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Review Article

# The potential of canola to decrease soybean meal inclusions in diets for broiler chickens

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ABSTRACT

Feedstuffs derived from canola, predominantly canola meals plus whole, "full-fat" canola seed, and even canola protein isolates and/or concentrates, have the potential to decrease soybean meal inclusions in diets for broiler chickens. The protein content of soybean meal exceeds that of canola meal; however, canola meal contains more methionine and cysteine in absolute and relative terms. The purpose of this review is to explore this potential as Australian chicken-meat production is uniquely positioned to take advantage of this opportunity to the extent that it can be realised. Australia harvests ample quantities of canola, the bulk of which is exported as seed; alternatively, soybean production is very limited; therefore, large quantities of soybean meal are imported as the principal source of dietary protein for broiler chickens. This importation of soybean meal is not sustainable; however, canola meal inclusions in broiler diets do not usually exceed 100 g/kg. Regression equations derived from 15 recent studies indicate that dietary inclusions of 150 g/kg solvent-extracted canola meal would compromise weight gain by 4.04% and feed conversion ratio (FCR) by 4.72%. The foremost factors driving these depressions in canola meal are probably (1) high fibre contents coupled with low energy densities and (2) the presence of glucosinolates, which may be converted into toxic metabolites including thiocyanates. Moreover, regression equations from nine studies suggest that calculated dietary glucosinolate concentrations of 2.00 μmol/g would compromise weight gain by 5.72% and FCR by 6.56%. The nutritive value of canola meal could be enhanced by improvements in canola breeding programs, processing methods in canola meal production, and dietary formulations including judicious application of exogenous enzymes. Consideration is given to these aspects in this review as any improvements would increase the extent to which canola meal can feasibly replace soybean meal in broiler diets. An additional pathway to decrease the reliance on soybean meal could be the adoption of reduced-crude protein (CP) diets containing canola meal. The combined strategy of canola meal replacing soybean meal in reduced-CP diets, if successful, would tangibly decrease soybean meal requirements in global chicken-meat production.


## 1. Introduction

The high Australian annual chicken-meat consumption of 50.1 kg per capita meant that the local industry processed 707 million birds to produce 1.373 million tonnes of chicken meat in 2022 to 2023 to satisfy this demand (ACMF, 2024). However, the local industry is dependent on the annual importation of approximately 700,000 tonnes of soybean meal as the principal source of

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protein in diets for broiler chickens. This reliance on imported soybean meal is not compatible with sustainable production, but Australia harvests an abundance of canola and Australian exports constitute 15% to 20% of global trade (AEGIC, 2024). It was estimated that 299,450 tonnes of canola meal were incorporated into animal feed in Australia by Spragg and Mailer (2007) of which 45.7%, was directed to poultry with the balance mainly channelled to dairy cattle (35.3%) and pigs (17.0%). More recently, Swick and Wu (2016) indicated that Australia harvested 3.415 million tonnes of canola seed in 2014, but canola meal production was limited to 490,000 tonnes. Australia harvested a record canola crop of 8.3 million tonnes in 2022 to 2023 according to Grain Central (2024) but has a canola crush capacity of only 1.2 million tonnes. This indicates that minimally 86% of Australia's crop is exported as whole canola seed, particularly from Western Australia (see Fig. 1).

Consequently, there is tremendous scope for the Australian chicken-meat industry to increase its usage of locally produced canola meal and, simultaneously, decrease its reliance on imported, expensive soybean meal (Fig. 2). However, there is a certain reluctance to include canola meal at elevated inclusion levels in broiler diets and the reasons for this conservative approach were comprehensively reviewed decades ago by Fenwick and Curtis (1980) and subsequently by Bell (1993) and Khajali and Slominski (2012). Thus, the purpose of this review is to consider the pathways that could lead to higher inclusions of canola meal, and other canola co-products, in Australian broiler diets to decrease the importation of soybean meal.

For purposes of clarification, the term “Canola” (an abbreviation of Canada and oil) was trade-marked in 1978 by the Canadian Canola Council to differentiate the plant, oil and meal from traditional rapeseed. To comply, canola oil should contain less than 20 g/kg erucic acid and canola meal less than 30 μmol/g glucosinolates (Casséus, 2009). The description “double-zero rapeseed” is used as an alternative to canola in some countries. Thus, the transition from rapeseed to canola was a real advance and, as outlined by Rakow et al. (2007), it may be expected that there will be a continuation of successful breeding and selection programs.

## 2. Background

Essentially, canola seed is a source of amino acids with a crude protein content in the order of 204 g/kg (Soumeh et al., 2011). The two major protein fractions are cruciferin and napin, which constitute approximately 60% and 20%, respectively, of canola protein. The isoelectric point (iP) of the globulin protein, cruciferin, is 7.5 and the albumin protein, napin, is 9 to 12 (Sharma et al., 2024); both isoelectric points are relatively high which probably exacerbates the negative impacts of protein-phytate interactions (Selle et al., 2012). Canola meals are produced from whole, "full-fat" canola seed by a range of processing methods, including solvent extraction, expeller extraction and cold-pressing. Solvent-extracted canola meal has an approximate CP content of 383 g/kg (Table 1), while expeller-extracted and cold-pressed canola meals have approximate CP contents of 337 and 326 g/kg, respectively (Toghyani et al., 2020). Canola protein isolates/concentrates will probably contain more than 900 g/kg CP. Numerous studies have been completed to identify the extent to which canola meal can replace soybean meal before compromising broiler growth performance. Fifteen studies were selected to assess the impact of dietary inclusions of canola meal at the expense of soybean meal on the growth performance of broiler chickens. The selection criteria were that the studies assessed solvent-extracted canola meals exclusively and were published in peer-reviewed journals since 2010. These studies used either Cobb, Arbor Acre or Ross birds. To the best of our knowledge the list of 15 papers, is complete and involves a total 81 sets of observations from 20 experiments.

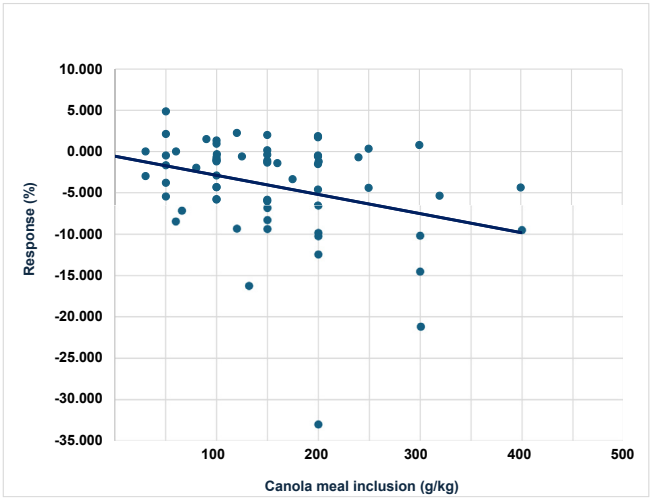


**Fig. 1.** Linear relationship ($r = -0.322$; $P = 0.010$) between canola meal inclusions and percentage responses in weight gain in broiler chickens from 3.4 to 35.3 days post–hatch where: Percentage response = −0.5756 − 0.0231 × canola meal.

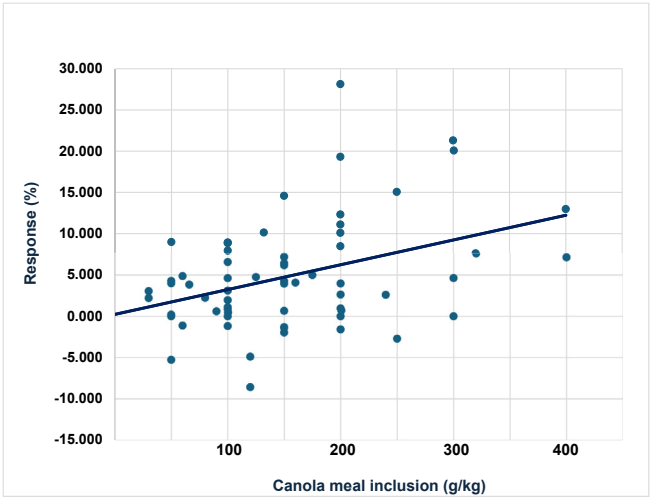


**Fig. 2.** Linear relationship ($r = 0.389$; $P = 0.002$) between canola meal inclusions and percentage responses in feed conversion ratio (FCR) in broiler chickens from 3.4 to 35.3 days post–hatch where: Percentage response = 0.2178 + 0.0300 × canola meal.

Across the 15 publications, average CP contents (when stated) of canola and soybean meals were 383 and 458 g/kg, respectively as detailed in Table 1. The overall mean dietary inclusion of canola meal was 111.8 g/kg which would notionally replace 92.2 g/kg soybean meal based solely on (stated or mean) CP levels. The average reported crude fibre CP content of canola meal was a quite consistent 118.6 g/kg. Reported glucosinolate concentrations averaged 11.67 ± 6.840 μmol/g but ranged widely from 2.55 to 23.28 μmol/g with a large 58.6% coefficient of variation. The average feeding period ranged from 3.4 to 35.3 days post–hatch. As shown in Figs. 1 and 2, substitutions of soybean meal with solvent-extracted canola meal across the selected studies linearly decreased weight gain ($r = -0.322$; $P = 0.010$) and linearly increased feed conversion ratio (FCR) ($r = 0.389$; $P = 0.002$). The regression equations predict that a 150 g/kg canola meal replacement of soybean meal would compromise weight gain by 4.04% and

**Table 1**
Summary of 15 studies published since 2010 assessing the replacement of soybean meal with solvent-extracted canola meal in diets for broiler chickens.

| Canola meal dietary inclusions, g/kg | Canola meal | | | Feeding period, days | Soybean meal CP, g/kg | Soybean meal replacement, g/kg[1] | Reference |
|---|---|---|---|---|---|---|---|
| | CP, g/kg | CF, g/kg | Glucosinolates, μmol/g | | | | |
| 0, 50, 100, 200. $\bar{x}$ = 87.5 | 360 | 120 | | 0–42 | 480 | 65.6 | Ahmed et al. (2014) |
| 0, 100, 200, 300. $\bar{x}$ = 150 | 400 | 124 | 23.28 | 1–35 | | 131.1 | Aljuobori et al. (2016) |
| 0, 30, 60, 90, 120, 150. $\bar{x}$ = 75 | 354 | 124 | | 0–10 | 445 | 59.7 | Amiri et al. (2024) [2] |
| 0, 100, 150, 200, 250. $\bar{x}$ = 140 | 354 | 124 | | 10–24 | 445 | 111.4 | Amiri et al. (2024) [3] |
| 0, 80, 160, 240, 350, 400. $\bar{x}$ = 205 | 354 | 124 | | 25–42 | 445 | 163.1 | Amiri et al. (2024) [4] |
| 0, 30, 50, 100, 150. $\bar{x}$ = 66 | 399 | 108 | 2.55 | 1–35 | | 57.6 | An et al. (2016) |
| 0, 66, 132, 200. $\bar{x}$ = 99.5 | | | | 0–42 | | 83.3 | Brand et al. (2018) |
| 0, 175. $\bar{x}$ = 87.5 | 363 | 104 | 3.80 | 15–42 | 470 | 67.6 | Disetlhe et al. (2018) |
| 0, 100, 201, 301. $\bar{x}$ = 150.5 | 341 | | | 0–39 | 453 | 113.3 | Ghazalah et al. (2020) |
| 0, 100, 200, 300, 400. $\bar{x}$ = 200 | 340 | | | 7–35 | 450 | 151.1 | Gopinger et al. (2014) |
| 0, 100, 200, 300. $\bar{x}$ = 150 | 351 | | 13.5 | 2–37 | 465 | 113.2 | Gorski et al. (2017) |
| 0, 50, 100, 150, 200, 250. $\bar{x}$ = 125 | | | | 0–28 | | 104.6 | Min et al. (2001) |
| 0, 60, 120. $\bar{x}$ = 60 | | | | 1–21 | 460 | 49.9 | Oliaei et al. (2016) |
| 0, 50, 100, 150, 200. $\bar{x}$ = 100 | 425 | | 5.95 | 1–42 | | 92.9 | Olukosi et al. (2017) [5] |
| 0, 50, 100, 150, 200. $\bar{x}$ = 100 | 385 | | 11.9 | 1–42 | | 84.2 | Olukosi et al. (2017) [6] |
| 0, 100, 200. $\bar{x}$ = 100 | | | 20.7 | 1–42 | | 83.7 | Payvastegan et al. (2013) |
| 0, 100, 125, 150, 200. $\bar{x}$ = 115 | | | | 0–42 | 440 | 100.1 | Rabie et al. (2015) |
| 0, 150. $\bar{x}$ = 75 | 472 | | 12.5 | 1–35 | | 77.4 | Rad-Spice et al. (2018) [7] |
| 0, 150. $\bar{x}$ = 75 | 411 | | 7.90 | 1–35 | | 67.4 | Rad-Spice et al. (2018) [8] |
| 0, 150. $\bar{x}$ = 75 | 434 | 120 | 14.6 | 1–35 | 480 | 67.8 | Rad-Spice et al. (2018) [9] |
| Mean values Inclusion: 111.8 | 382.9 | 118.6 | 11.67 | 3.4–35.3 | 457.5 | 92.2 | |

CP = crude protein; CF = crude fibre.
[1] Calculated solely on stated or mean CP, concentrations.
[2] Experiment 1.
[3] Experiment 2.
[4] Experiment 3.
[5] PR46W21 variety.
[6] DK, Cabernet variety.
[7] *B. juncea*, yellow.
[8] *B. napus*, black.
[9] *B. napus*, yellow.

FCR by 4.72%. It is notable that both Figures illustrate considerable variation in the capacity of birds to accommodate increased canola meal inclusions. This substantial variation reflects real differences in the nutritive value in the canola meals evaluated, which presumably stems from both the inherent quality of canola seed and processing methods and conditions for its conversion to canola meal. This outcome demonstrates the challenge of elevating canola meal inclusions in broiler diets. In contrast, Leeson et al. (1987) asserted that canola meal could totally replace soybean meal in broiler diets without adversely effecting general performance and nutrient retention. While this positive assertion is encouraging, the realisation of this promise is not straightforward.

An informal survey of several local, "hands-on" broiler nutritionists gauged their attitudes towards canola in the formulation of their diets. The respondents indicated that average inclusions of up to 96 g/kg canola meal and 76 g/kg whole canola seed were incorporated into broiler diets. The acceptance of canola seed relative to canola meal is notable. The key canola shortcomings were, ranked in descending order: fibre, lignin, glucosinolates, phytate and non-starch polysaccharides. However, there were real differences between respondents as to the gravity of these properties. Pellet quality was considered an issue with both canola meal and, more so, whole canola seed, but their combined inclusions in diets were common. Finally, variations in protein contents of canola meal from different processors was a frequent complaint.

The depressions in broiler growth performance across the 15 selected studies justify the reluctance of nutritionists to incorporate canola meal into broiler diets at elevated levels. Clearly, the challenge is to identify the limiting factors inherent in canola meal so that strategies to avoid or counteract them may be developed.

## 3. Comparison: Canola meal versus soybean meal

Comparisons between canola meal and soybean meal need to be drawn and, as is evident in Tables 2 and 3, canola meal is inferior to soybean meal in several respects as a feedstuff for broiler chickens. Although, one advantage that canola meal holds is that it possesses higher concentrations of methionine and cysteine, two critical amino acids. Table 2 is based on an instructive Australian comparison completed by Ravindran et al. (2005), in which total digestible amino acid concentrations were 54.8% (372.9 versus 241.7 g/kg) higher in soybean meal than canola meal. Nevertheless, canola meal contained more digestible methionine by 10.2% (5.85 versus 5.31 g/kg) and cysteine by 12.4% (6.16 versus 5.48 g/kg) than soybean meal in absolute terms. These higher digestible concentrations in canola meal are noteworthy as it has long been recognised that methionine and cysteine are pivotal to the growth performance of broiler chickens (Baker, 2009; Sasse and Baker, 1974). In the Ravindran et al. (2017) collaborative study, mean apparent ileal amino acid digestibility coefficients in canola meal ranged from 0.681, through 0.699 to 0.745. Thus, the validity of the Ravindran et al. (2005) data is supported by the fact that all assays of 19 samples were completed at the one institute.

As outlined in Table 3, both canola meal and soybean meal contain large amounts of carbohydrates, mainly in the form of non-starch polysaccharides (NSP), but their starch contents are negligible (Choct, 2015). The levels of NSP in canola and SBM are similar but the total fibre (NSP + lignin) contents are very different. Carbohydrates and fibre are discussed in more detail in Section 4.2. Other major comparisons between the two feedstuffs relate to phosphorus (P) and phytate concentrations, which were analysed

**Table 2**
Total AA concentrations, AID coefficients and digestible amino acid concentrations in canola meal and soybean meal.[1]

| Amino acid | Canola meal mean: 350 g/kg CP ($n = 9$) | | | Soybean meal mean: 475 g/kg ($n = 10$) | | |
|---|---|---|---|---|---|---|
| | Concentration, as-is, g/kg | AID | Digestible AA, g/kg | Concentration, as-is, g/kg | AID | Digestible AA, g/kg |
| Arginine | 21.7 | 0.85 | 18.45 | 36.1 | 0.88 | 31.77 |
| Histidine | 11.2 | 0.81 | 9.07 | 13.8 | 0.82 | 11.32 |
| Isoleucine | 14.6 | 0.77 | 11.24 | 21.7 | 0.83 | 18.01 |
| Leucine | 25.2 | 0.78 | 19.66 | 37.2 | 0.83 | 30.88 |
| Lysine | 20.1 | 0.81 | 16.28 | 30.0 | 0.85 | 25.50 |
| Methionine | 6.8 | 0.86 | 5.85 | 6.4 | 0.83 | 5.31 |
| Phenylalanine | 14.4 | 0.80 | 11.52 | 24.8 | 0.84 | 20.83 |
| Threonine | 16.0 | 0.69 | 11.04 | 19.8 | 0.76 | 15.05 |
| Valine | 18.3 | 0.76 | 13.91 | 23.2 | 0.82 | 19.02 |
| Alanine | 15.5 | 0.80 | 12.40 | 21.2 | 0.81 | 17.17 |
| Aspartate | 25.2 | 0.74 | 18.65 | 55.7 | 0.80 | 44.56 |
| Cysteine | 8.0 | 0.77 | 6.16 | 7.3 | 0.75 | 5.48 |
| Glutamate | 62.7 | 0.85 | 53.30 | 87.3 | 0.86 | 75.08 |
| Glycine | 17.7 | 0.76 | 13.45 | 20.5 | 0.78 | 15.99 |
| Serine | 17.0 | 0.72 | 12.24 | 26.2 | 0.84 | 22.01 |
| Tyrosine | 11.0 | 0.77 | 8.47 | 18.9 | 0.79 | 14.93 |
| Mean | | 0.784 | | | 0.818 | |
| Total | 305.4 | | 241.7 | 450.1 | | 372.9 |

CP = crude protein; AA = amino acid; AID = apparent ileal digestibility.
[1] Adapted from Ravindran et al. (2005).

**Table 3**
Fibre, non-starch polysaccharide, lignin and phytate concentrations in canola meal and soybean meal (g/kg).

| Parameter | Canola meal | Soybean meal |
|---|---|---|
| Bach Knudsen (1997) | ($n = 4$) | ($n = 6$) |
| Total sugars | 82 | 137 |
| Starch | 18 | 27 |
| Soluble NSP | 55 | 63 |
| Insoluble NSP | 123 | 92 |
| Klason lignin | 134 | 16 |
| Dietary fibre | 354 | 233 |
| Carbohydrate + lignin | 454 | 400 |
| Mailer er al. (2008) | ($n = 8$) | |
| Crude fibre | 119.6 | |
| Neutral detergent fibre | 341.4 | |
| Acid detergent fibre | 185.6 | |
| Selle et al. (2003) | ($n = 16$) | ($n = 22$) |
| Phytate ($IP_6$) | 23.7 | 16.1 |
| Total P | 8.76 | 6.66 |
| Phytate-P | 6.69 | 4.53 |
| Proportion, % | 76.4 | 68.3 |

in 38 canola meal and soybean meal samples sourced in Australia by Selle et al. (2003). Phytate concentrations were 47.2% (23.7 versus 16.1 g/kg) higher in canola than soybean meal which adversely influences canola protein quality.

## 4. Critical properties of canola meal

Canola meal possesses several critical, anti-nutritive properties capable of depressing broiler growth performance and the diversity of these properties complicates any assessments of their importance. Some thirty years ago, Bell (1993) suggested that relatively low available energy levels in canola meal may have replaced glucosinolates as the first-limiting factor in canola meal usage. This opinion may be valid, but it is difficult to compare the two distinctly different factors. Eight West Australian single press canola meals with average concentrations of 327 g/kg CP, 10.5 mmol/kg total glucosinolates and 136 g/kg crude fibre were used in a pig evaluation by Mullan et al. (2000). The researchers concluded that, despite the canola meals evaluated being notionally "low glucosinolate" varieties, canola meal inclusions of more than 150 g/kg resulted in higher glucosinolate intakes, which were associated with thyroid hypertrophy and depressed growth performance in grower–finisher pigs. The 150 g/kg canola meal inclusion would have equated to a dietary glucosinolate concentration of 1.58 mmol/kg.

### 4.1. Glucosinolates

Dietary glucosinolate concentrations exceeding 10 μmol/g cause significant growth depression in broiler chickens according to Mawson et al. (1994), with the caveat that trends towards compromised growth performance become evident between 2 and 4 μmol/g glucosinolate. Subsequently, glucosinolates were identified as the major anti-nutritive factor present in canola in diets for poultry and pigs by Woyengo et al. (2017). Thus, the presence of aliphatic and aromatic glucosinolates inherent in canola in diets for broiler chickens are clearly detrimental and yet, paradoxically, glucosinolates per se are not harmful; however, they are degraded to a range of toxic metabolites, including isothiocyanates, nitriles and thiocyanates (Tripathi and Mishra, 2007; Melrose, 2019). It appears that the capacity of broiler chickens to accommodate these glucosinolate-derived, anti-nutritive factors is highly variable. This probably reflects both the diversity of glucosinolates, as more than 120 entities have been identified (Tripathi and Mishra, 2007), and their propensity to be degraded to toxic metabolites. In theory, glucosinolates are degraded via four pathways: (1) enzymatically by myrosinase, which is heat labile, following disruption of cells in canola and during oil extraction processes, (2) by acidic conditions in the anterior gastrointestinal tract, (3) by microbial myrosinase in the posterior gastrointestinal tract and (4) directly by thermal degradation during extraction processes (Lee et al., 2020). Thus, it appears that dietary concentrations of glucosinolate-derived toxic metabolites from canola meal stem largely from exposure to heat during processing, which would deactivate myrosinase. However, acidic pH of 3.61 in the proventriculus and 2.99 in the gizzard have been reported in broiler chickens (Heller and Penquite, 1936), which may further degrade glucosinolates and may denature myrosinase.

A “very low” glucosinolate canola meal (6.27 μmol/g) and a standard canola meal (15.30 μmol/g) were compared in broiler chickens by Classen et al. (1991). The two meals were included in a basal diet at 150, 300 and 450 g/kg, so calculated dietary

glucosinolate concentrations ranged from 0.94 to 2.82 μmol/g and from 2.30 to 6.89 μmol/g in the 'very low' and standard diets, respectively. Instructively, the 'very low' canola meal supported superior energy utilisation (AME) by an average of 1.39 MJ (9.14 versus 7.75 MJ/kg). Moreover, it may be deduced from the Classen et al. (1991) data that dietary glucosinolate concentrations linearly depressed AME ($r = -0.865$; $P = 0.026$), as shown in Fig. 3. The regression equation predicts that a dietary level of 2.00 μmol/g glucosinolate would depress energy utilisation by 1.36 MJ and the $r^2$ value suggests that glucosinolate was responsible for 75% of the variations observed in energy utilisation.

Glucosinolate metabolites interfere with the synthesis of thyroid hormones by impeding uptakes of iodine. The impacts of thiocyanate overload on thyroid function and the roles of thyroid hormones in avian species have been reviewed by Erdogan (2003) and Decuypere et al. (2005). Isothiocyanates derived from progoitrin cyclise to produce goitrin, which interferes with thyroidal iodine uptake and has been shown to depress plasma tetraiodothyronine (T4) levels in pigs (Schöne et al., 1997). In diets for broiler chickens, 160 g/kg rapeseed meal (114.4 mmol/kg glucosinolates) was incorporated into maize-based diets essentially at the expense of soybean meal, which compromised day 46 weights by 8.48% (1436 versus 1569 g/bird) in Schöne et al. (1993). In addition, the dietary incorporation of rapeseed decreased plasma T4 concentrations by 45.8% (7.7 versus 14.2 nmol/L) and increased relative thyroid weights by 130% (747 versus 325 mg/kg).

Glucosinolate concentrations in canola meals were determined in 7 studies (Aljuobori et al., 2016; An et al., 2016; Disetlhe et al., 2018; Gorski et al., 2017; Olukosi et al., 2017; Payvastegan et al., 2013; Rad-Spice et al., 2018) of the 15 papers listed in Table 1, which permitted dietary glucosinolate concentrations to be calculated. Dietary glucosinolate concentrations were linearly related ($r = -0.549$; $P = 0.006$) to depressions in weight gain (Fig. 4) and linearly related ($r = 0.468$; $P = 0.021$) to inflations in feed conversion ratios (Fig. 5). The regression equations predict that a dietary glucosinolate concentration of 2.0 μmol/g would compromise weight gain by 5.72% and feed conversion by 6.46% and the combined $r^2$ values suggest that glucosinolate was responsible for 26% of the variations observed in growth performance.

Nevertheless, interpretation of glucosinolate concentrations in canola meals and diets that contain canola meal is not straightforward despite their obvious detrimental impacts. Fundamentally,

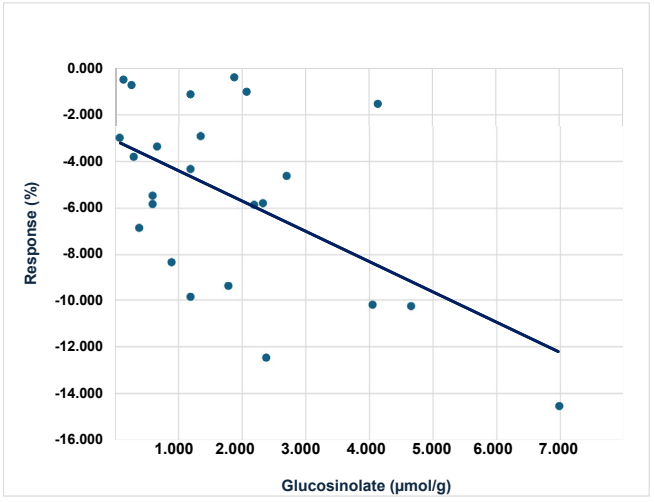


**Fig. 3.** Linear relationship ($r = -0.549$; $r^2 = 0.301$; $P = 0.006$) between calculated dietary glucosinolate concentrations and percentage responses in weight gain in broiler chickens from 3.4 to 35.3 days post–hatch where: Percentage response = −3.118 − 1.302 × glucosinolate.

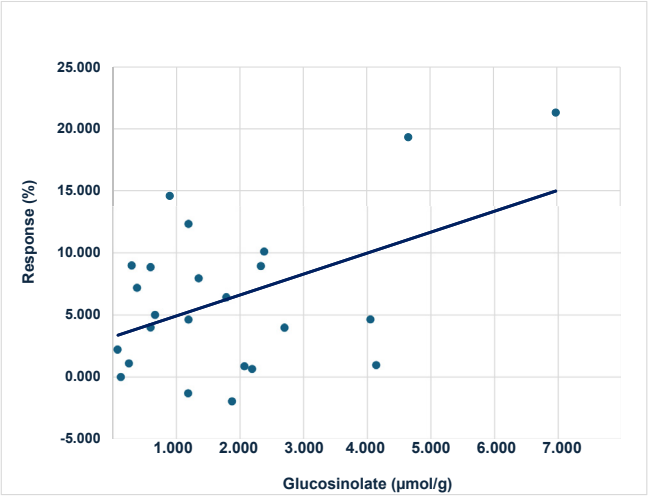


**Fig. 4.** Linear relationship ($r = 0.468$; $r^2 = 0.219$; $P = 0.021$) between calculated dietary glucosinolate concentrations and percentage responses in feed conversion ratio (FCR) in broiler chickens from 3.4 to 35.3 days post–hatch where: Percentage response = 3.190 + 1.687 × glucosinolate.

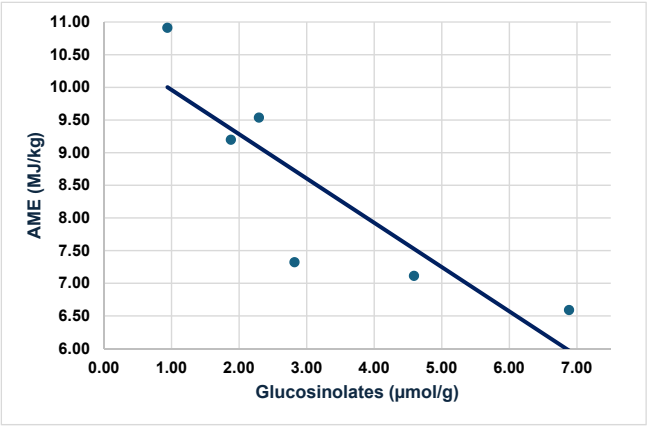


**Fig. 5.** Linear relationship ($r = -0.865$; $P = 0.026$) between glucosinolate concentrations in canola meals and apparent metabolisable energy (AME) in broiler chickens where: AME = 10.639 − 0.678 × glucosinolate. Adapted from Classen et al. (1991).

glucosinolates are not thermostable and heat-treatment alone will at least partially degrade glucosinolates to their toxic metabolites. This was evident in Oerlemans et al. (2006) in which microwaving red cabbage at over 100 °C degraded all the identified glucosinolates to varying extents. In this experiment myrosinase was inactivated by prior thermal treatment. Earlier, Vallejo et al. (2002) reported that microwaving broccoli reduced aromatic glucosinolate concentrations by 73.5% (6.0 versus 22.6 μmol/g) on a dry matter basis. Thus, the glucosinolates and myrosinase present in raw canola have been partially degraded or deactivated by heating during the oil extraction processes to yield canola meal. The metabolic fate of intact glucosinolates consumed in poultry diets containing canola meal requires clarification. In laying hens, Slominski et al. (1988) concluded that the absorption of intact glucosinolates along the digestive tract was low but they were degraded by microbial activity in the hind-gut. Alternatively, Michaelsen et al. (1994) reported large reductions, from 3- to 20-fold, in glucosinolate concentrations in digesta from the stomach and proximal small intestine in rodents. Presumably, the combination acidic pH, myrosinase activity and absorption was

responsible for this observation. In humans, as reviewed by Barba et al. (2016), some intact glucosinolates are absorbed through the gastrointestinal mucosa but more are degraded by myrosinase in the proximal gastrointestinal tract. In broiler chickens offered steam-pelleted diets containing solvent-extracted canola meal, the likelihood is that myrosinase activity would be negligible. It appears that some intact glucosinolates may be absorbed, some may be degraded by the acidic conditions prevailing in the proventriculus and gizzard and some may be degraded by hind-gut fermentation. Nevertheless, the breeding of canola varieties with low glucosinolate concentrations should be a high priority. Equally, any means by which the degradation of glucosinolate to toxic metabolites can be attenuated, either during processing of canola meal and/or in the avian digestive tract, should be investigated.

### 4.2. Fibre

Nutritionists focus on ingredients such as canola meal and soybean meal as a protein source, ignoring the fact that these raw materials contain more non-protein constituents. Canola meal, for instance, contains 37% protein and 63% non-protein components which include carbohydrates 35% to 38%, lignin 11% to 15%, moisture 10% to12%, ash 6% to 8% and fat 3% to 4% (Finlayson, 1977). Also, Finlayson (1977) reported that of the carbohydrates, 20% to 25% are NSP and the balance consists of di- and oligosaccharides and in addition to a small amount of sucrose, there are 7.0% to 7.4%; raffinose, 0.33%; stachyose, 2.5%; galactinol, 0.1%; and di-galactosyl glycerol, 0.1%; starch is less than 1%. These low-molecular weight carbohydrate contents in canola vary depending on the variety and growing conditions. Thus, it is reported that the sucrose content in different cultivars of rapeseed ranged from 2.33% to 2.85% (Theander et al., 1977). The sucrose concentrations in canola and soybean meals are highly related to their energy values and the sucrose level in 14 soybean samples was 5.60% as determined HPLC in Teixeira et al. (2012). From a quantitative point of view, the total carbohydrate level of canola is comparable to that of soybean meal. For instance, Choct et al. (2010) showed that the highest protein soybean meal is about 52% non-protein, that includes 35% carbohydrates (NSP, disaccharides, oligosaccharide and less than 1% starch), 10% water, 5% minerals and less than 1% each of oil and other minor constituents. The carbohydrates in soybean meal consist of 20% to 25% NSP and 10% to 15% low-molecular weight carbohydrates, including approximately 5% sucrose, 4% stachyose and 1% raffinose.

From a qualitative perspective, however, there are fundamental differences between canola and soybean meals in terms of the types of carbohydrates and fibre present. Many vegetable protein ingredients such as canola and soybean meals contain pectins, the most representative of the numerous pectic polymers is rhamnogalacturonan Type I (RG-I). This is a highly complex domain composed of repeating units of galacturonic acid (GalA) residues and rhamnose (Rha) linked via [→4-α-D-GalpA-(1 → 2)-α-L-Rhap-(1→] etc. The fine structural differences of RG-I between canola and soybean meals that may require different types of pectinases to affect a partial depolymerisation. Apart from RG-I, canola also contains homogalacturonan, highly branched arabinogalactans (type II), and glucuronoxylan (Long et al., 2022), whereas some of these pectins do not appear to be present in soybean.

In describing fibre, it is difficult to avoid the entity called crude fibre (CF). Unfortunately, CF is a 19th century relic that does not describe a chemical entity, nor a functional nutrient. It is highly inaccurate (Choct, 2015). Therefore, the use of dietary fibre (DF) is preferred in animal nutrition, referring to the sum of NSP and lignin. In human nutrition, there are various definitions of DF, depending on whether it includes oligosaccharides and/or resistant starch. The total DF content of canola meal 35.4%, whereas that in soybean meal is 23.3% according to Bach Knudsen (1997; 2014). The difference is attributable to their lignin content (13.4% vs 1.6%; canola vs. SBM). Lignin represents a complex array of polyphenolic compounds that are completely non digestible in poultry. Phenolics will be discussed later in this review.

The metabolisable energy values of six batches of an Australian expeller extracted canola meal were determined by Toghyani et al. (2014) where the mean glucosinolate concentration was 7.32 μmol/g, which ranged from 6.32 to 8.10 μmol/g. The AME of diets containing 300 g/kg canola meal ranged from 8.74 to 11.11 MJ/kg around a mean AME of 10.12 g/kg. However, there was a negative Pearson correlation ($r = -0.70$; $P = 0.001$) between glucosinolate concentrations and AME. In addition, AME was negatively impacted by crude fibre ($r = -0.58$; $P = 0.002$), neutral detergent fibre (r = −0.93; $P = 0.001$) and acid detergent fibre ($r = -0.67$; $P = 0.001$) in the Toghyani et al. (2014) study. Average concentrations of crude fibre (108 g/kg DM), neutral detergent fibre (235 g/kg DM) and acid detergent fibre (175 g/kg) in the canola meals tested are shown in parentheses. Concentrations of glucosinolates were negatively correlated with neutral detergent fibre ($r = -0.58$; $P = 0.002$), but not with crude fibre and acid detergent fibre.

Canola meal contains in the order of 130 g/kg lignin, which is both substantial and disadvantageous as demonstrated in the following two studies. The impact of dietary lignin in broiler chickens was assessed by De Souza Leite et al. (2024) at inclusion rates of 0, 10, 20 and 30 g/kg. The dietary inclusion of 30 g/kg lignin numerically decreased weight gain by 2.42% (2909 versus 2981 g/bird) and numerically increased feed intake by 3.13% (4421 versus 4287 g/bird) and FCR by 4.06% (1.511 versus 1.452) from 1 to 42 days post−hatch. Also, lignin marginally depressed carcass yield from 69.06% to 68.08% at 42 days. In an earlier study, Nunes et al. (2022) included purified lignin in broiler diets at 0, 5, 10 and 15 g/kg. At 15 g/kg, lignin numerically depressed weight gain by 4.58% (1895 versus 1986 g/bird), fractionally increased feed intake by 0.78% (3626 versus 3598 g/bird) and numerically compromised FCR by 6.08% (1.92 versus 1.81) from 22 to 42 days post−hatch in birds subjected to cyclic heat stress.

### 4.3. Phytate

Canola meal contains more phytate than soybean meal in absolute terms, as shown in Table 3; probably more importantly, canola meal contains considerably more phytate relative to protein than soybean meal. Indeed, Serraino and Thompson (1984) explored the possibility of removing phytate from rapeseed in view of protein-phytate interactions. Nevertheless, the anti-nutritive properties of phytate are routinely counteracted by exogenous phytases, very often at elevated inclusion rates, in broiler diets (Selle et al., 2023a). Additions of up to 2000 FTU/kg phytase activity to atypical diets containing 450 g/kg canola meal, dextrose and corn starch were evaluated in broiler chickens by Parsons and Rochell (2024) in which canola meal was the only dietary P source. The addition of 2000 FTU/kg phytase increased ileal digestibility of P by 20.6% (0.563 versus 0.467) and decreased ileal digesta concentrations of IP6 and IP5 phytate esters by 59.5% (13.83 versus 34.19 μmol/g). The anti-nutritive properties of phytate esters less than $IP_6$ and $IP_5$ are relatively innocuous (Luttrell, 1993). Kong and Adeola (2011) reported that a bacterial phytase (1500 FTU/kg) increased the linear regression-derived mean true ileal digestibility coefficient of 10 indispensable amino acids by 3.66% (0.764 versus 0.737) in broilers where canola meal was the only source of dietary protein. Individual phytase responses ranged from −0.83% (tryptophan) to 9.56% (lysine), but none of the responses were statistically different to the control values. However, in a comparative study, a fungal phytase (1200 FTU/kg) significantly increased mean

apparent ileal digestibilities of 14 amino acids by 2.70% (0.799 versus 0.778) in canola meal as opposed to 4.17% (0.850 versus 0.816) in soybean meal (Ravindran et al., 1999a). Amino acid digestibility responses to exogenous phytase are probably largely dependent on the rapid degradation of $IP_6$ phytate to innocuous, lesser phytate esters primarily in the gizzard, which prevents the de novo formation of binary protein-phytate complexes (Selle et al., 2012). Thus, the relatively inferior phytase responses in canola meal may partially stem from the higher fibre concentrations in canola than soybean meal (Table 3). The higher canola meal fibre concentrations may be impeding the access of phytase to its substrate, thereby retarding the rapid degradation of $IP_6$ phytate. It then follows that with the tandem inclusions of phytase and fibre-degrading enzymes the access of phytase to its substrate will be enhanced. The inclusion of either phytase or an NSP-degrading enzyme (xylanase and β-glucanase) both increased mean apparent ileal digestibility coefficients of 14 amino acids in broilers offered wheat-based diets by 4.88% (0.839 versus 0.800) in (Ravindran et al., 1999b). However, the combined inclusion of phytase and an NSP-degrading enzyme increased digestibility coefficients by 8.63% (0.869 versus 0.800). The likelihood is that the genesis of the amplified response to the tandem inclusion was partially due to the provision of better substrate access for phytase by the fibre-degrading enzyme.

### 4.4. Phenolic compounds

Phenolic compounds are a diverse group of phytochemicals, ranging from phenolic acids to condensed tannin to lignin. Lignin is the third largest component of canola meal, after carbohydrates and protein. It represents a group of polyphenolic compounds that serve as a skeleton support, providing rigidity to plant. Apart from the function of lignin as part of fibre (lignocellulose compounds) in terms of gut development, the literature largely ignores the nutritional effects of lignin itself on poultry. Likewise, the focus of this section is phenolic substances, other than lignin.

Indeed, the total phenolic concentrations, excluding lignin, in rapeseed of 639.9 mg/100 g exceeded the 23.4 mg/100 g total concentration in soybean meal (Shahidi and Naczk, 1992). Average condensed tannin concentrations in canola meals prepared from seven canola varieties ranged from 133 to 706 mg catechin equivalents/100 g depending on the extraction method (Shahidi and Naczk, 1989). Tannins have the capacity to bind with and precipitate proteins at pH values close to their isoelectric points and sorghum tannins can precipitate 12 times their own weight of protein (Jansman, 1993). Interestingly, Yapar and Clandinin (1972) found that the removal of tannin from rapeseed meal offered to broiler chickens had little effect on intestinal protein (N) uptakes of protein. The nutritional significance of polyphenolic compounds has been extensively reviewed by Bravo (1998).

Sinapine, the choline ester of sinapic acid, and free sinapic acid account for more than 80% of the total phenolic acids in rapeseed meal (Qiao and Classen, 2003). Graded inclusions of sinapic acid (0, 0.25, 0.50, 1.00 g/kg) in maize-soy broiler diets were evaluated by Qiao and Classen (2008). They concluded that sinapic acid was not toxic at the levels investigated but allowed that sinapic acid may have negative effects on amino acid digestibilities at higher levels. Given that interactions between phenolic compounds and proteins in canola and have been reported (Xu and Diosady, 2000), this presumption may be valid.

### 4.5. Erucic acid

Erucic acid is monounsaturated fatty acid which is synthesized in the seeds of many plants from the *Brassicaceae* family, including canola and erucic acid is considered to have both the beneficial and toxic properties (Galanty et al., 2023). Five different rapeseed oils with erucic acid contents ranging from 3.0 to 35.0 g/kg were compared with soybean oil at inclusions of 150 g/kg in broiler diets based on wheat and soybean meal by Vogtmann et al. (1975). Soybean oil diet supported significantly heavier body weight at 56 days post–hatch by 5.68% (1266 versus 1198 g/bird) and numerically better FCR by 3.75% (2.31 versus 2.40) than the average of five rapeseed oils. However, two of the rapeseed oils supported statistically similar growth performance to soybean oil. Subsequently, Vogtmann and Clandinin (1974) compared inclusions of rapeseed oil and soy oil in broiler diets at 50 and 150 g/kg and concluded both were nutritionally satisfactory. More recently, Attia et al. (2020) compared canola oil with fish oil and coconut oil at 15 g/kg inclusions in diets for broiler chickens. Canola oil supported significantly better weight gains to 42 days post–hatch than fish oil by 2.38% (2107 versus 2058) and coconut oil by 3.39% (2107 versus 2038). Advantages were also observed for canola oil in respect of FCR and carcass yields. Overall, the researchers concluded that 15 g/kg oil supplementation was beneficial and the effect of oil source depended on the response criteria.

The inclusion of five different rapeseed oils with erucic acid contents ranging from 3.0 to 35.0 g/kg were compared with soybean oil at inclusions of 150 g/kg in broiler diets based on wheat, soybean meal and cellulose by Vogtmann et al. (1975). Soybean oil diet supported significantly heavier body weight at 56 days post–hatch by 5.68% (1266 versus 1198 g/bird) and numerically better FCR by 3.75% (2.31 versus 2.40) than the average of five rapeseed oils. However, two of the rapeseed oils supported statistically similar growth performance to soybean oil. Given the high oil inclusions (150 g/kg), this suggests that the toxicity of erucic acid is of little concern in practice.

## 5. Enhancing the nutritive value of canola meal

### 5.1. Breeding

The development of "high protein-low fibre" varieties of canola has obvious appeal and the value of canola meal from breeding for increased protein and decreased fibre contents was recently addressed by King et al. (2023). A high protein-low fibre or "test" canola meal was compared with a standard canola meal by Chen et al. (2015). The CP content was higher (494 versus 415 g/kg) and both the neutral detergent fibre (207 versus 327 g/kg) and acid detergent fibre (153 versus 212 g/kg) levels lower, in the test canola meal. The standardised digestibilities of 17 amino acids were determined in precision-fed, caecectomised roosters where mean digestibility coefficients were 5.21% (0.869 versus 0.826) higher in the test canola meal and the most pronounced 13.4% response was observed for lysine. Also, true metabolisable energy was numerically higher by 0.75 MJ (10.27 versus 9.52 MJ/kg) in birds offered the test canola meal. Therefore, the continued development of high protein-low fibre canola meals appears to hold real promise.

The stated aim of one breeding program was to develop true breeding, yellow-seeded cultivars of *Brassica napus* that are high yielding, resistant to diseases and have high oil and protein contents (Rakow et., 2007). To this end, the yellow-seeded *B. napus*, with a higher oil content in seed and a lower fibre content meal, was bred by crossing *Brassica napa* with *Brassica juncea*. Strong correlations have been demonstrated between seed colour and meal fibre reduction (Relf-Eckstein et al., 2007). For instance, compositions of meal from a yellow-seeded *B. napus* were compared with a black-seeded *B. napus* by Slominski et al. (2012). Crude protein was higher by 60 g/kg (498 versus 438 g/kg), dietary fibre was lower by 60 g/kg (241 versus 301 g/kg), and there was a

substantial decrease in glucosinolates (17.1 versus 27.1 μmol/g). The N-corrected apparent metabolisable energy (AMEn) values of yellow-seeded *B. napus* meal exceeded and black-seeded meal (8.36 versus 7.86 MJ/kg DM) in broiler chickens respectively in Rad-Spice et al. (2018). Thus, the ongoing efforts in breeding and selecting agronomically viable, "low fibre-high protein" canola varieties should enhance the value of canola as an alternative protein source.

### 5.2. Processing

It would be difficult to over-estimate the importance of processing, or the extraction of oil from canola seed to produce canola meal, for the nutritive value of canola meal as a feedstuff for broiler chickens. Canola meals produced by either expeller cold-pressed or pre-pressed, solvent-extracted processes were compared by Agyekum and Woyengo (2022). The solvent-extracted canola meal had higher CP concentrations (429 versus 359 g/kg), neutral detergent fibre (315 versus 289 g/kg) and acid detergent fibre (205 versus 198 g/kg). The mean apparent ileal digestibility coefficient of 18 amino acids in broiler chickens was superior in cold-pressed canola meal by 10.9% (0.856 versus 0.722) where pronounced increases were observed for threonine (16.9%) and valine (14.6%). Also, energy utilisation was superior in the cold-pressed meal by 1.43 MJ (7.41 versus 5.98 MJ/kg AMEn). The protein solubility (0.2% KOH) of canola meal has been shown to decline from 85% at the expeller stage to 42% following solvent extraction (Anderson-Hafermann et al., 1993). Moreover, this was accompanied by a decrease in the mean ileal digestibility coefficient of ten amino acids of 5.65% (0.801 versus 0.849) in broiler chickens. Arguably, protein solubility is a valuable indicator of the adequacy of canola processing (Pastuszewska et al., 1998) and could be used as a routine quality control procedure by the chicken-meat industry.

Variations across canola meals from different processing plants have also been reported. Canola meal samples collected from eleven Canadian facilities from 2011 to 2014 inclusive were assessed in Adewole et al. (2016). The mean protein content was 417 g/kg CP on a dry matter basis with a narrow range from 409 to 429 g/kg CP. In contrast, the glucosinolates concentration was 4.65 ± 2.417 μmol/g, which ranged broadly from 1.90 to 9.70 μmol/g, as reflected in the high 52% coefficient of variation. This variation probably stems from thermal decomposition of glucosinolates during the desolventisation of canola seed when they are degraded to thiocyanates (Campbell and Slominski, 1990). Nevertheless, it could be more instructive to determine concentrations of thiocyanates, rather than glucosinolates, simply because thiocyanates are toxic and glucosinolates are innocuous. Thiocyanate concentrations may be completed by high-performance liquid chromatography with fluorometric detection (Chen et al., 1996), which should be more indicative of the nutritive quality of canola meal than glucosinolate levels.

Variation in energy utilisation across canola meals was also evident in an Australian study (Toghyani et al., 2014) in which the average AME and AMEn in broiler chickens was 12.12 and 9.45 MJ/kg, respectively, across five canola meal samples. However, AME ranged from 8.74 to 11.11 MJ/kg and AMEn from 8.27 to 10.38 MJ/kg. The impacts of the desolventising/toasting process on the protein quality of four rapeseed meals in which residence time in the desolventizer/toaster was increased from 48 to 64, 70 and 93 min were investigated by Mosenthin et al. (2016). These treatments linearly reduced glucosinolate concentrations by 60% (6 versus 15 μmol/g) and concentrations of reactive lysine by 22 %, (12.5 versus 16.0 g/kg). Therefore, the increased residence time both increased the degradation of glucosinolates to harmful metabolites and decreased reactive lysine; it would be anticipated that both outcomes would compromise the nutritive value of rapeseed meal.

A schematic representation of pre-press solvent extraction processing to yield canola meal is shown by Newkirk et al. (2003a) and the effects of canola meal processing conditions was also investigated by Newkirk and Classen (2002) and Newkirk et al. (2003b). In the Newkirk et al. (2003a) study pre-press solvent extraction increased the CP content of canola by 79.3% from 217 to 389 g/kg but significantly decreased lysine concentrations by 15.4% (5.50 versus 6.50 g/kg). Processing reduced the apparent ileal digestibility coefficient of CP by 9.24% (0.766 versus 0.844) and of lysine by 10.2% (0.793 versus 0.833). Also, processing reduced the mean apparent ileal digestibility coefficient of 19 amino acids by 7.98% (0.784 versus 0.852). The desolventising/toasting stage of the process was the most damaging as this step reduced CP digestibility by 10.3% (0.738 versus 0.814) and lysine digestibility by 9.22% (0.792 versus 0.865). In addition, across two experiments, processing reduced the apparent metabolisable energy of canola products by an average of 11.83 MJ (10.10 versus 21.92 MJ/kg DM). It is noteworthy that the desolventising/toasting step involves the application of temperatures of 100 to 110 °C (Newkirk et al., 2003a); the importance of thermal treatment in relation to protein utilisation is discussed in the next section.

Extrusion of individual feed ingredients or complete diets involves heat treatment, pressure, friction and shear-force without or with steam application. Interestingly, Ahmed et al. (2014) reported that extrusion of canola meal per se improved ileal amino acids digestibility and energy utilisation in broiler chickens. Canola meal extrusion increased the mean apparent ileal digestibility coefficient of 18 amino acids by 11.3% (0.776 versus 0.697) where the largest response of 24.1% (0.706 versus 0.569; $P = 0.012$) was observed for threonine. Also, energy utilisation was increased by 1.48 MJ (10.87 versus 9.39 MJ/kg AME; $P < 0.001$). This may be the only evaluation of extruded canola meal in poultry and the 20.9% (98.2 versus 124.2 g/kg DM) reduction in analysed crude fibre in canola meal may have contributed to the positive response in energy utilisation.

#### 5.2.1. Thermal treatment and protein utilisation

The exposure of protein to high temperatures reduces its solubility, digestibility and the post-enteral availability of amino acids. The damaging effects of heat-treatment on amino acid digestibility and their post-enteral availability, especially lysine, was critically investigated by Dr Ted Batterham and his colleagues in pigs (Van Barneveld et al., 1994a,b). The effects of heat-treatment on the nutritional quality of canola meal in broiler chicks were assessed by Anderson-Hafermann et al. (1993). Autoclaving a canola meal (438 g/kg CP) and maize broiler diet for 90 min depressed weight gain by 43.1% (70 versus 123 g/bird) and FCR by 32.2% (2.481 versus 1.681) from 8 to 17 days post−hatch. This was aligned with a reduction in protein solubility from 40% to 22% in the first experiment. In the second experiment, the diet was autoclaved for 0, 10, 20, 30, 40 and 60 min which reduced (0.5% KOH) protein solubility from 52% to a minimum of 32%. Of note was that protein solubility was linearly related to both weight gain ($r = 0.919$; $P = 0.010$) and FCR ($r = -0.926$; $P = 0.008$). There is not an agreement as to the reliability of KOH protein solubility as an indicator of protein quality as Goh et al. (1980) proposed that KOH protein solubility was not a suitable method to predict the quality of commercial rapeseed meals; however, this opinion was not shared by Pastuszewska et al. (1998).

Canola seed is not subjected to elevated temperatures when cold-pressed and oil is extracted only via mechanical means according to the Canola Council of Canada (2024). Cold-pressed canola meal is preferred to extracted canola meals in Australia and may attract a price premium. A cold-pressed canola meal was compared to soybean meal by Toghyani et al. (2017). The canola meal contained 339 g/kg CP, 120 g/kg crude fat, 159 g/kg acid

detergent fibre, 214 g/kg neutral detergent fibre, 18.4 g/kg phytate and 23.8 μmol/g glucosinolates based on near-infrared spectroscopy. Similarly, the soybean meal contained 478 g/kg CP, 17 g/kg crude fat, 45 g/kg acid detergent fibre, 82 g/kg neutral detergent fibre and 14.4 g/kg phytate on an 'as-is' basis. Broiler chickens were offered grower (209 g/kg CP, 12.97 MJ/kg ME) and finisher (191 g/kg CP, 13.18 MJ/kg ME) diets from 10 to 35 days post–hatch. In grower diets, 243 g/kg soybean meal was replaced with a blend of 240 g/kg canola meal and 8.5 g/kg soybean meal. In finisher diets, 197 g/kg soybean meal was replaced with a blend of 266 g/kg canola meal and 28 g/kg soybean meal. The soybean meal-based diet supported higher weight gains by 5.70% (2355 versus 2228 g/bird) and feed intakes by 11.2% (3558 versus 3201 g/bird), but the canola meal-based diet supported better FCR by 4.90% (1.437 versus 1.511). Interestingly, mean apparent ileal digestibility coefficients of 17 amino acids were comparable in the soybean (0.828) and canola (0.824) diets as were carcass (742.5 versus 746.7 g/kg) and breast-meat (216.1 versus 219.1 g/kg) yields. Given that the elevated inclusions of cold-pressed canola meal reduced dietary soybean meal levels by 97% in the grower, and 86% in the finisher phases, without having a real influence on performance, the elimination of heat treatment during the oil extraction process was advantageous.

A cold-pressed canola meal and an expeller-pressed canola meal were evaluated in a second comparison by Toghyani et al. (2020). In this study, birds were offered atypical diets containing either 621 g/kg cold pressed or 602 g/kg expeller-pressed canola meal and dextrose with CP contents of 233 and 243 g/kg, respectively. The cold-pressed canola meal supported numerical improvements of 5.20% (607 versus 577 g/bird) in weight gain, 8.43% (1.663 versus 1.816) in FCR and 4.80 percentage units (61.7% versus 56.9%) in N retention from 21 to 28 days post–hatch. The mean digestibility coefficient of 16 amino acids in the distal jejunum was higher by 10.4% (0.423 versus 0.383) in birds offered cold-pressed canola meal with notable advantages being observed for lysine (44.9%), proline (20.5%), aspartic acid (20.1%), glycine (19.2%), histidine (17.5%) and threonine (12.8%). In the distal ileum, the mean apparent distal ileal digestibility coefficient of 16 amino acids were comparable for cold-pressed (0.697) and expeller-pressed (0.685) canola meal, although lysine digestibility in the cold-pressed canola meal was still superior by 20.8% (0.680 versus 0.563).

Heat damage, including Maillard reactions, to protein and amino acids in feedstuffs and diets with an emphasis on lysine were reviewed by Oliveira et al. (2021). Reactions between the terminal ε-amino group of amino acids, especially lysine, and reducing sugars constitute the Maillard reaction, which effectively reduces amino acid concentrations in relevant feed ingredients. Additionally, the bonding of ε-amino groups of lysine and carboxyl groups of aspartic and glutamic acids generate indigestible peptides which reduce protein digestibility. Lysine concentrations are reduced in heat damaged proteins whereas CP concentrations remain constant and the lysine:CP ratio may be used to gauge heat damage. According to Oliveira et al. (2021), a lysine:CP ratio of less than 5.2 in canola meal is indicative of heat damage. Earlier, Oliveira et al. (2020) advised the risk of overheating canola meal can be substantially reduced if crushing plants can avoid processing temperatures of more than 110 °C. However, in complete broiler diets the contribution of lysine from canola meal is limited, which masks the poor lysine digestibility from this source and this is further concealed by routine inclusions of lysine monohydrochloride in standard broiler diets.

### 5.3. Diet formulations

Appropriate, precise formulations of broiler diets should facilitate the replacement of soybean meal with canola meal. As an example, the replacement of 20%, 40%, 60% and 80% of soybean meal in broiler diets with two rapeseed meals was investigated by Hulan and Proudfoot (1981). The two rapeseed meals, Tower and Candle, were low in both glucosinolates and erucic acid contents. In the 80% replacement starter diets inclusions of rapeseed meal increased from 0 to 268 g/kg, fishmeal from 50 to 80 g/kg and fat from 20 to 45 g/kg, but soybean meal decreased from 335 to 67 g/kg and maize from 300 to 235 g/kg. A similar pattern was followed in the finisher diets. The soybean, Tower and Candle diets supported similar weight gains (1962, 1954, 1947 g/bird, respectively) and FCR (2.04, 2.03, 2.01, respectively) at 49 days post–hatch. Thus, the replacement of soybean meal with rapeseed meals did not tangibly influence broiler growth performance which the researchers maintained were due to adjusting the diets to compensate for any shortfalls in amino acids with additional fishmeal and in metabolisable energy with additional fat.

Presently, such adjustments would be routine via least-cost dietary formulations. However, as discussed in the next section, the salient point in the Hulan and Proudfoot (1981) study was that amino acid shortfalls were met by protein-bound amino acids (fishmeal) rather than non-bound (synthetic, crystalline) amino acids.

Equally, inclusions of phytate-degrading enzymes in all practical broiler diets are a matter of routine. However, as already mentioned, the addition of an appropriate multi-carbohydrase feed enzyme to diets containing canola meal should be advantageous both directly and indirectly from the enhancement of phytase efficacy. Broiler diets, containing 584 g/kg canola meal as the only protein source, were supplemented with phytase (1000 FTU/kg) and xylanase (2000 U/kg) individually and in combination in Moss et al. (2018). Individually, phytase increased the mean apparent ileal digestibility coefficient of 16 amino acids by 5.09% (0.723 versus 0.688) and xylanase by 2.91% (0.708 versus 0.688). However, phytase plus xylanase in tandem increased the mean digestibility coefficient by 20.9% (0.832 versus 0.688), which clearly exceeds the additive individual response of 8.00% by a factor of 2.61. Indeed, synergistic responses were detected for the digestibilities of all 16 amino acids, especially threonine and lysine. Similar results were reported by Olukomaiya et al. (2021) where the apparent metabolizable energy content of canola meal for broilers was increased from 14.0 to 14.1 MJ/kg with phytase supplementation, to 14.2 MJ/kg with xylanase but to 14.7 MJ/kg with a combination of phytase and xylanase. Similar synergistic effects of xylanase and phytase were observed for protein digestibility (75.8%, 75.9%, 76.2% and 78.1%, respectively for canola meal, phytase, xylanase and phytase + xylanase) and for most of the essential and non-essential amino acids. These results from Moss et al. (2018) and Olukomaiya et al. (2021) demonstrate the need to identify the most appropriate fibre-degrading enzyme to accompany the inclusion of phytase in diets containing canola meal.

A multi-carbohydrase feed enzyme was evaluated in a maize-soy broiler diet containing 270 g/kg canola meal in the starter phase and 290 g/kg in the grower phase by Niu et al. (2023). The canola meal used in the study contained 388 g/kg CP, 213 g/kg total non-starch polysaccharides, 341 g/kg total dietary fibre, 21.0 g/kg phytate and 1.51 μmol/g glucosinolates. The carbohydrase cocktail preparation increased the total tract digestibility of non-starch polysaccharides by a 13-fold factor (0.184 versus 0.014) at the higher inclusion rate. At this inclusion, the feed enzyme significantly increased weight gains of male Ross 308 chicks by 5.47% (829 versus 786 g/bird) from 1 to 20 days post–hatch. This was aligned with numerical improvements of 3.49% (1097 versus 1060 g/bird) in feed intake and 1.48% (1.33 versus 1.35) in FCR. While Ross 308 performance objectives were not met, the Niu et al. (2023) study demonstrates the anti-nutritive properties of non-starch polysaccharides in canola meal.

The efficacy of an exogenous protease in diets based on either soybean meal or canola meal for young broiler chicks were evaluated by Cowieson et al. (2016). The growth performance of birds offered canola meal was relatively inferior; however, protease generated more pronounced weight gain and FCR responses in canola meal diets. This resulted in a significant treatment interaction between protein meals and protease.

## 6. Canola meal in reduced-crude protein diets

The formulation of typical reduced-CP broiler diets automatically depresses soybean meal inclusions. Thus, if, in addition, soybean meal can be partially replaced with canola meal in this context, the successful coupling of these two strategies would tangibly reduce soybean meal inclusions in diets for broiler chickens. However, wheat is the dominant feed grain in Australian chicken-meat production and the reduction of dietary CP levels in wheat-based broiler diets constitutes a real challenge (Selle et al., 2023b). The promise and the pitfalls of developing reduced-CP broiler diets were declared in Chrystal et al. (2021), as detailed in Table 4. Broiler chickens offered 165 g/kg CP maize-based diets clearly outperformed their wheat-based counterparts but CP reductions in maize-based diets compromised FCR and increased fat deposition.

The replacement of soybean meal with canola meal as the principal source of 'intact' protein in reduced-CP, wheat-based diets would reduce wheat (and starch) inclusions as more canola meal would be required to meet given CP targets. This, in turn, would reduce rapidly digestible dietary starch as the digestion rates of wheat starch are more rapid than maize or sorghum (Giuberti et al., 2012; Selle et al., 2021). The rapid digestion rate of wheat starch is one of the likely factors contributing to the shortfalls of CP-reduced, wheat-based broiler diets (Selle et al., 2022a). Capping dietary starch:protein ratios has shown promise in reduced-CP diets based on both wheat (Greenhalgh et al., 2020) and maize (Greenhalgh et al., 2022). Capping dietary starch:protein ratios was essentially achieved by the incorporation of full-fat soy (362 g/kg CP) at the expense of soybean meal (505 g/kg CP). Importantly, whole canola seed could be used instead of full-fat soy to achieve similar adjustments.

The feasibility of replacing soybean meal with canola meal in reduced-CP diets was investigated in Macelline et al. (2023). This study compared two 190 g/kg CP, wheat-based broiler diets containing either soybean meal or canola meal as the only other source of "intact" protein. The soy diets contained 844 g/kg wheat, 37.4 g/kg soybean meal and 39.0 g/kg non-bound amino acids and the canola diets contained 617 g/kg wheat, 150 g/kg canola meal and 35.4 g/kg non-bound amino acids. There were no significant differences between the soy and canola diets in weight gain, feed intake and FCR in broiler chickens from 15 to 36 days post–hatch. Also, yields of breast meat and thigh meat were not significantly influenced in this comparison. However, the canola diet supported higher distal jejunal starch digestibility coefficients by 2.79% (0.959 versus 0.933; $P = 0.002$), higher AMEn by 0.66 MJ (13.63 versus 12.97 MJ/kg DM; $P < 0.001$) and higher ileal methionine digestibility coefficients by 2.14% (0.955 versus 0.935; $P = 0.017$).

Canola meal contains more digestible cysteine and digestible methionine in relative and absolute terms than soybean meal (Table 1), clearly this should be beneficial. Methionine is usually the first limiting amino acids in broiler diets and methionine may be converted to cysteine in the liver and feather follicles via the transsulphuration pathway (Brosnan and Brosnan, 2006). In practice, total sulphur amino acid (TSAA) requirements in reduced-CP diets are usually met by additional non-bound methionine because it is more economical than cysteine. This is based on the premise that sufficient methionine is converted to cysteine at adequate rates, but this approach compresses dietary cysteine:methionine ratios. However, Kalinowski et al. (2003) contended that cysteine should represent 44% of TSAA in diets for slow-feathering birds and 47% for fast-feathering birds. This raises the likelihood that levels of cysteine per se may decline to inadequate levels in reduced-CP diets. Feathers contain an abundance of cysteine (75.3 versus 7.1 mg/g) relative to methionine (Adler et al., 2018) and it is likely that partitioning of amino acids give preference to feathering in poultry (Wylie et al., 2003). It is unlikely that non-bound and protein-bound amino acids are totally bioequivalent (Selle et al., 2022b), thus the higher concentrations of cysteine in canola meal could be advantageous.

Interestingly, Bos et al. (2007) considered that the metabolic utilisation of rapeseed protein is very high in humans. These researchers found high values for the net postprandial utilisation (70.5%) and the postprandial biological value (83.8%) for a rapeseed protein isolate. They commented that rapeseed protein has a low real ileal digestibility compared with other plant proteins but also exhibits a very low deamination rate and concluded that the postprandial biological value of rapeseed protein is excellent in humans. Therefore, a novel approach to reduced-CP broiler diet formulations would be the inclusion of canola protein isolates/concentrates as a source of protein-bound amino acids, rather than non-bound amino acids, to meet specifications. This may become feasible in the future. That the post-enteral deamination rate of amino acids from a rapeseed protein isolate was described as 'very low' by Bos et al. (2007) is of real interest. Pursuant to post-enteral amino acid imbalances, the excessive deamination amino acids in broiler chickens offered reduced-CP diets could result in ammonia intoxication or 'ammonia overload' and depressed growth

**Table 4**
Impacts of CP reductions in maize or wheat-based broiler diets on dietary inclusions of grain, soybean meal and NBAA and growth performance and relative abdominal fat-pad weights from 7 to 35 days post–hatch .[1]

| Dietary CP, g/kg | Formulation[2], g/kg | | | Growth performance | | | |
|---|---|---|---|---|---|---|---|
| | Grain | Soybean meal | NBAA | Gain,g/bird | Intake,g/bird | FCR, g/g | Fat-pad, g/kg |
| **Maize** | | | | | | | |
| 222 | 511 | 334 | 7.23 | 2214 | 3208 | 1.453 | 6.4 |
| 193 | 615 | 228 | 19.47 | 2396 | 3386 | 1.415 | 11.1 |
| 165 | 721 | 113 | 38.49 | 2370 | 3481 | 1.473 | 12.8 |
| **Wheat** | | | | | | | |
| 222 | 525 | 300 | 7.30 | 2403 | 3487 | 1.453 | 6.4 |
| 193 | 637 | 177 | 26.36 | 2386 | 3507 | 1.471 | 8.5 |
| 165 | 751 | 48 | 49.39 | 1549 | 2843 | 1.840 | 7.5 |

CP = crude protein; NBAA = non-bound amino acids.
[1] Adapted from Chrystal et al. (2021).
[2] All diets contained 60.0 g/kg canola seed.

performance. Plasma ammonia concentrations determined in several broiler studies (Namroud et al., 2008; Ospina-Rojas et al., 2013, 2014; Aguihe et al., 2022) support the likelihood that ammonia overload adversely impacts broiler performance. Also, Macelline et al. (2023) found a linear relationship ($r = -0.607$; $P = 0.010$) between dietary CP levels (210, 190, 170 g/kg) and plasma ammonia concentrations. Therefore, if amino acids in canola protein isolates are less likely to be deaminated in broiler chickens this should prove advantageous as ammonia overload would be attenuated. However, it remains to be seen if the dietary inclusion costs of canola protein isolates/concentrates will permit their feasible incorporation into poultry diets.

## 7. Summary

Canola meals certainly have the potential to decrease soybean meal inclusions in diets for broiler chickens, as is the case for whole canola seed and, possibly in the future, canola protein isolates or concentrates. However, if this potential is to be realised the nutritive value of canola needs to be upgraded by breeding programs, processing technologies or dietary formulations and, ideally, improvements can and will be achieved in all three pathways. The selection of canola varieties with higher protein but lower fibre contents, and higher energy densities, would be a huge advance, provided they are agronomically viable. Exogenous enzymes targeting pectins and hemicelluloses present in canola may be able to increase the amount of digestible carbohydrates in the diet. Investigations into the degradation of glucosinolates to toxic metabolites should prove fruitful and it may be possible to develop processing procedures that limit the conversion of glucosinolates into toxic metabolites. Also, determinations of thiocyanate concentrations in canola or broiler diets may be more instructive than glucosinolate concentrations. Certainly, experiments involving the substitution of soybean meal with canola meal in reduced-CP broiler diets are to be encouraged as this combination strategy appears to hold promise.

## CRediT authorship contribution statement

**Milan Kandel:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Shemil P. Macelline:** Writing – review & editing, Writing – original draft, Conceptualization. **Mehdi Toghyani:** Writing – review & editing, Writing – original draft. **Peter V. Chrystal:** Writing – review & editing, Writing – original draft. **Mingan Choct:** Writing – review & editing, Writing – original draft, Conceptualization. **Aaron J. Cowieson:** Writing – review & editing, Writing – original draft, Conceptualization. **Sonia Yun Liu:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Peter H. Selle:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

## Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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