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Review article

Utilisation of canola meal as protein source in dairy cow diets: a review

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Abstract

Growth in food consumption demand since 2005 has steadily driven increases in canola production. Crushing of canola generates valuable commodities including high-value meal traded worldwide as a protein source. Due to its balanced amino acid profile and high digestibility, canola meal is supplemented into dairy cattle feed to optimise milk protein synthesis and lactation output. This review provides an overview of canola meal, including production techniques, protein characteristics, methods to quantify protein quality and factors contributing to variation of rumen-undegraded protein content. To assist dairy industries to reduce N wastes, this review consolidates current understanding of dairy cattle lactation performance in response to dietary supplementation of canola meal. The effects of processing conditions, levels of rumen-undegraded protein, and lactation response to canola meal relative to other protein sources are evaluated. Novel physical and chemical treatments developed to increase post-ruminal supply of canola meal protein for animal utilisation are examined.

Introduction

The term ‘canola’ (Canadian oil, double-zero rapeseed) is a registered trademark introduced in 1978 to differentiate rapeseed plant varieties including *Brassica napus*, *B. rapa* (*B. campestris*), and *B. juncea* cultivated to produce oil with less than 2% erucic acid and less than 30 micromoles of glucosinolates per g oil-free meal. The seed of these *Brassica* spp. is small, round and 1−2 mm in diameter. Whole seeds contain approximately 37.2−49.6% oil (at 6% moisture) and 21−23% protein (seed dry weight). Canola is an economically important oilseed crop grown by 63 countries worldwide (Nadathur et al., 2017). Since 2005, increases in food consumption have driven the growth of canola production (ABARES, 2015). In 2019, 68.2 million t of canola was produced globally. Major producers of canola seed include the European Union, Canada, China, and India (USDA, 2020a). Seasonal conditions affect canola yield; for example, production in drought years declined by 0.6 t/ha (ABARES, 2015). To extract seed oil and generate meal, solvent-based and mechanical processes exist (DPI, 2014). Following oil extraction, the residual meal contains 33.3−43.7% crude protein (CP), depending on the extraction method used (Seberry et al., 2014). The amino acid (AA) profile of canola meal has been extensively reviewed and published (Table 1). Crushing of canola yields valuable commodities, including: oil for retail, food services, manufacturing, and renewable fuel industries; and, meal traded worldwide as a protein source for aquaculture, and poultry, porcine, beef and dairy cattle industries (Newkirk, 2009; Nadathur et al., 2017). Canola meal protein isolates show potential for human food applications (Nadathur et al., 2017).

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Table 1 Amino acid composition of canola meal from published literature

Item (% of CP)	Newkirk*	Paz†	Archarya‡	Paula§
Histidine	3.11	2.66	1.15	2.52
Isoleucine	4.33	3.90	1.67	3.53
Leucine	7.06	7.07	3.04	6.39
Lysine	5.56	5.36	2.38	4.87
Methionine	2.06	1.94	0.89	1.88
Phenylalanine	3.83	4.03	1.74	3.74
Threonine	4.39	4.13	1.96	3.87
Tryptophan	1.33	1.39	0.47	1.35
Valine	5.47	5.14	2.33	4.47
Arginine	5.78	5.93	2.54	5.90
Total essential AA	43.20	41.50	15.80	39.30
Alanine	4.36	4.36	1.92	4.43
Glycine	4.92	5.04	2.23	5.13
Proline	5.97	6.11	2.66	6.20
Serine	4.00	3.55	1.66	4.12
Tyrosine	3.22	2.71	1.17	2.90
Glutamate + glutamine	18.10	16.50	7.23	22.70
Cysteine	2.39	2.29	1.04	2.43
Aspartate + asparagine	7.25	6.88	3.20	7.34
Total non-essential AA	50.30	47.40	21.80	49.00

CP = crude protein; AA = amino acid

* Canola meal (% of CP) (Newkirk, 2009)

† Canola meal (% of CP) (Paz et al., 2014)

‡ Canola meal (%Total AA) (Acharya et al., 2015)

§ Canola meal (%Total AA) (Paula et al., 2019).

Processing of canola seed to produce oil and meal

In 2019, 38.7 million t of canola meal was produced globally (USDA, 2020b). Canola seed is traditionally processed by pre-press solvent-extraction. This process uses solvent-extraction to separate the oil from the meal. The stages of solvent-extraction include seed handling, cleaning, air aspiration (exit temperature at approximately 52°C), conditioning (30−78°C, 30−40 min), flaking, cooking (75−120°C, at an approximate optimum of 88°C, 15−40 min), expelling, solvent-extraction (50−60°C, 90 min), desolventiser-toasting using steam-injection to remove solvent (95−160°C, 30−60 min), cooling, air-blowing, granulating and then pelleting or storage as mash (AOF, 2007; Newkirk, 2009). Crushing plants in cooler climates may pre-heat (at approximately 35°C) stored seed entering the flaking unit utilising grain dryers to prevent seed shattering (Unger, 1990). During cooking, seed flakes pass through a series of steam-heated drum or stack-type cookers to thermally rupture oil cells, reduce oil viscosity and encourage coalescence of oil droplets. Phospholipid material removed from the extracted crude oil, termed 'gum', can be added to the meal at 1−2% after desolventiser-toasting. The gum functions reduce dustiness of meal and increase metabolisable energy values for dairy cattle maintenance and milk production (NRC, 2001).

Expeller oil extraction uses moderate temperatures (95−135°C) to generate meal with 36.8% protein and 8−15% oil (Leming and Lember, 2005; AOF, 2007; Newkirk, 2009). Increasing rotation speed in a pilot-scale screw press (0−40 kg/hr, 0−18.2 rpm) enhanced press capacity, and reduced passage time, extraction yield and energy consumption (Bogaert et al., 2018). Screw press geometry was sectioned into functional categories of feed, compression and mixing/relaxation. High pressure in the compression sections led to oil extraction and the formation of hard cake. In the mixing sections, press-cake became friable due to a drop of pressure to zero. Inside the screw press cage an oil reflux phenomenon occurred. Double-press expelling has lower capital costs than solvent-extraction and is common practice by smaller refineries, biodiesel plants, or in regions with limited canola access. During cold-press oil extraction, seeds are mechanically pressed at low heat (≤ 65°C) from frictional forces in the barrel (Leming and Lember, 2005; AOF, 2007). Extrusion involves passing seed through a set of dies under high-pressure heat with steam (Woodroofe and Cockbill, 2000).

Characteristics and utilisation efficiency of canola meal protein for dairy cow diets

The value of canola and rapeseed meal protein as a feed source has been investigated in dairy cattle, as reviewed by Newkirk (2009). Canola meal contains adequate protein concentrations and an AA profile suitable for dairy cattle (Brito and Broderick, 2007). Martineau et al. (2013) reviewed the milk yield responses of dairy cattle to dietary inclusion of canola meal. Broadening existing knowledge of the effect of canola meal's protein composition on dairy cattle milk production may assist dairy industries to reduce N wastes without compromising animal production.

Trading standards to define the price of canola meal include percent protein, oil, moisture, fibre, glucosinolates and contaminants (AOF, 2020; COPA, 2020). The protein content of canola meals vary with seasonal conditions, harvest year and rainfall and inversely relate to oil levels (Si et al., 2003). Literature analysis revealed broad ranges of CP (32.9−45.9% dry matter (DM)), intestinal CP digestibility (71.6–77.4%), and total CP digestibility (85.1−90.8%) in canola meals (Table 2). The mean metabolisable protein (MP) content of canola meal was reported as 92 g/kg DM (Huhtanen et al., 2011). Inconsistent CP content (34.8−45.9% at 10% moisture in oil-free meal) in Australian canola meal was associated with agronomic and processing technique variations (DPI, 2014).

Solubility and fractionation of canola meal

Almost 90% of the proteins in canola are storage proteins, consisting of 60% cruciferin (11S globulin) and 20% napin (1.7−2S albumin) and non-storage proteins, incorporating oil body proteins (caleosin, oleosin, and steroleosin), trypsin inhibitors, and lipid transfer proteins (Wanasundara, 2011). Literature analysis revealed soluble CP content in rapeseed and canola meal range from 24.6−34.8% and Cornell Net Carbohydrate and Protein System fractions (%CP) in order of abundance range from: intermediately degraded (B2, 34.4−61.8); rapidly degraded (B1, 7.54−34.1); non-protein N (A, 4.93−27.2); slowly degraded (B3, 0.80−20.9); and, undegraded (C, 3.32−13.7) (Table 3). *In situ* protein degradation parameters (%CP) reported by Ørskov et al. (1980) indicate canola meal consists more of potentially degraded CP (B, 62.4−83.0) than rapidly degraded CP (A, 11.8−29.0) and undegraded CP (C, 1.50−14.6).

Rumen degraded and undegraded protein characteristics

Analysis of feed library data shows *in vitro* rumen degraded protein (RDP) and rumen-undegraded protein (RUP) content of canola meal ranged from 38.9−61.3 % CP and 38.7−61.1 %CP (*n* = 391), respectively (DairyOne, 2016). Literature analysis found the RUP content of canola meal varied broadly from 10.1−75.0 % CP (NRC, 2001; Woodroofe and Purser, 2004). *In vitro* RUP content of canola meal samples (*n* = 144) collected during 2011−2014 from 12 Canadian (solvent-extraction (*n* = 11) and expeller (*n* = 1)) plants varied from 43−51% (Broderick et al., 2016). *In situ* RUP content of canola meal from 7 Canadian (solvent-extraction (*n* = 6) and mechanical-extraction (*n* = 1)) plants ranged from 31.0−53.8 %CP (Jayasinghe et al., 2014). Paz et al. (2014) noted RUP content of canola meal was lower *in situ* (24.3 %CP) than when measured *in vitro* by ammonia release (27.1−37.1 %CP). Ruminal degradability of canola and rapeseed meal protein has been evaluated *in situ* utilising steers (McKinnon et al., 1995; Homolka et al., 2007), non-lactating (Theodoridou and Yu, 2013a, b) and lactating dairy cattle (Johansson and Nadeau, 2006; Stockdale, 2008; Hristov et al., 2011; Maxin et al., 2013). Canola meal proteins are extensively degraded in the rumen (Khorasani et al., 1993). Electrophoretic analysis of canola meal incubated in the rumen of Holstein steers revealed napin protein subunits disappeared at the commencement of incubation, while cruciferin were resistant to degradation until 24 hr of incubation (Sadeghi and Shawrang, 2007). Comparisons between studies are challenged by inherent animal variation, differences in experimental designs, feeding strategies and materials.

Table 2 Protein composition of canola meal from published literature

Component*	NRC[†]	Jayasinghe[‡]	Chrenkova[§]	Maxin[¶]	Shannak[#]	Xin & Yu**
Crude protein (%DM)	37.8±1.10 (*n* = 230)	–	36.7±3.84	40.1	35.8	40.4
Buffer soluble protein (%CP)	–	–	25.5±0.87	25.3	–	34.8
ADICP (%CP)	2.40±0.70 (*n* = 19)	–	–	7.7	–	1.34
NDICP (%CP)	6.30±2.50 (*n* = 16)	–	–	16.7	–	6.91
In situ RUP (%CP)	26.6	32.3–53.8	–	52.2	17.8–30.3	–
Intestinal CP digestibility	–	71.6–77.4	–	–	–	–
Total CP digestibility	–	85.1–90.8	–	–	–	–
In situ effective degradability CP	–	–	–	47.5	–	–

* DM = dry matter; CP = crude protein; ADICP = acid-detergent insoluble CP; NDICP = neutral-detergent insoluble CP; RUP = rumen-undegraded protein

[†] Mechanically extracted: conducted in lactating dairy cattle; values are mean±SD (NRC, 2001)

[‡] Conducted in lactating dairy cattle; SE of the mean = 1.32 (*n* = 7) (Jayasinghe et al., 2014)

[§] Solvent-extracted rapeseed meal: conducted in cows; values are mean±SD of three biological determinations (Chrenkova et al., 2014)

[¶] Solvent-extracted canola meal: conducted in Holstein dairy cattle; values are mean±SD (Maxin et al., 2013)

[#] Expeller rapeseed meal: conducted in steers (Shannak et al., 2000)

** Conducted *in vitro* (Xin and Yu, 2013)

Table 3 Protein fractions of canola meal from feed libraries and published literature, as determined by the Cornell Net Carbohydrate and Protein System (CNCPS; Sniffen et al., 1992) and *in situ* Ørskov et al. (1980) protein degradation parameters

Component	Protein fraction	Maxin*	NRC†	Jayasinghe‡	Chrenkova§	Shannak¶	Xin & Yu#	Ramirez-Bribiesca**
CNCPS (%CP)								
A	Non-protein N	–	–	–	6.6±1.67	7.2	27.2	14.1–18.2
B1	Rapidly degraded true protein, Soluble CP – A	–	–	–	19.2±1.03	34.1	7.54	20.9–21.8
B2	Intermediately degraded true protein, 100 – A + B1 + B3 + C	–	–	–	60.4±0.68	51.9	48.1	34.4–37.2
B3	Slowly degraded cell-wall associated true protein, NDIP – ADIP	–	–	–	2.50±0.19	0.80	13.8	12.9–20.9
C	Indigested bound protein, ADICP Heat-damaged protein and nitrogen associated with lignin	–	–	–	11.6±1.59	5.90	3.32	6.07–13.7
In situ								
A	Rapidly degraded CP	12.9±1.07	23.2±5.80 (n = 22)	17.8–26.6	–	–	–	–
B	Potential degraded CP	80.1±2.91	70.4±7.00 (n = 22)	62.4–79.9	–	–	–	–
C	Undegraded CP	–	6.40±5.40 (n = 22)	1.50–14.6	–	–	–	–
Kd	Degradation rate of (%/hr) of B	0.06±0.01	10.4	4.00–9.70	–	–	–	–

CP = crude protein; NDIP = neutral-detergent insoluble protein; ADIP = acid-detergent insoluble protein; ADICP = acid-detergent insoluble CP
* Solvent-extracted canola meal: conducted in Holstein dairy cattle; values are mean±SD (Maxin et al., 2013)
† Mechanically extracted: conducted in lactating dairy cattle; values are mean±SD (NRC, 2001)
‡ Conducted in lactating dairy cattle; SE of the mean = 1.32 (n = 7) (Jayasinghe et al., 2014)
§ Solvent-extracted canola meal: conducted in cows; values are mean±SD of three biological determinations (Chrenkova et al., 2014)
¶ Expeller rapeseed meal: conducted in steers (Shannak et al., 2000)
# Conducted *in vitro* (Xin and Yu, 2013)
** Conducted *in vitro* with cold-press and solvent-extracted canola meal (Ramirez-Bribiesca et al., 2017)

Monitoring of protein quality for ruminants

The protein content of canola meal is generally quantified by titration (AOAC, 2005a), N combustion (AOAC, 2005b) and near-infrared spectroscopy (AOF, 2008). To evaluate protein quality of rapeseed meal protein solubility in 0.2% (Anderson-Hafermann et al., 1993) and 0.5% KOH (Pastuszewska et al., 1998) have been used. Pastuszewska et al. (1998) reported strong correlation (r = 0.95) between 0.5% KOH solubility and available lysine, to develop a predictor of over-processing of oilseed meal. Using molecular spectroscopy, correlation between changes in the protein structure of press-cake, extruded and solvent-extracted canola meal with ruminal degradability in dairy cattle have been reported (Theodoridou and Yu, 2013a; Peng et al., 2014). The amide II area and β-sheet height were good predictors of digestible protein contents (Peng et al., 2014); and, the ratio of amide I to II positively correlated (R = 0.99, $p < 0.01$) with the immediately solubilised protein (A) and with slowly ruminally degraded protein (B3) (Theodoridou and Yu, 2013a). Studies of canola seed (Samadi et al., 2013), and tissue (Yu, 2013) characterised changes in molecular protein structure from dry heat and moist heat pressure (MHP) treatments. Samadi et al. (2013) reported dry heating (120°C, 1 hr) or MHP treatment (120°C, 1 hr) of canola seeds increased ($p < 0.0001$) and decreased ($p < 0.0001$) the ratio of α-helix to β-sheet, respectively. The microscopic structure of solvent-extraction rapeseed meal was characterised by Yiu et al. (1983).

Factors contributing to variation of ruminal undegraded protein in canola meal

Canola species

In Canada and Australia, harvested canola (*B.* spp. *napus*, *rapa* and *juncea*) seed is pooled to form heterogeneous lots (of species and cultivar) for trade and meal production (AOF, 2020; CCC, 2015). Theodoridou and Yu (2013b) observed variance in RUP content between solvent-extraction meals of *B. napus* (black and brown) and *B. juncea* (yellow). Although hundreds of canola cultivars are grown globally (AOF, 2015), limited knowledge exists of the ruminal protein digestibility within germplasm and resultant meals.

Different oil extraction techniques

Deacon et al. (1988) proposed heat during expeller and solvent-extraction, unlike cold-press, induced the formation of insoluble peptide chain and carbohydrate complexes, which contribute to greater RUP content in these meals. During solvent-extraction, desolventer-toasting induces Maillard browning reactions (Newkirk et al., 2003). Mustafa et al. (2000) reported stages prior to solvent oil extraction had minimal effect on canola meal *in vitro* CP digestibility (IVCPD); where expelling increased CP and reduced IVCPD relative to initial seed and desolventiser-toasting decreased CP solubility and IVCPD compared to the prior solvent-extraction meal. Cooking of canola meal (90°C, 20−30 min) reduced digestible CP and desolventier-toasting decreased the uniformity, quality and digestible AA content (Newkirk et al., 2003). Broderick et al. (2016) reported *in vitro* RUP content of Canadian canola meal did not vary among 2011−2014 harvests, however, varied by 8% among an expeller and 11 solvent-extraction plants.

The CCC (2015) noted the effects of friction-associated heat (≤ 160°C) during expelling can be minimised by low moisture content and short duration to retain protein quality; and, delayed cooling after extraction may affect protein quality. Deacon et al. (1988) reported extrusion of canola seed had nil effect on RUP or total tract CP disappearance and noted responses were subjective to proportions of albumins, globulins and other proteins. Santos et al. (2012) found extrusion of canola seed increased ($p < 0.05$) protein availability in the small intestine of ruminants relative to control seed.

Approaches to increase canola meal post-ruminal protein supply for dairy cows

To increase RUP content in livestock feeds, physical treatments function to protect dietary protein from ruminal degradation and include micronisation, microwave irradiation, dry heat, moist heat with or without pressure, and coating with resistant materials such as whey protein and casein. Physical treatments reported to increase canola meal post-ruminal protein supply for dairy cows are summarised below and outlined in Table 4.

Micronisation applies infrared light to expose feeds to rapid surface and internal heating. Wang et al. (1997) reported micronisation of canola meal reduced ($p < 0.01$) ruminal CP degradability. Microwave irradiation (4 min, 800 W) of canola meal reduced ($p < 0.001$) *in sacco* ruminal degradation of CP and increased resistance of cruciferin and napin subunits to ruminal degradation (Sadeghi and Shawrang, 2007).

Dry heating of oilseeds denatures the protein matrix surrounding fat droplets, thereby protecting dietary fatty acids from biohydrogenation by ruminal bacteria (Kennelly, 1996). Prolonged forced-air oven heat (110°C, 2 hr) reduced ($p < 0.05$) protein degradability of canola meal (Mir et al., 1984). Short to moderate term dry heat (125°C, 10−30 min) reduced ($p < 0.01$) ruminal degradation of CP in canola meal without increasing indigestible protein (McKinnon et al., 1995). However, ruminal degraded protein content was similar when heifers were fed dry heat treatment high-RUP canola meal (55 %CP) relative to cold-press canola cake from biodiesel oil extraction (Gozho et al., 2009).

Moist heat pressure treatment (117 kPa 127°C, 15 min) decreased ($p < 0.01$) ruminal degradability and increased ($p < 0.01$) intestinal availability of canola meal protein relative to untreated meal (Moshtaghi Nia and Ingalls, 1992) and increased ($p < 0.01$) RUP-AA for small intestine digestion (Moshtaghi Nia and Ingalls, 1995). A patented cooker-extruder process of heat, pressure and shear force with carbohydrate addition increased canola meal RUP content from 8 %CP to 50 %CP (Woodroofe and Cockbill, 2000).

To increase RUP content in livestock feeds, chemical treatments function to combine with or denature protein structure. Chemical treatments reported to increase canola meal post-ruminal protein supply for dairy cows are summarised below and outlined in Table 5.

Table 4 Physical treatments to increase canola meal post-ruminal protein supply for dairy cows

Treatment	Function	Method and result	p	Reference
Micronisation	Exposes feed to rapid surface and internal heating	Reduced ruminal CP degradability	< 0.01	Wang et al. (1997)
		Microwave irradiation (4 min, 800 W) reduced *in sacco* ruminal degradation of CP and increased resistance of cruciferin and napin subunits to ruminal degradation	< 0.001	Sadeghi and Shawrang (2007)
Dry heating	Denatures protein matrix surrounding fat droplets. Protects dietary fatty acids from biohydrogenation by ruminal bacteria.	Prolonged forced-air oven heat (110°C, 2 hr) reduced protein degradability	< 0.05	Mir et al. (1984)
		Short to moderate term dry heat (125°C, 10–30 min) reduced ruminal degradation of CP without increasing indigestible protein	< 0.01	McKinnon et al. (1995)
Moist heat pressure	Concurrent use of heat, pressure and shear force	Autoclave treatment (117 kPa 127°C, 15 min) decreased ruminal degradability and increased intestinal availability of protein relative to untreated	< 0.01	Moshtaghi Nia and Ingalls (1992)
		Autoclave treatment (117 kPa 127°C, 15 min) increased RUP-AA for small intestine digestion	< 0.01	Moshtaghi Nia and Ingalls (1995)
	Utilises reaction between proteins and reducing carbohydrate to protect protein from ruminal degradation	Cooker-extruder with carbohydrate addition increased RUP from 8 %CP to 50 %CP		Woodroofe and Cockbill (2000)

CP = crude protein; RUP = rumen-undegraded protein; AA = amino acid

Table 5 Chemical treatments to increase canola meal post-ruminal protein supply for dairy cows

Treatment	Function	Method and result	p	Reference
Formaldehyde	Reduces rumen degradability by forming reversible cross-linkages with AAs and amide groups of protein	Treatment (8 g/kg CP) decreased protein degradability from 42.8% to 19.8%	< 0.05	Mir et al. (1984)
		Treatment (15 g/kg meal) reduced *in situ* ruminal protein degradability from 65.5% to 22.2%	< 0.05	Ha and Kennelly (1984)
Acid	Induces structural changes to reduce susceptibility to intestinal enzymes and improve post-ruminal resistance	Spraying with glacial acetic acid (17.5 M/L), formic acid (19.5 M/L), propionic acid (13.4 M/L) at 2.5% or 5% (v/w), then drying (105°C, 20 hr), decreased CP solubility and ruminal degradability. No adverse effect on true intestinal RUP digestibility.	< 0.05	Khorasani et al. (1989)
Alkali	Modification of protein structure to decrease protease specific bonds cleaved by microbial enzymes	Treatment (50% NaOH, 30 g/kg CP) reduced ruminal protein degradation without negatively impacting true protein digestibility	< 0.05	Mir et al. (1984)
		Lignosulfonate then moist heat increased *in situ* ruminal bypass protein from 32 %CP to 70−79 %CP, with no adverse effect on intestinal digestibility.		Mason (2002)

CP = crude protein; RUP = rumen-undegraded protein; AA = amino acid

Formaldehyde treatment reduces rumen degradability of oilseed meal by forming reversible cross-linkages with AAs and amide groups of protein. Acidic conditions of the abomasum may break linkages; however, formation of irreversible linkages may provide resistance to enzymatic digestion. Formaldehyde treatment (8 g/kg CP) of canola meal decreased ($p < 0.05$) protein degradability from 42.8% to 19.8% (Mir et al., 1984); formaldehyde treatment (15 g/kg meal) of canola meal reduced ($p < 0.05$) *in situ* ruminal protein degradability from 65.5% to 22.2% (Ha and Kennelly, 1984).

Structural changes induced by acid treatment of canola meal can reduce susceptibility to intestinal enzymes and improve post-ruminal resistance. Spraying canola meal with glacial acetic acid (17.5 M/L), formic acid (19.5 M/L) or propionic acid (13.4 M/L) at either 2.5% or 5% (v/w) followed by drying (105°C, 20 hr), decreased ($p < 0.05$) CP solubility and ruminal degradability with no adverse effect on true intestinal digestibility of RUP (Khorasani et al., 1989). In comparison, spraying canola meal with formic acid or soaking with acetic acid (30 mL/kg DM, air dry 3 hr) did not affect CP digestibility (McKinnon et al., 1991). Subsequently, McKinnon et al. proposed acid and heat were required to decrease ruminal CP degradability.

Alkali treatment (50% NaOH, 30 g/kg CP) of canola meal reduced ($p < 0.05$) ruminal protein degradation without negatively impacting true protein digestibility (Mir et al., 1984). Lignosulfonate moist heat treatment canola meal increased *in situ* ruminal bypass protein from 32 %CP to 70−79 %CP, with no adverse effect on intestinal digestibility (Mason, 2002).

Effects of using canola meal in diet on milk yield of dairy cows

Impact of oil extraction technique

Studies report dietary inclusion of canola meal from different processing techniques can alter milk output in high-producing dairy cattle. For example, replacement of solvent-extraction canola meal with mechanical extraction canola or rapeseed meal decreased ($p < 0.05$) milk production by 2.2 kg/d and 2.1 kg/d, respectively (Hristov et al., 2011). Decreased milk yield was due to lowered feed intake through energy intake regulation or palatability by the high-producing cows.

Dietary inclusion of cold-press rapeseed meal increased ($p < 0.05$) milk yield by 3 kg/d relative to a protein supplement (Johansson and Nadeau, 2006). The authors referenced milk yield as reliant on the synchronisation of carbohydrate and protein degradation for optimal fermentation and efficient synthesis of rumen microbial protein (Børsting et al., 2003). Similar milk production by dairy cows fed mixed rations supplemented with either cold-pressed rapeseed cake or full-fat rapeseed, implied initial increases in milk yield were not associated with processing method (Johansson et al., 2015). Indifference of milk yield by dairy cows after dietary inclusion of extruded canola seeds suggested that responses in milk yield are due to protein as opposed to energy (Neves et al., 2009).

Contribution of rumen-undegraded protein

As rapeseed concentrate CP level increased (low versus high) in silage-based dairy cow diets, milk yield also increased (30.8 kg/d verses 32.0 kg/d) (Puhakka et al., 2016). Increased rapeseed concentrate enabled a greater supply of essential AAs or a more balanced AA profile, which in turn may have increased the energy demand, DM intake (DMI) and production. Improved milk yield with canola meal supplementation has been attributed to the RUP-AA profile of canola meal being complementary to microbial protein (Brito and Broderick, 2007), as well as increasing MP supply including essential AAs, particularly histidine, lysine and methionine (Broderick and Colombini, 2010). However, Broderick and Faciola (2014) reported milk yield by dairy cows was not statistically different after dietary inclusion of rapeseed meal with rumen-protected methionine and lysine, suggesting that increased supply of these particular AA does not fully explain the milk yield response. The RUP content of canola meal does not necessarily impact milk yield response, as Woodroofe and Purser (2004) reported milk yield by high-producing dairy cows was similar after long-term dietary inclusion of low-RUP (10.1 %CP) and high-RUP (70.0 %CP) canola meal. Incorporating larger quantities of feed was foreseen to increase milk yield; consequently, evaluating the impact of RUP levels in feed at very early and late stages of lactation was recommended.

Impact of physical and chemical treatments

Dietary inclusion of dry heat treatment (125°C, 20 min) canola meal increased ($p < 0.05$) milk yield in primiparous cows (Jones et al., 2001). Dietary inclusion of mechanically extracted heat-pressure treatment or mechanically extracted canola meal pellets, increased ($p < 0.05$) dairy cattle production (34.0 kg milk/d and 33.3 kg milk/d, respectively) relative to a control supplement (30.5 kg milk/d), and was related to improved use of metabolisable energy (Stockdale, 2008). Milk yields by dairy cattle were not statistically different following dietary inclusion of solvent-extraction canola meal treated with (35.3 kg/d) or without (34.8 kg/d) MHP (hydrothermal cooking, 2% H_20, 100°C, 120 min) (Wright et al., 2005). Likewise, Paula et al. (2018) found milk yield by dairy cattle was similar following dietary inclusion of solvent-extraction canola meal with (41.3 kg/d) or without MHP treatment then extrusion (40.5 kg/d). In contrast, Gidlund et al. (2015) reported an increase ($p < 0.05$) of milk yield (2.3 kg/d) when control meal was replaced by MHP treatment solvent-extracted canola meal, was due to lower ruminal CP degradability and calculated MP intake. The inclusion of lignosulfonate-treatment canola meal in dairy cattle diets did not affect milk yield (Neves et al., 2009; Santos et al., 2012), and was attributed to reduced AA availability (Rae et al., 1983). Mason (2002) reported addition of lignosulfonate MHP canola meal in dairy cow diets increased milk yield by 1.8 kg/d, stating the meal was used more efficiently and was an effective source of bypass protein. Furthermore, Wright et al. (2005) found addition of 5% lignosulfonate then dry heat (100°C, 120 min) treatment solvent-extracted canola meal in silage-based dairy cattle diets increased ($p < 0.05$) milk yield by 1.8 kg/d. The treatment effectively increased the proportion of CP digested in the lower digestive tract of lactating cows, and therefore, was used more effectively as a source of protein.

Comparisons with other feed sources

A meta-analysis of 292 treatment means from 122 studies found dietary inclusion of canola meal (3.49 kg/d) or heat-treatment canola meal (3.79 kg/d) produced larger ($p < 0.01$) daily milk yield responses than soybean meal (2.19 kg/d) (Huhtanen et al., 2011). Improved performance was partially attributed to enhanced energy as opposed to protein, where the contribution of higher CP concentration could not be ruled out. Milk yield was not statistically different when canola meal replaced soybean meal (Brito and Broderick, 2007; Jayasinghe et al., 2014), cottonseed meal (Sánchez and Claypool, 1983; Brito and Broderick, 2007), dried distillers grains (Acharya et al., 2015), dried distillers grains with solubles (Mulrooney et al., 2009) and wheat-based dried distillers grains with solubles (Chibisa et al., 2012; Mutsvangwa et al., 2016). Inclusion of rapeseed meal in cows fed grass silage-based diets increased ($p < 0.001$) milk yield by 3.1 kg/d relative to fava bean (Puhakka et al., 2016), in part due to decreased silage DMI in the fava bean diet. Replacing rapeseed meal with fava bean in total mixed ration diets of dairy cattle reduced milk yield by 2.5 kg/d and was attributed to poorer value of fava bean protein than rapeseed protein for milk production (Lamminen et al., 2019). Increased milk yield by dairy cattle fed canola meal versus corn dried distillers grains with solubles was associated with differences in available absorbable AA (Swanepoel et al., 2014). Replacing solvent-extracted soya-bean meal with heat-treated expeller rapeseed meal in grass-silage dairy cow diets elicited a higher ($p < 0.01$) milk yield response (Shingfield et al., 2003). Replacing solvent-extraction soybean meal with solvent-extraction canola meal in corn silage, alfalfa-based cattle diets increased ($p < 0.05$) milk yield by 1.1 kg/d (Broderick et al., 2015). The increase was associated with decreased ruminal ammonia and branched-chain volatile fatty acids, indicating lower ruminal degradation of canola meal protein.

Supplementation with expeller rapeseed meal in cows fed clover/grass silage-based diets increased ($p < 0.01$) energy-corrected milk yield by 2.1 kg/d relative to expeller soybean meal (Rinne et al., 2015). A meta-analysis by Martineau et al. (2013) of 49 isonitrogenous experiments substituting canola meal for other feed sources (for example, soybean meal, corn gluten meal, and cottonseed meal) found canola meal increased lactation output by dairy cattle. Martineau et al. (2013) concluded inclusion of canola meal in dairy cattle diets could fulfil RDP and RUP needs, and in turn increase milk production. Huhtanen et al. (2011) partly related improved performance with the inclusion of canola meal to enhanced energy rather than protein.

The protein content in canola meal may vary with harvest year, rainfall, season, soil conditions and agronomic and processing techniques. Analysis revealed canola meal mostly consists of potentially and intermediately degraded protein fractions and varies broadly in RUP content. Factors contributing to the latter include differences in quantification methods, species and oil extraction plants.

Further evaluation of the roles of oil extraction conditions, cultivar, geographical location, season and soil conditions to the variability of RUP content in canola meal is required. Dairy cattle lactation studies suggest the dietary inclusion of canola meal can outperform numerous other protein sources. Lactation output was increased relative to control meals by short-term dry heat treatment, and by mechanical extraction with and without heat-pressure. Opportunity exists to study the impact of oil extraction techniques and physical and chemical treatments on dairy cattle lactation output. Specifically, there is need to broaden knowledge of: the mechanism of moist heat pressure; effects of double-pressing, gumming, and expeller barrel dry heat temperature range on protein degradability; and, examination of the molecular and microscopic structures of canola meals produced by alternative oil extraction techniques to identify characteristics which promote resistance to enzymatic degradation. Evaluation of the impact of larger feed quantities and RUP levels in canola meal on milk yield by dairy cows during early and late stages of lactation is recommended. To assist the dairy industry to reduce N wastes, this review consolidates current understanding of the effects of canola meal's protein composition on dairy cattle milk production and summarises advances in oil extraction techniques and treatments to increase lactation output.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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