extended storage of fresh beef patties stored in MAP at 4 °C. Feeding distillers' grains does not enhance the antioxidant capacity and oxidative stability of LT muscle possibly due to the lack of deposition of phenolic compounds in the muscle. Ferulic acid is the most abundant phenolics in CDGS (Luthria et al., 2012) and it has been shown that dietary supplementation of ferulic acid did not enhance the oxidative stability of beef (Torres et al., 2016).

3.4. Instrumental texture and sensory quality characteristics of beef

The perception of texture is an important quality attribute that influences the palatability of meat and consumer satisfaction. Animal diet can impact meat texture by directly influencing muscle structure and physicochemical composition (Andersen, Oksbjerg, Young, & Therkildsen, 2005) or indirectly influencing oxidative processes that affect lipid and protein degradation in muscle tissues (Bekhit et al., 2013). Instrumental TPA gives a detailed assessment of different textural attributes (such as hardness, springiness, and adhesiveness) that better define meat tenderness (De Huidobro, Miguel, Blázquez, & Onega, 2005). In the present study, hardness, springiness, cohesiveness and chewiness of beef patties increased ($P < 0.05$) over the 7-day storage period while adhesiveness was not affected ($P > 0.05$) by storage time (Table 5). Hardness is the most important singular TPA parameter and increased values as a function of storage time indicates decreased tenderness of beef patties, reducing palatability and consumer acceptance (Caine, Aalhus, Best, Dugan, & Jeremiah, 2003; De Huidobro et al., 2005). However, dietary treatment and dietary treatment x storage time did not affect ($P > 0.05$) any of the TPA parameters despite the observed increase in lipid oxidation in beef patties from steers fed CDGS or WDGS during the 7-day storage period. Previous studies have also shown that feeding CDGS or WDGS (up to 40% DM) did not influence instrumental textural properties (Warner-Bratzler shear force) in fresh beef aged for up to 42 days (Aldai, Aalhus, et al., 2010a; De Mello et al., 2018; Koger et al., 2010).

Furthermore, untrained panellists did not detect storage time or treatment differences ($P > 0.05$) in the sensory attributes (appearance, odour, texture, juiciness, flavour and overall acceptability) of beef patties stored in MAP over a 7-day storage period. This outcome is particularly interesting given that increased lipid oxidation in beef patties from CDGS or WDGS did not result in perceivable rancidity that could negatively influence consumer acceptability of beef. Previous sensory evaluation studies have reported inconsistent effects of dietary distillers' grains on eating attributes of beef. However, none of these studies has evaluated the sensory attributes of beef over the shelf-life period as examined in the present study.

Using trained or untrained sensory panellists, it has been shown that the sensory characteristics of beef were not affected by substituting corn with wet or dried CDGS (up to 35% DM) in concentrate feedlot rations (Buttrey et al., 2013; De Mello et al., 2018; Gill et al., 2008). In contrast,

Table 5
Effect of including corn or wheat dried distillers' grains with solubles in supplementary concentrates of steers on instrumental texture parameters and sensory eating quality of beef patties stored in modified atmosphere packs at 4 °C for up to 7 days.

Parameter	Diet (D)			Storage time (T, day)			*P*-value[1]		
	CON	CDGS	WDGS	2	7	SEM	D	T	D x T
Textural attributes									
Hardness	20.26	22.04	20.13	16.58[a]	25.04[b]	1.209	0.445	<0.001	0.362
Springiness	0.84	0.85	0.84	0.83[a]	0.86[b]	0.005	0.483	0.020	0.650
Cohesiveness	0.60	0.62	0.59	0.58[a]	0.63[b]	0.012	0.512	0.031	0.403
Chewiness	10.33	12.03	10.11	8.02[a]	13.64[b]	0.857	0.317	<0.001	0.552
Adhesiveness	−1.48	−1.24	−1.06	−1.31	−1.21	0.115	0.386	0.668	0.384
Eating quality									
Appearance	5.72	6.10	6.14	5.86	6.11	0.142	0.400	0.367	0.554
Odour	6.01	5.90	6.16	5.95	6.10	0.131	0.709	0.579	0.627
Texture	4.45	5.05	5.03	4.93	4.75	0.146	0.173	0.534	0.978
Juiciness	3.30	3.72	3.86	3.77	3.48	0.133	0.206	0.277	0.621
Flavour	5.77	5.65	5.53	5.82	5.49	0.131	0.753	0.194	0.743
Overall acceptability	5.07	5.42	5.22	5.36	5.11	0.121	0.473	0.270	0.827

[a,b]Within row, different superscript letters indicate differences ($P < 0.05$) between storage/incubation time.
[1]*P*-values for the effects of the dietary treatment (D), time of storage (T) and D × T interaction.
CON: control; CDGS: corn distillers' grains with solubles; WDGS: wheat distillers' grains with solubles; SEM: Standard error of mean.

other studies using trained panellists reported that replacement of corn with dried CDGS (up to 75% DM) improved beef tenderness (Depenbusch et al., 2009) while the inclusion of CDGS or WDGS (up to 40% DM) in barley-based finishing diets enhanced the flavour desirability of beef (Aldai, Aalhus, et al., 2010a). Moreover, Aldai, Aalhus, et al. (2010a) indicated that panellists rated beef steaks from steers fed CDG as more tender and palatable compared to the control (barley-based diet) while beef steaks from WDGS had intermediate scores for such attributes. The ability of CDGS to improve sensory characteristics have been attributed to changes in muscle physicochemical properties such as the amount of connective tissues and fat content (Aldai, Aalhus, et al., 2010a; Depenbusch et al., 2009). On the contrary, the current study indicated that dietary CDGS or WDGS did not affect the IMF content and instrumental texture parameters which may explain the similarity in beef sensory attributes such as the liking of flavour and texture.

4. Conclusions

The inclusion of CDGS or WDGS in supplementary concentrates offered to steers fed grass silage may increase the proportion of health-promoting fatty acids (CLA and PUFA) in beef. However, feeding distillers' grains increased the susceptibility to lipid oxidation and colour deterioration in fresh beef patties stored in MAP, with CDGS exhibiting an intermediate effect between CON and WDGS. The retail shelf-life of beef patties from steers fed CDGS and WDGS may be limited to 7 days while the CON treatment may extend retail shelf-life up to 10 days. Nonetheless, feeding distillers' grains did not negatively influence the eating attributes of beef patties stored in MAP for up to 7 days.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was conducted as part of a PhD thesis project supported by the Agricultural Transformation by Innovation (AGTRAIN) Erasmus Mundus Joint Doctorate Program, funded by the EACEA (Education, Audiovisual and Culture Executive Agency) of the European Commission. The authors acknowledge the technical assistance provided by Bernardo Valenti, University of Catania, Italy. The animal production component of the study was funded by the Department of Agriculture, Food and the Marine Competitive Research Programme (11/S/122, FEFAN).

References

Aldai, N., Aalhus, J., Dugan, M., Robertson, W., McAllister, T., Walter, L., & McKinnon, J. (2010a). Comparison of wheat-versus corn-based dried distillers' grains with solubles on meat quality of feedlot cattle. *Meat Science, 84*(3), 569–577.

Aldai, N., Dugan, M., Aalhus, J., McAllister, T., Walter, L., & McKinnon, J. (2010b). Differences in the trans-18: 1 profile of the backfat of feedlot steers fed wheat or corn based dried distillers' grains. *Animal Feed Science and Technology, 157*(3), 168–172.

Andersen, H. J., Oksbjerg, N., Young, J. F., & Therkildsen, M. (2005). Feeding and meat quality–a future approach. *Meat Science, 70*(3), 543–554.

AOAC. (1996). *Association of Official Analytical Chemists* (16th ed.). Gaithersburg, MD: Official Methods of Analysis.

Bekhit, A. E. D. A., Hopkins, D. L., Fahri, F. T., & Ponnampalam, E. N. (2013). Oxidative processes in muscle systems and fresh meat: Sources, markers, and remedies. *Comprehensive Reviews in Food Science and Food Safety, 12*(5), 565–597.

Benzie, I. F., & Strain, J. (1999). Ferric reducing/antioxidant power assay: Direct measure of total antioxidant activity of biological fluids and modified version for simultaneous measurement of total antioxidant power and ascorbic acid concentration. *Methods in Enzymology, 299*, 15–27.

Bessa, R. J., Alves, S. P., & Santos-Silva, J. (2015). Constraints and potentials for the nutritional modulation of the fatty acid composition of ruminant meat. *European Journal of Lipid Science and Technology, 117*(9), 1325–1344.

Bligh, E. G., & Dyer, W. J. (1959). A rapid method of total lipid extraction and purification. *Canadian Journal of Biochemistry and Physiology, 37*(8), 911–917.

Buttrey, E., Jenkins, K., Lewis, J., Smith, S., Miller, R., Lawrence, T., … MacDonald, J. (2013). Effects of 35% corn wet distillers grains plus solubles in steam-flaked and dry-rolled corn-based finishing diets on animal performance, carcass characteristics, beef fatty acid composition, and sensory attributes. *Journal of Animal Science, 91*(4), 1850–1865.

Buttriss, J. L., & Diplock, A. T. (1984). High-performance liquid chromatography methods for vitamin E in tissues. *Methods in Enzymology, 105*, 131–138.

Caine, W., Aalhus, J., Best, D., Dugan, M., & Jeremiah, L. (2003). Relationship of texture profile analysis and Warner-Bratzler shear force with sensory characteristics of beef rib steaks. *Meat Science, 64*(4), 333–339.

Campo, M., Nute, G., Hughes, S., Enser, M., Wood, J., & Richardson, R. (2006). Flavour perception of oxidation in beef. *Meat Science, 72*(2), 303–311.

Chao, M. D., Domenech-Pérez, K., & Calkins, C. (2017). Feeding vitamin E may reverse sarcoplasmic reticulum membrane instability caused by feeding wet distillers grains plus solubles to cattle. *The Professional Animal Scientist, 33*(1), 12–23.

Chao, M. D., Domenech-Pérez, K. I., Voegele, H. R., Kunze, E. K., & Calkins, C. R. (2018). Effects of dietary antioxidant supplementation of steers finished with 30% wet distillers grains plus solubles on fatty acid profiles and display life of strip loins. *Animal Production Science, 58*(10), 1949–1957.

Cherif, M., Valenti, B., Abidi, S., Luciano, G., Mattioli, S., Pauselli, M., … Salem, H. B. (2018). Supplementation of Nigella sativa seeds to Barbarine lambs raised on low-or high-concentrate diets: Effects on meat fatty acid composition and oxidative stability. *Meat Science, 139*, 134–141.

Corl, B. A., Baumgard, L. H., Dwyer, D. A., Griinari, J. M., Phillips, B. S., & Bauman, D. E. (2001). The role of Δ 9-desaturase in the production of cis-9, trans-11 CLA. *The Journal of Nutritional Biochemistry, 12*(11), 622–630.

De Huidobro, F. R., Miguel, E., Blázquez, B., & Onega, E. (2005). A comparison between two methods (Warner–Bratzler and texture profile analysis) for testing either raw meat or cooked meat. *Meat Science, 69*(3), 527–536.

De Mello, A., Jenschke, B., Senaratne, L., Carr, T., Erickson, G., & Calkins, C. (2018). Effects of finishing diets containing wet distillers grains plus solubles on beef quality attributes and fatty acid profile. *Meat Science, 136*, 16–22.

Depenbusch, B., Coleman, C., Higgins, J., & Drouillard, J. (2009). Effects of increasing levels of dried corn distillers grains with solubles on growth performance, carcass characteristics, and meat quality of yearling heifers. *Journal of Animal Science, 87*(8), 2653–2663.

Dilzer, A., & Park, Y. (2012). Implication of conjugated linoleic acid (CLA) in human health. *Critical Reviews in Food Science and Nutrition, 52*(6), 488–513.

Dixon, R., & Stockdale, C. (1999). Associative effects between forages and grains: Consequences for feed utilisation. *Australian Journal of Agricultural Research, 50*(5), 757–774.

Domenech-Pérez, K., Calkins, C., Chao, M., Semler, M., Varnold, K., & Erickson, G. (2017). Impact of feeding de-oiled wet distillers grains plus solubles on beef shelf life. *Journal of Animal Science, 95*(2), 709–717.

Dugan, M., Aldai, N., Kramer, J., Gibb, D., Juárez, M., & McAllister, T. (2010). Feeding wheat dried distillers grains with solubles improves beef trans and conjugated linoleic acid profiles. *Journal of Animal Science, 88*(5), 1842–1847.

Faustman, C., & Cassens, R. (1990). The biochemical basis for discoloration in fresh meat: A review. *Journal of Muscle Foods, 1*(3), 217–243.

Faustman, C., Sun, Q., Mancini, R., & Suman, S. P. (2010). Myoglobin and lipid oxidation interactions: Mechanistic bases and control. *Meat Science, 86*(1), 86–94.

Fritsche, S., & Fritsche, J. (1998). Occurrence of conjugated linoleic acid isomers in beef. *Journal of the American Oil Chemists' Society, 75*(10), 1449–1451.

Gill, R., VanOverbeke, D., Depenbusch, B., Drouillard, J., & DiCostanzo, A. (2008). Impact of beef cattle diets containing corn or sorghum distillers grains on beef color, fatty acid profiles, and sensory attributes. *Journal of Animal Science, 86*(4), 923–935.

Hayes, J., Stepanyan, V., Allen, P., O'Grady, M., O'Brien, N., & Kerry, J. (2009). The effect of lutein, sesamol, ellagic acid and olive leaf extract on lipid oxidation and oxymyoglobin oxidation in bovine and porcine muscle model systems. *Meat Science, 83*(2), 201–208.

He, M., Yang, W., Dugan, M., Beauchemin, K., McKinnon, J., & McAllister, T. (2012). Substitution of wheat dried distillers grains with solubles for barley silage and barley grain in a finishing diet increases polyunsaturated fatty acids including linoleic and alpha-linolenic acids in beef. *Animal Feed Science and Technology, 175*(3–4), 114–120.

Hood, D., & Riordan, E. (1973). Discolouration in pre-packaged beef: Measurement by reflectance spectrophotometry and shopper discrimination. *International Journal of Food Science & Technology, 8*(3), 333–343.

ISO. (2007). *International Standard ISO 8589: sensory analysis: General guidance for the design of test rooms*.

Jenkins, T., Wallace, R., Moate, P., & Mosley, E. (2008). Board-invited review: Recent advances in biohydrogenation of unsaturated fatty acids within the rumen microbial ecosystem. *Journal of Animal Science, 86*(2), 397–412.

Jiménez-Escrig, A., Jiménez-Jiménez, I., Pulido, R., & Saura-Calixto, F. (2001). Antioxidant activity of fresh and processed edible seaweeds. *Journal of the Science of Food and Agriculture, 81*(5), 530–534.

Klopfenstein, T. J., Erickson, G. E., & Bremer, V. R. (2008). Board-invited review: Use of distillers by-products in the beef cattle feeding industry. *Journal of Animal Science, 86*(5), 1223–1231.

Koger, T., Wulf, D., Weaver, A., Wright, C., Tjardes, K., Mateo, K., … Smart, A. (2010). Influence of feeding various quantities of wet and dry distillers grains to finishing steers on carcass characteristics, meat quality, retail-case life of ground beef, and fatty acid profile of longissimus muscle. *Journal of Animal Science, 88*(10), 3399–3408.

Liu, Q., Scheller, K., Arp, S., Schaefer, D., & Williams, S. (1996). Titration of fresh meat color stability and malondialdehyde development with Holstein steers fed vitamin E-supplemented diets. *Journal of Animal Science, 74*(1), 117–126.

Luthria, D. L., Liu, K., & Memon, A. A. (2012). Phenolic acids and antioxidant capacity of distillers dried grains with solubles (DDGS) as compared with corn. *Journal of the American Oil Chemists' Society, 89*(7), 1297–1304.

MacFie, H. J., Bratchell, N., Greenhoff, K., & Vallis, L. V. (1989). Designs to balance the effect of order of presentation and first-order carry-over effects in hall tests. *Journal of Sensory Studies, 4*(2), 129–148.

McGee, M. (2005). Recent developments in feeding beef cattle on grass silage-based diets. In R. S. Park, & M. D. Stronge (Eds.), *Proceedings of the XIVth international silage conference, July 2005, Belfast, Northern Ireland* (pp. 51–64).

McGee, M., Kelly, M. J., Kelly, A. K., & Moloney, A. P. (2019). Intake, growth, carcass and selected meat quality traits of steers offered grass silage and supplementary concentrates containing maize or wheat dried distillers grains. *Advances in Animal Biosciences, 10*(1), 62.

McKeown, L., Chaves, A., Oba, M., Dugan, M. E., Okine, E., & McAllister, T. (2010). Effects of corn-, wheat-or triticale dry distillers' grains with solubles on in vitro fermentation, growth performance and carcass traits of lambs. *Canadian Journal of Animal Science, 90*(1), 99–108.

Mello, A., Jenschke, B., Senaratne, L. S., Carr, T. P., Erickson, G. E., & Calkins, C. R. (2012). Effects of feeding modified distillers grains plus solubles on marbling attributes, proximate composition, and fatty acid profile of beef. *Journal of Animal Science, 90*(12), 4634–4640.

Mensink, R. P. (2005). Effects of stearic acid on plasma lipid and lipoproteins in humans. *Lipids, 40*(12), 1201–1205.

Min, Y., Li, L., Waldroup, P., Niu, Z., Wang, Z., Gao, Y., & Liu, F. (2012). Effects of dietary distillers dried grains with solubles concentrations on meat quality and antioxidant status and capacity of broiler chickens. *Journal of Applied Poultry Research, 21*(3), 603–611.

Moroney, N., O'Grady, M., O'Doherty, J., & Kerry, J. (2013). Effect of a brown seaweed (Laminaria digitata) extract containing laminarin and fucoidan on the quality and shelf-life of fresh and cooked minced pork patties. *Meat Science, 94*(3), 304–311.

Nade, T., Uchida, K., Omori, K., & Kimura, N. (2013). The effects of feeding a low level of distiller's dried grains with solubles (DDGS) to yearling H olstein steers. *Animal Science Journal, 84*(6), 476–482.

O'Grady, M., Monahan, F., Burke, R., & Allen, P. (2000). The effect of oxygen level and exogenous α-tocopherol on the oxidative stability of minced beef in modified atmosphere packs. *Meat Science, 55*(1), 39–45.

O'Kiely, P. (2011). Intake, growth and feed conversion efficiency of finishing beef cattle offered diets based on triticale, maize or grass silages, or ad libitum concentrate. *Irish Journal of Agricultural and Food Research*, 189–207.

O'Sullivan, M., Byrne, D., & Martens, M. (2003). Evaluation of pork colour: Sensory colour assessment using trained and untrained sensory panellists. *Meat Science, 63*(1), 119–129.

Palmquist, D. L., Lock, A. L., Shingfield, K. J., & Bauman, D. E. (2005). Biosynthesis of conjugated linoleic acid in ruminants and humans. *Advances in Food and Nutrition Research, 50*, 179–217.

Park, P., & Goins, R. (1994). In situ preparation of fatty acid methyl esters for analysis of fatty acid composition in foods. *Journal of Food Science, 59*(6), 1262–1266.

Qwele, K., Hugo, A., Oyedemi, S., Moyo, B., Masika, P., & Muchenje, V. (2013). Chemical composition, fatty acid content and antioxidant potential of meat from goats supplemented with Moringa (Moringa oleifera) leaves, sunflower cake and grass hay. *Meat Science, 93*(3), 455–462.

Salami, S., Guinguina, A., Agboola, J., Omede, A., Agbonlahor, E., & Tayyab, U. (2016). In vivo and postmortem effects of feed antioxidants in livestock: A review of the implications on authorization of antioxidant feed additives. *Animal, 10*(8), 1375–1390.

Salami, S., Luciano, G., O'Grady, M., Biondi, L., Newbold, C., Kerry, J., & Priolo, A. (2019). Sustainability of feeding plant by-products: A review of the implications for ruminant meat production. *Animal Feed Science and Technology, 251*, 37–55.

Salami, S., O'Grady, M., Luciano, G., Priolo, A., McGee, M., Moloney, A., & Kerry, J. (2020). Quality indices and sensory attributes of beef from steers offered grass silage and a concentrate supplemented with dried citrus pulp. *Meat Science*, 168. https://doi.org/10.1016/j.meatsci.2020.108181.

Schoonmaker, J., Trenkle, A., & Beitz, D. (2010). Effect of feeding wet distillers grains on performance, marbling deposition, and fatty acid content of beef from steers fed low- or high-forage diets. *Journal of Animal Science, 88*(11), 3657–3665.

Segers, J., Stewart, R., Lents, C., Pringle, T., Froetschel, M., Lowe, B., … Stelzleni, A. (2011). Effect of long-term corn by-product feeding on beef quality, strip loin fatty acid profiles, and shelf life. *Journal of Animal Science, 89*(11), 3792–3802.

Singleton, V. L., Orthofer, R., & Lamuela-Raventós, R. M. (1999). Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent. *Methods in Enzymology, 299*, 152–178.

Siu, G., & Draper, H. (1978). A survey of the malonaldehyde content of retail meats and fish. *Journal of Food Science, 43*(4), 1147–1149.

Smith, S., Kawachi, H., Choi, C., Choi, C., Wu, G., & Sawyer, J. (2009). Cellular regulation of bovine intramuscular adipose tissue development and composition. *Journal of Animal Science, 87*, E72–E82.

Torres, E. P., Rios, H. G., Lagarda, T. I., Melendres, M. V., Ramos, A. P., Garcia, L. Z., … Ramirez, J. D. (2016). Ferulic acid in diets of heifers and its effect on the oxidative stability of meat stored in refrigeration. *Journal of Animal Science, 94*, 431–432.

Ulbricht, T., & Southgate, D. (1991). Coronary heart disease: Seven dietary factors. *The Lancet, 338*(8773), 985–992.

Vander Pol, K. J., Luebbe, M. K., Crawford, G., Erickson, G. E., & Klopfenstein, T. J. (2007). Digestibility, rumen metabolism, and site of digestion for finishing diets containing wet distillers grains or corn oil. *Nebraska Beef Cattle Report, MP90*, 39–42.

Vasta, V., & Luciano, G. (2011). The effects of dietary consumption of plants secondary compounds on small ruminants' products quality. *Small Ruminant Research, 101*(1), 150–159.

Xu, L., Jin, Y., He, M., Li, C., Beauchemin, K., & Yang, W. (2014). Effects of increasing levels of corn dried distillers grains with solubles and monensin on ruminal biohydrogenation and duodenal flows of fatty acids in beef heifers fed high-grain diets. *Journal of Animal Science, 92*(3), 1089–1098.

Yang, W., & Li, Y. (2017). In R. Wanyera (Ed.), *Use of wheat distiller grains in ruminant diets wheat improvement, management and utilization*. InTech. https://doi.org/10.5772/67113.

Yen, G. C., & Wu, J. Y. (1999). Antioxidant and radical scavenging properties of extracts from Ganoderma tsugae. *Food Chemistry, 65*(3), 375–379.