Journal of Applied Veterinary Sciences, 9 (1): 73-84 (January 2024).
ISSN: Online: 2090-3308, Print: 1687-4072
Journal homepage : https://javs.journals.ekb.eg

Factors Influencing Dietary Tannin Inclusion in Dairy Diets: A review

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ABSTRACT

The objective of this paper was to evaluate factors affecting tannin dietary inclusion on enteric methane emission (CH_4) and performance in dairy cows. Dairy production contributes to the greenhouse effect as it naturally emits enteric CH_4. Therefore, this has sparked a need to control enteric methane emissions using anti-methane natural compounds such as tannins. Even at moderate dietary inclusions, tannin use in animal diets can occasionally reduce dairy performance and enteric CH_4. This is due to the fact that most studies employ tannins to reduce enteric CH_4 in dairy cows excluding other influential factors by focusing on the tannin inclusion effect alone. Therefore, there is a need to study different factors that influence the effect of tannins on enteric CH_4 and dairy performance regardless of dietary tannin inclusion to improve the control of enteric CH_4 at no expense to dairy performance. Hence, there is a need to identify factors that affect dietary tannin inclusion, such as tannin source, diet and animal factors that need consideration to prevent the control of enteric CH_4 by tannins at the expense of animal performance. This approach would inform future studies relevant to the use of tannins in dairy diets to improve the effect of this treatment through in *vivo* and *in vitro* studies to ensure dairy production is harmless to the environment while meeting production targets.

Review Article:
DOI:https://dx.doi.org/10.21608/javs 023.242317.1282
Received : 13 October, 2023.
Accepted :27 Novemer, 2023.
Published in January, 2024.

J. Appl. Vet. Sci., 9(1): 73-84.

Keywords: Animal-environment relationship**, D**airy production**, E**nteric methane emissions**,** Tannins.

INTRODUCTION

The importance of dairy products to human health as a source of proteins remains undisputed. This animal production provides milk, meat, and by-product commodities such as hides to provide food security. The increase in human population necessitates an increase in animal production to meet the nutritional requirements for the survival of humanity. This demand would accelerate the negative effect of animal production on the environment. Dairy and beef production are two major sources of livestock-related enteric methane (CH_4) emissions **(Caro *et al.*, 2016).** A by-product of rumen fermentation, which occurs when feed is transformed into nutrients, is CH_4. However, CH_4 gas is a greenhouse gas with a heating power of 25-folds or more than that of carbon dioxide **(Rira *et al.*, 2015)** and constitutes about 55 % of gases released by ruminants **(Rira *et al.*, 2015).** Controlling CH_4 emissions in dairy cattle is a challenge due to the intensification of the dairy industry.

This challenge has sparked interventions into the control of ruminal digestion to discriminate against the production of CH_4 gas to promote animal production that is harmless to the environment **(Nawab *et al.*, 2020).** Therefore, phytochemicals can potentially restrict the pathway of microorganisms involved in the formation of CH_4 without negatively affecting the environment **(Patra and Puchala, 2023).** Condensed tannins are natural polyphenolic phytochemicals found in tropical and temperate foliage that can decrease methanogens and fibre digestion **(Jayanegara *et al.*, 2015).** This lowers the availability of hydrogen molecules, which are needed for the formation of CH_4 during fermentation. Another benefit of condensed tannin inclusion in dairy rations is the promotion of small-intestinal absorption of proteins by forming a protein-tannin complex that shields proteins from premature digestion in the rumen **(Anas *et al.*, 2015).**

Dietary inclusion of tannins is influential when studying the effect of condensed tannin inclusion on CH_4 emissions and ruminant performance **(Denninger *et al.,* 2020).** It is claimed that including condensed tannin at a rate of less than 3% in animal diets reduces CH_4 emissions without changing milk parameters **(Naumann *et al.,* 2017).** Contrarily, a different study found that tannins reduced CH_4 while impairing milk production **(Huyen *et al.,* 2016).** Milk yield and quality, nutritional digestibility, and feed intake appear to be impaired and exhibit different responses **(Henke *et al.,* 2017)** when condensed tannins are included in dairy rations to decrease CH_4 production **(Cardoso-Gutierrez *et al.,* 2021).**

The dietary inclusion of condensed tannins in dairy rations has been the main factor considered for the control of CH_4 emissions without affecting milk parameters **(Avila *et al.,* 2020b),** but the results produced are conflicting. The conflicting effects of tannin sources on CH_4 and ruminant performance could be credited to the structural chemistry of tannins. Tannins consist of prodelphinidins (PD) or procyanidins (PC) in their structural chemistry and the PD to PC ratio differs in different tannin sources **(Quijada *et al.,* 2018).** The inclusion level (<2%) of dietary *Acacia mearnsii* condensed tannins demonstrated a decrease in CH_4 and no effect on milk yield or quality, although protein digestibility was decreased **(Alves *et al.,* 2017a).** The 3% inclusion of *Mimosa tenuiflora* extract failed to decrease CH_4 **(Lima *et al.,* 2019).** It has been established that *A. mearnsii* condensed tannins (400 g/d) decrease both CH_4 and milk yield **(Williams *et al.,* 2020).** Other studies have proven that the inclusion level (0–3%) of quebracho or *A. mearnsii* condensed tannins does not affect milk yield even though CH_4 was not measured **(Henke *et al.,* 2017; Gerlach *et al.,* 2018).** Some studies reported that dietary inclusions of condensed tannins up to 7.5% or 10% could be used without affecting the milk yield or quality **(Griffiths *et al.,* 2013; Kapp-Bitter *et al.,* 2020).**

These milk performance variations for different dietary tannin inclusions suggest that other factors may need consideration to reduce CH4 without negatively impacting milk production and feed intake. Therefore, factors that influence the condensed tannin effect on dairy performance and CH_4 need to be identified. This would improve the discovery of a dietary inclusion of tannins that depresses CH_4 without depressing milk or intake performance. The objective of this review was to describe tannin source, dietary and animal factors that affect tannin results on dairy performance and enteric CH_4, and the effects of A. mearnsii tannins on dairy performance and enteric CH_4.

1. Intrinsic factors affecting tannin activity

The chemical composition influences the effect of tannins on animal performance and CH_4. This can be attributed to the tannin effect being different depending on tannin sources.

1.1. Structural Form

The structural formation of condensed tannins consists of prodelphinidins (PD) or procyanidins (PC) in nature **(Quijada *et al.,* 2018).** Condensed tannins have both structures, but one of these structures tends to be dominant, resulting in a varying PD/PC ratio per source of condensed tannins. A higher PD/PC ratio of condensed tannins has been found to reduce *in vitro* CH_4 emissions better than an inverse form of the ratio **(Niderkorn *et al.,* 2020).** Higher PD/PC ratio condensed tannins may possess the rumen-digestion-resistant 5-deoxy flavan-3-ol subunit by stimulating the exertion of persistent anti-methanogenesis **(Niderkorn *et al.,* 2020).** The explanation offered is that condensed tannins with a low PD/PC ratio may contain the typical 5-hydroxyl group and this hydroxyl group is susceptible to breakdown during ruminal digestion **(Naumann *et al.,* 2018).**

Available studies have used PD-condensed tannins from sainfoin pellets and PC-condensed tannins from hazelnut pericarps and there have been contrasting results. *In vivo* Sainfoin inclusion decreased CH_4 emissions with increased milk yield without the depression of protein digestibility **(Huyen *et al.,* 2016).** Hazelnut inclusion *in vivo* decreased CH_4 emissions without a change in milk yield **(Terranova *et al.,* 2021).** These limited studies demonstrate that condensed tannin sources with a higher PD/PC ratio are more effective in controlling CH_4 emissions and have positive effects on milk performance. These findings imply that studies that use condensed tannins to decrease CH_4 emissions in dairy diets need to consider the PD/PC ratio of the tannin source to improve the incorporation of condensed tannins in animal diets to prevent deleterious effects on animal performance.

1.2.Molecular weight

Observations show that high molecular weight (MW) condensed tannins exert a higher depression of CH_4 emission and acetate concentration than low MW condensed tannins **(Saminathan *et al.,* 2015; Petlum *et al.,* 2019)**. High MW condensed tannins can decrease CH_4 and protein digestibility without decreasing dry matter digestibility **(Saminathan *et al.,* 2015)**. The positive association between reduced protein digestibility and the high MW of condensed tannins suggests that using a moderate MW condensed tannins is recommended. This would prevent tannins from decreasing CH_4 emissions and animal performance parameters. Condensed tannins with higher MW are associated with high protein binding ability which decreases CH_4 but renders proteins unavailable for absorption in the small intestines and depresses milk performance **(Saminathan *et al.*, 2015; Petlum *et al.*, 2019).**

High MW condensed tannins may lack a consistent effect on methanogens. Higher MW condensed tannins decrease hydrophilic methanogen order (*Methanomicrobiales, Methanopyrales, Methano-coccales, Methanobacteriales, Methanocellales* and *Methanosarcinales*) and increase the methylamine using methanogens (*Methanoplasmatales* or *Thermoplasmatales)* **(Saminathan *et al.*, 2016).** Therefore, the mode of action of high MW condensed tannins may not be broad-spectrum but only based on suppressing a certain methanogen group. Such inconsistent effects of tannins may result in the proliferation of other methanogens. Conversely, tannin effect on methanogens may be coated because condensed tannins may fail to affect protozoa which may benefit methanogens as they depend on protozoa for methanogenesis **(Sarnataro *et al.*, 2020).** This could be the cause of condensed tannin inclusions being ineffective on CH_4 emissions in some studies **(Focant *et al.*, 2019).**

2.Dietary factors

Tannins influence ruminant performance by modulating crude protein digestion and fibre digestibility. The chemical composition of the diet supplemented with tannins also influences the effect of tannins on ruminant performance and CH_4.

2.1. Crude protein Digestibility

One of the main challenges that result from the addition of condensed tannins to animal diets is the suppression of crude protein **digestibility (Zhang *et al.*, 2019).** The compromise of crude protein digestibility suppresses milk production parameters **(Henke *et al.*, 2017).** There is a suggestion that aiming for crude protein content that is excessive in the basal diet could counter the suppression of crude protein digestibility by dietary condensed tannins which affect milk parameters **(Denninger *et al.*, 2020).** Finding the crude protein inclusion level to use in a condensed tannin-enriched diet without affecting milk production remains less studied. Diets enriched with 20.4% crude protein content and 2.5% *A. mearnsii* tannins supported conditions that increased CH_4 emissions. In that study, there was an increased acetate-to-propionate ratio and decreased propionate and total tract digestibility **(Koenig and Beauchemin, 2018).** In a tanniferous diet with low crude protein, there has been an observation that protein synthesis remains unchanged when protein digestibility is also unchanged **(Avila *et al.*, 2020b).**

Manipulation of tannin sources seems to be part of the solution to increase protein synthesis and offer moderate protein digestibility that can maintain animal performance. Bayberry condensed tannins (3%) depressed protein digestibility more than *A. mangium* condensed tannins **(Zhang *et al.*, 2019).** A similar trend persisted when *Leucaena leucocephala* decreased protein digestibility more than *A. saligna* condensed tannins in Barki rams **(El-Zaiat *et al.*, 2020).** Identifying tannin sources with low suppression of protein digestibility could preserve animal performance. High protein content in the diet increases protein digestibility and milk production without influencing CH_4 **(Niu *et al.*, 2016).** However, findings remain contrasting regarding dietary protein content in relation to CH_4 emissions and protein digestibility.

Higher dietary protein content (15.2-18.5%) increased the digestibility of crude protein but did not affect CH_4 emissions, milk yield and feed intake **(Niu *et al.*, 2016).** Increasing protein levels (10-19%) in the concentrate sometimes increases CH_4 emissions **(Van Dung *et al.*, 2019).** Increasing the crude protein content (14.1-18.1%) in the diet did not affect protein digestibility and CH_4 emissions **(Hynes *et al.*, 2016)**, thus, suggesting that the protein content in the diet may need to be below 18% for CH_4 emissions to decrease and increase the impact of condensed tannins addition in animal diets for controlling CH_4. The addition of quebracho tannin extract (0-2%) in a diet with 16% crude protein decreased protein digestibility and did not affect CH_4 emissions **(Beauchemin *et al.*, 2007).**

2.2.Fiber digestion

Condensed tannins seem to exert their CH_4 depression ability by decreasing fiber-digesting and methanogenic microorganisms **(Díaz Carrasco *et al.*, 2017)**. This is often attributed to condensed tannins increasing propionate formation over that of acetate from the pyruvate **(Moats *et al.*, 2018)**. Fiber digestion promotes the release of H_2 needed for the formation of CH_4. Promoting the lower acetate-to-propionate ratio by condensed tannins decreases the H_2 needed for the formation of CH_4 **(Geneviève *et al.*, 2018)**. Formation of strategies to ensure that condensed tannins remain effective in stimulating CH_4 suppression by decreasing fiber-digesting microorganisms and methanogens is needed. Exertion of this effect by condensed tannins on methanogens may depend on the absence of microbes that counter the tannin-protein complex, decreasing the ruminal digestion of crude protein. *Selenomonas ruminantium* bacteria are reported to exert a the premature dissociation of the tannin-protein complex **(Díaz Carrasco *et al.,* 2017)**. The blend of quebracho and chestnut tannins increased *S. ruminantium* population **(Díaz Carrasco *et al.,* 2017)**. There has also been a further demonstration of increasing acetate and gas production in cultures with prior condensed tannins adaptation **(Hoehn *et al.,* 2018)**.

These studies demonstrate that the resistance of rumen microbes to condensed tannins may occur. Therefore, information on the response of fibrolytic microbes to sources of condensed tannins is necessary to improve the control of CH_4 production using condensed tannins.

2.3.Substrate

The source of the basal diet remains part of the contributing factors in the conflicting results found when condensed tannins are incorporated in dairy diets to decrease CH_4 without limiting animal performance. Adding condensed tannins in accordance with the basal diet source could assist in decreasing CH_4 emissions without depressing milk production and other performance parameters. Increasing the concentrate-to-forage ratio (40:60 and 60:40) suppressed CH_4 emissions **(Na *et al.,* 2013).** Increasing forage levels (37.4% or 53.3%) decreased milk yield and feed intake but increased CH_4 emissions per day without affecting protein digestibility **(Niu *et al.,* 2016).** This suggests that a certain forage-to-concentrate ratio in the total-mixed ration could suppress CH_4 emission and improve milk production parameters. Hence, the addition of condensed tannins in the diet may lack suppression of CH_4 emissions and the improvement of milk production if the concentrate-to-forage ration in the total mixed ration is low. This could explain findings that demonstrated that total mixed ration enriched with condensed tannins (0-2%) did not affect yield, fat and protein of milk, dry matter intake and CH_4 emission **(Denninger *et al.,* 2020).**

The selective mixing of pastures in pasture-based animals could suppress CH_4 and enhance milk yield in animal diets by condensed tannins in pasture-based dairy cows. Including white clover in ryegrass pasture at a rate of 0-60% increased milk yield and CH_4 suppression **(Lee *et al.,* 2004).** Feeding less fibrous and highly digestible pastures or tannin-rich pastures can improve the efficacy of tannin sources inclusion level to control methanogenesis without affecting animal parameters.

3. Animal factors

The effect of dietary tannins on ruminant performance may be influenced by lactation factors, gut infestations, animal genetics, and how rumination time and digesta passage rate respond to dietary tannins.

3.1. Lactation

The current findings have shown that dietary condensed tannin inclusion levels are suitable for inclusion in diets of dry cows as milk yield may be interrupted. As days in milk increase, CH_4 emissions increase in dairy cows **(Wall *et al.,* 2012; Alstrup *et al.,* 2015).** The explanation for this observation was that as days in milk increase, the passage rate in cows decreases, causing feed to be retained in the rumen, increasing the digestibility of fibre, which is conducive to CH_4 formation **(Alstrup *et al.,* 2015).** The increase in parity of the animal has also been associated with the increase in CH_4 **(Bittante *et al.,* 2018).** Further findings have shown that primiparous cows have a diverse methanogenic population compared to multiparous cows **(Kumar *et al.,* 2015).** This suggests that as parity increases methanogens of different survival modes persist making the need for a rumen fermentation additive that can control various methanogen archaea at one time essential. This further emphasizes the need to understand the effect of condensed tannins per methanogen type in cows at different parities to control CH_4 production without limiting animal performance.

3.2. Gut infestations

Gastrointestinal nematode infestations have increased CH_4 in ruminants **(Fox *et al.,* 2018).** The mechanism by which gastrointestinal nematodes increase CH_4 in the rumen is unclear but could be attributed to these parasites contributing to the effects that support CH_4 production such as fibre digestion. Gastrointestinal nematodes have been associated with an increased protozoa population, producing hydrogen that methanogens use to produce CH_4 **(Szulc *et al.,* 2020).** The effect of gastrointestinal nematodes on CH_4 may influence the tannin effect on CH_4. It has been reported that nematode infestations render condensed tannins ineffective against CH_4 emission **(Lima *et al.,* 2019).** Future studies need to investigate the effect of condensed tannins on gastrointestinal nematodes and CH_4 emissions in one experiment to better understand the relationship between condensed tannins inclusion levels and CH_4 per gastrointestinal infestation in animals.

Studies on the control of gastrointestinal nematodes using condensed tannins need to consider investigating the effect of condensed tannins on the different life stages of these parasites. Findings suggest that dietary condensed tannin supplementation can decrease faecal egg count and larval populations of gastrointestinal nematodes **(Pathak, 2013; Costa-Júnior *et al.*, 2014).** Drenching condensed tannins according to body weight to control gastrointestinal nematodes is a promising intervention as it can control gastrointestinal nematodes **(Ahmed *et al.*, 2014; Mhlongo, 2018).** This intervention is more practical for uniformly controlling gastrointestinal nematodes in animals. An *in vitro* study demonstrated that condensed tannins decrease eggs' hatchability and larval development **(Molan and Faraj , 2010).** In most studies, the response to condensed tannins of gastrointestinal nematodes has been conducted more in small rather than large stock. Liver flukes rather than nematodes being the main parasites affecting cattle limit the extrapolation of the response of nematodes to condensed tannins in cattle. Studying the response of CH_4 emissions in infested cattle fed condensed tannins may improve the development of the inclusion level that decreases CH_4 without disrupting animal performance.

3.3. Animal genetics

Understanding the effect of genetics on CH_4 is part of the under-considered factors that could assist in better controlling CH_4 emission and performance in animals using condensed tannins. Crossbred cows emit more CH_4 than purebred cows **(Pedreira *et al.*, 2009).** The breed also affects CH_4 emissions as Jersey cows were found to emit less CH_4 than the Holstein-Friesian breed **(Ricci *et al.*, 2014).** The lactation stage influences CH_4 in cows as dry cows have been found to emit less CH_4 than lactating cows **(Dall-Orsoletta *et al.*, 2016).** Ruminant animal species influence CH_4 emissions in animals as cattle have been found to emit more CH_4 gas than sheep or goats **(Giamouri *et al.*, 2023).** Animals with a lower feed intake emit fewer CH_4 emissions **(Bell *et al.*, 2011).** Rumination time has a genetic positive correlation with the yield of milk and protein and a negative genetic correlation with CH_4 yield **(López-Paredes *et al.*, 2020).**

3.4. Digesta passage rate

Tannin dietary additions decrease nutrient digestibility **(Ahnert *et al.*, 2015).** Tannins decrease fiber digestion which affects the digesta passage rate. This is due to the positive correlation between feed intake and the passage rate of digesta **(Al-Kindi *et al.*, 2017).** Increased mean retention time (MRT) of digesta has been found to increase CH_4 emission and the digestion of fibre and organic matter which form conditions that favour the production of CH_4 gas **(Huhtanen *et al.*, 2016).** Low MRT decreases CH_4 emissions by prioritising energy for the improvement of the efficiency of microbial protein synthesis instead of volatile fatty acids (VFAs) **(Tymensen *et al.*, 2012).** This implies that this technique removes hydrogen which is needed for the formation of CH_4 gas by decreasing the acetate-to-propionate ratio. Contrary to the rumen, the addition of carob leaf condensed tannins increased MRT of liquid digesta in the intestines, total gastrointestinal tract (GIT), omasum and abomasum, and foregut, but solid digesta MRT increased in the intestines and total GIT **(Silanikove *et al.*, 2001).**

Quebracho tannin inclusion (2 or 4%) did not affect total MRT, caecum MRT or passage rate in the mixing compartment **(Al-Kindi *et al.*, 2017).** *A. mearnsii* condensed tannin (0–2.25%) decreased the disappearance rate of rumen solids, digestion rate in the rumen and passage rate of undigested residues **(Tseu *et al.*, 2020).** The difference in the effect of condensed tannins on the passage rate of digesta may be due to feed intake. These studies demonstrated that feed intake increased when the passage rate was not changed but decreased where the passage rate increased.

3.5. Rumination Time

Regarding the feeding behaviour of ruminants, higher rumination time has been associated with high CH_4 emissions **(Watt *et al.*, 2015).** This finding makes studying the feeding behaviour of animals fed condensed tannin-enriched diets important for improving animal performance and decreasing CH_4 emissions. *A. mearnsii* condensed tannin extract powder inclusion (0–2.25%) **(Tseu *et al.*, 2020)** and *Mimosa tenuiflora* condensed tannin extract inclusion (0–3%) **(Lima et al., 2019)** did not affect the total ruminating time but decreased total eating time. Wherein chestnut condensed tannin powder inclusion (0–10%) **(Kapp-Bitter *et al.*, 2020)** and tanniferous Sainfoin hay inclusion (0–1%) **(Scharenberg *et al.*, 2009)** lacked an effect on rumination and eating time. *Mimosa tenuiflora* condensed tannins extract (0–7.5%) increased ruminating, eating and chewing time and decreased idling time **(Nascimento *et al.*, 2021).**

This result suggests that animals fed diets with added condensed tannins tend to adopt strategies to compensate for the decrease in digestibility that is associated with condensed tannin addition. Those strategies may include decreasing eating time by eating the feed in small amounts to deal with the astringent effect in tannin-enriched feeds if the condensed tannins used have high astringency. This also suggests that the astringency of the condensed tannins may disturb the normal breakdown of feed in animals. This results in increased rumination time to break down the feed into smaller particles. Rumination time seems to also be influenced by the lactation stage of the animal. Cows in early lactation ruminate less due to the smaller rumen size but gradually ruminate more as the rumen increases in size and so does CH_4 emission **(López-Paredes *et al.*, 2020).** This suggests inclusion level of the effect of condensed tannins on CH_4 emission and milk production needs to correlate with the lactation stage to improve the CH_4-decreasing while maintaining the milk production effect on condensed tannin-rich diets.

4. *A. mearnsii* tannin effect on dairy performance

A. Mearnsii is one of the most commonly used tannin sources to control CH_4 and improve dairy production. However, this tannin source has contrasting dairy performance and CH_4 results **(Lazzari *et al.*, 2023).** The contrast in results may be due to a low understanding of the effect of this tannin source on nutrient digestibility, feed intake, and rumen fermentation using similar dietary inclusions.

4.1. Rumen volatile fatty acids

Rumen volatile fatty acids (VFAs) influence CH_4 and milk performance. Acetate correlates with milk fat **(Seymour *et al.*, 2005)** and CH_4. While propionate negatively correlates with CH_4 and positively correlates with milk performance (Wu *et al.*, 2021), *A. mearnsii* tannins need to be studied for their effect on rumen VFAs. The addition of *A. mearnsii* tannins (0–41 g/d) decreased acetate but increased propionate and the acetate–propionate ratio (ATPR) **(Carulla *et al.*, 2005).** Dietary inclusions (0–1.49% DM) of *A. mearnsii* tannins have been noted for decreased ATPR and acetate and increased propionate and total VFAs **(Krueger *et al.*, 2010).** Dietary inclusions of *A. mearnsii* tannins (0–1.5%) did not affect acetate, propionate, butyrate, ATPR or total VFAs **(Perna Junior *et al.*, 2022).** Adding 0-2.5% of *A. mearnsii* tannins affected ATPR, butyric acid, decreased propionic acid, and did not affect acetic acid **(Koenig and Beachemin, 2018).** Encapsulated or non-encapsulated *A. mearnsii* tannin did not affect rumen VFAs at 2% dietary inclusions **(Ibrahim and Hassen, 2022).** Dietary inclusions of *A. mearnsii* tannins have been found to have no effect on rumen VFAs except for decreasing acetate and butyrate **(Avila *et al.*, 2020a).** These results suggest that tannins have a contrasting effect on rumen VFAs, which may lead to an inconsistent effect on CH_4 and milk performance.

4.2. Milk performance

Tannins benefit milk performance as they bind to proteins in the rumen. The protein-tannin complex reduces rumen crude protein digestion, increasing crude protein digestion in the small intestines. Increased rumen undegradable protein increases milk yield **(Mikolayunas-Sandrock *et al.*, 2009).** Adding *A. mearnsii* tannins (2% DM) has been found to not affect milk yield and milk fat or protein percentages **(Alves *et al.*, 2017b; Orlandi *et al.*, 2020a).** The dietary addition of *A. mearnsii* tannins (0–2% DM) did not affect milk parameters **(Avila *et al.*, 2020b)**. Inclusion at 0-3% of *A. mearnsii* tannins has been reported to have no effect on milk parameters **(Gerlach *et al.*, 2018).** The addition of 0-1% of *A. mearnsii* tannin in diets has been reported to have no effect on milk parameters **(Orlandi *et al.*, 2020).** Drenching cows with *A. mearnsii* tannin (0–400 g/day) decreased milk yield and fat but did not affect milk protein **(Williams *et al.*, 2020).** Similarly, **Grainger *et al.*, (2009)** drenched cows with *A. mearnsii* tannins and noted decreased milk yield and no effect on milk protein or fat percentages. These results demonstrate that dietary inclusions of *A. mearnsii* of 0-3% are ineffective in modulating milk parameters while drenching 200–400 *A. mearnsii* would negatively affect milk yield.

4.3. Nutrient intake

Dairy performance relies on the optimum nutrient intake to maintain dairy production. *A. mearnsii* tannins need to be evaluated for their effect on the intake to prevent the decrement of CH_4 at the expense of milk performance. Dietary incorporation of *A. mearnsii tannins* (0–2% DM) has been noted to have no effect on the intake of DM, OM and NDF **(Avila *et al.*, 2020a).** Similarly, the addition of *A. mearnsii* tannins (4.2% DM) did not affect DM, OM, CP or NDF intakes **(Adejoro *et al.*, 2020).** The addition of lipid-encapsulated or none-encapsulated *A mearnsii* (0 or 4% DM) tannin did not affect DM, OM, NDF or ADF intake **(Adejoro *et al.*, 2019).** Intraruminal infusion of *A. mearnsii tannins* (0–6% DM) decreased DM, OM, and NDF intake **(Kozloski *et al.*, 2012).** Dietary supplementation of *A. mearnsii tannins* (0–8% DM) decreased DM, CP, and ether extract intake **(de S. Costa *et al.*, 2021a).** These results show that *A. mearnsii* inclusion of up to 4% does not affect the intake of nutrients. However, nutrient intake decreases when the inclusion of *A. mearnsii* tannins increases to 8%. This may be due to the astringent effect of tannins that decreases intake. Interventions such as encapsulation of tannins have been tried to evade the effect of tannin astringency **(Adejoro *et al.*, 2019).**

Dairy performance relies on the optimum nutrient intake to maintain dairy production. *A. mearnsii* tannins need to be evaluated for their effect on the intake to prevent the decrement of CH_4 at the expense of milk performance. Dietary incorporation of *A. mearnsii* tannins (0–2% DM) has been noted to have no effect on the intake of DM, OM and NDF **(Avila *et al.*, 2020b).** Similarly, the addition of lipid-encapsulated or none-encapsulated *A. mearnsii* (0 or 4% DM) tannin did not affect DM, OM, NDF, or ADF intake **(Adejoro *et al.*, 2019).** Intraruminal infusion of *A. mearnsii* tannins (0–6% DM) decreased DM, OM and NDF intake **(Kozloski *et al.*, 2012).** Dietary supplementation of *A. mearnsii* tannins (0–8% DM) decreased DM, CP and ether extract intake **(de S. Costa *et al.*, 2021b).** These results show that *A. mearnsii* inclusion of up to 4% does not affect the intake of nutrients. However, nutrient intake decreases when the inclusion of *A. mearnsii* tannins increases to 8%. This may be due to the astringent effect of tannins and the astringent effect of tannins decreases intake **(Mhlongo *et al.*, 2023).** Interventions such as encapsulation of tannins have been tried to evade the effect of tannin astringency **(Adejoro *et al.*, 2019).**

4.4. Nutrient digestibility

A. Mearnsii tannins are to be investigated for their effect on nutrient digestibility to prevent the limitation of dairy performance. This is due to tannins' ability to control CH_4 by decreasingfibrer and crude protein digestion in the rumen. Supplementation of *A. mearnsii* tannins decreased DM, NDF, ADF and hemicellulose digestibility but did not affect CP digestibility **(Carulla *et al.*, 2005).** *A. mearnsii* tannins addition in diets decreased only crude protein digestibility **(Avila *et al.*, 2020b).** The dietary addition of lipid-encapsulated *A. mearnsii* tannins(0–4%% DM) increased the digestibility of DM, OM, CP, NDF and ADF **(Adejoro *et al.*, 2020).** *A. mearnsii* addition in diets(0–8%)) decreased the digestibility of DM, OM, CP and NDF **(de S. Costa *et al.*, 2021a).** *A. mearnsii*tannins additions(0–2%% DM) increased DM and decreased NDF digestibility **(Avila *et al.*, 2020b).** The addition of *A. mearnsii* tannins at a rate of 0.6 % DM **(Perna Junior *et al.*, 2022)** and 0.77 % DM **(Orlandi *et al.*, 2020a)** did not affect the digestibility of nutrients. These studies show that moderate inclusions of *A. mearnsii* tannins do not affect nutrient digestibility. However, 8 % tannin inclusion in diets will likely decrease nutrient digestibility. This may be due to the tannin-protein complex not reasonably reversing in the abomasum and small intestines to allow nutrient digestibility. This shows that encapsulation of tannins may be beneficial in preventing the adverse effect of tannins on nutrient digestibility.

4.5. Enteric CH_4

Dietary inclusions of *A. mearnsii* tannins (0–2% DM) decreased CH_4 **(Alves *et al.*, 2017b).** Dietary inclusions of *A. mearnsii* tannins (0–20%) decreased *in vitro* CH_4 **(Hassanat and Benchaar, 2013).** Inclusions of *A. mearnsii* tannins (0–4.2% DM) did not affect CH_4 **(Adejoro *et al.*, 2020).** *Acacia mearnsi* addition in diets (0–1.5% DM) decreased CH_4 **(Perna Junior *et al.*, 2022).** Dietary *A. mearnsii tannins* (0–4%DM) decreased CH_4 but had a better effect when they were not encapsulated **(Adejoro *et al.*, 2019).** Drenching *A. mearnsii* tannins (0–263 g/d) decreased CH_4 **(Grainger *et al.*, 2009).** However, 0-0.6% DM of *A. mearnsii* tannins decreased CH_4 **(Perna Junior *et al.*, 2022).** Condensed tannins control CH_4 by decreasing rumen microbial populations. Tannin decreases CH_4 by reducing methanogens and fibrolytic rumen populations. During fermentation, fibrolytic microbes release H_2, which methanogens use for methanogenesis. Dietary inclusions of *A. mearnsii* tannins (0–2% DM) decreased protozoa populations (*Entodinium*) **(Avila *et al.*, 2020b).** Dietary additions of *A. mearnsii* tannins (0-0.6% DM) did not affect protozoa populations **(Kozloski *et al.*, 2012).** Tannin introduction to animals by drenching rather than diet incorporation may be a more effective way to control CH_4 without affecting feed palatability.

CONCLUSION

Basal diet source, mode of action of the tannin source, condensed tannin source, crude protein content, lactation stage, animal genetics, gut health, rumination time, molecular weight of tannin source, on-farm applicability, digesta passage rate and structural form of condensed tannins may influence the effect of the inclusion level of condensed tannins on the control of CH_4 production and performance in ruminants. There is a lack of consistent consideration of these factors in some of the available studies when exploring the inclusion of condensed tannins in the control of CH_4 production, which perpetuates the inconsistent results. These variables need to be considered to improve the consistency of the effect of the condensed tannins as a treatment for reversing CH_4 production and improving performance in ruminants.

Acknowledgement

We would like to thank CSIR-Interbury and HWSETA bursary for funding the first author.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the research data and tools used in this review.

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How to cite this article:
Lindokuhle Christopher Mhlongo, Cresswell Mseleku, Thando Tenza and Ignatius Verla Nsahlai, 2024. Factors Influencing Dietary Tannin Inclusion in Dairy Diets: A review. Journal of Applied Veterinary Sciences, 9 (1): 73-84.
DOI:**https://dx.doi.org/10.21608/javs.2023.242317.1282**