TYPE Review
PUBLISHED 26 May 2023
DOI 10.3389/fanim.2023.1137562

OPEN ACCESS

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RECEIVED 04 January 2023
ACCEPTED 25 April 2023
PUBLISHED 26 May 2023

CITATION
Amad AA and Zentek J (2023) The use of *Moringa oleifera* in ruminant feeding and its contribution to climate change mitigation.
Front. Anim. Sci. 4:1137562.
doi: 10.3389/fanim.2023.1137562

The use of *Moringa oleifera* in ruminant feeding and its contribution to climate change mitigation

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Livestock production in developing countries faces several difficulties such as a general shortage of feed resources, regional availability, and quality. Climate change further exacerbates these problems, leading to a massive reduction in ruminant productivity. Therefore, there is a need for the use of adaptable and resilient forage plants that can also contribute to reducing greenhouse gases. The *Moringa oleifera* tree is well known as an agroforestry tree and has adapted to growing in harsh conditions. It produces a high amount of biomass in a short period and contains high levels of nutrients and biologically active components. All parts of the *Moringa* tree are valuable and have multiple benefits and applications. Therefore, *Moringa oleifera* has great potential and can be used as a forage crop, storing carbon dioxide (CO_2) and improving ruminant performance and the livelihoods of farmers in the tropics. This article aimed to present the results and findings of studies related to the use of *Moringa* in ruminant feed (cattle, sheep, and goats) and its contribution to climate protection. Several studies highlighted that *M. oleifera* can be used as green fodder either individually or in combination with other crops or concentrate feeds to improve the performance of ruminants, such as the growth rate, milk yield, and milk constituents, without negatively impacting animal health. This improvement in performance could be attributed to the favorable nutrient content in *M. oleifera*, delivering proteins in conjunction with bioactive compounds such as alkaloids, flavonoids, phenolics, glucosinolates, carotenoids, sterols, saponins, phenolic acids, tannins, and isothiocyanates. Furthermore, it has been shown that this plant can be produced in high yields and thus might be an excellent carbon dioxide sink to absorb and utilize carbon dioxide, reducing the anthropogenic load of carbon dioxide in the atmosphere. In addition, feeding cattle and other ruminants with *M. oleifera* leaves or seeds significantly decreases ruminal methane emissions, which could contribute to adapting to climate-friendly farming. Thus, the use of *Moringa* can make a sustainable contribution to strengthening animal production, especially in countries with limited feed resources.

KEYWORDS

ruminants, performance, agroforestry, climate change, methane emission, carbon dioxide mitigation

Introduction

Ruminant production is a very important sector for farmers in developing countries. The meat and milk from ruminants are relevant sources of nutrients such as proteins, essential amino acids, calcium, and vitamin D, contributing to a balanced diet in humans. Ruminant production faces multiple and global challenges such as limited arable land, feed availability due to ongoing reduction in pasture and cultivable areas for crop production, water deficiency, and accelerating climate change (Halmemies-Beauchet-Filleau et al., 2018). Climate change is a challenge for plant and animal production and it is expected to have important consequences on environmental performance, especially in tropical and semitropical regions. Drought periods, heat waves, and seasonal variation in rainfall impair crop production and thus can also threaten the requirements and supplies of adequate and high-quality feed for farm animals. In the past three decades, climate change has reduced global agricultural production by 1–5% per decade (Thornton et al., 2015). In addition, in developing countries, the cost of feed ingredients is volatile and constantly increasing, which are the main constraints in low-income countries (Devendra and Leng, 2011), further complicating animal production and making products unaffordable for the consumer. Therefore, mitigating and reducing these impacts requires creative and innovative efforts by scientists and specialists worldwide, which may also help to stabilize and increase livestock productivity. Studies show that the environmental and climate impact of livestock farming can be improved through sustainable animal feeding by selecting optimal and innovative feeds, as well as by using adaptive and resilient forage plants that also have a positive effect by limiting the CO_2 footprint. Gedefaw (2015) reported that there is an urgent need to implement climate-friendly strategies that can build more resilient food and feed systems to combat climate change. Trees and shrubs in the tropics play very important roles in human and livestock nutrition (Smith, 1994). Moreover, reports showed that tree leaves are one of the most promising protein substitutes, with high nutritional value, medicinal benefits, and low market prices (Kakengi et al., 2005). In this context, the *M. oleifera* tree has great potential as a foliage plant to improve the livelihoods of farmers in the tropics (Gedefaw, 2015). The *Moringa oleifera* is a fast-growing softwood tree and is well adapted to growing in harsh conditions such as those in arid and semiarid areas. *Moringa oleifera* possesses not only a high nutritional profile (protein, fat, and minerals) but it is also an excellent source of biologically active compounds, and, furthermore, it has a low quantity of antinutritional factors such as tannins and saponins. All parts of *Moringa* (leaves, seeds, pods, flowers, bark, and roots) are valuable and have multiple benefits and uses. Its products have been traditionally used in medicine, human nutrition, feed for animals, water purification, fuel wood, dye, conservation, and green manure. Therefore, it is known as miracle or a multipurpose tree (Koul and Chase, 2015; Rizwan et al., 2022). In addition, it has been reported as one of the most widely used fodder crops, with potential as a browse plant in ruminant dietary supplementation (Makkar and Becker, 1996) and it is considered a beneficial and ideal tree for agroforestry (Horn et al., 2022). Moreover, *M. oleifera* is a suitable plant for climate protection due to its high use and adaptability in agriculture and the environment (Ndubuaku et al., 2015; Daba, 2016).

As mentioned above, the foliage of trees and shrubs can be used as feed or supplements to provide animals with nutrients (proteins and minerals). In addition, these trees contain secondary metabolites (tannins and saponins) that reduce methane production, with antimethanogenic properties (Kamra et al., 2008; Jayanegara et al., 2009; Delgado et al., 2012; Palangi and Lackner, 2022). In this context, this review highlights and discusses the main research findings related to *M. oleifera* as a readily available and cheap feed for ruminants (cattle, sheep, and goats) in combination with its effects on animal performance. Moreover, this review aims to explain the use of parts of this plant as feed or dietary supplements to reduce rumen methane formation and also to understand its contribution to climate change adaptation in livestock production in developing countries.

Biological characteristics of *M. oleifera* and its cultivation

Moringa oleifera is a slender softwood plant belonging to the monogeneric family *Moringaceae* which includes approximately 13 species. This tree, native to the foothills of the Himalayas, India, has been introduced and cultivated in many tropical and subtropical countries (Bosch, 2004; Price, 2007). *Moringa* is a fast-growing, deciduous tree and branches freely. This plant can withstand dry seasons. It is a perennial plant and can grow to a height of 10 m and a trunk diameter of 40 cm. *Moringa oleifera* is considered a small- to medium-sized tree that is well adapted to the temperature range 20–40°C. It grows in the wild and is also planted on farms and compounds. It can be grown in all kinds of soils. However, it is best suited to fertile and well-drained soils and it tolerates slight frosts (Price, 2007; Trigo et al., 2021). *Moringa* trees have large and deep taproots, are white in color, have a distinctive pungent odor, and very sparse lateral roots that allow them to grow in areas with little rainfall (Mohanty et al., 2020). Its leaves are tripinnate and compound, feathery and small in size, with green to dark green elliptical leaflets 1–2 cm long. The leaves grow on trees with drooping and hanging branches, mostly at the tips of the branches (Paliwal et al., 2011). The flowering of moringa occurs 4–12 months after planting. However, some varieties can flower at 4–5 months after planting. The flowers tend to have yellow-white petals with a pleasantly light fragrance. Its immature fruit (pods) are green in color, 10–60 cm in length, contain 15–20 seeds, and at maturity change color to brown. The shape of a dry seed is round or triangular and it is covered by a light woody shell with papery wings; each tree can produce between 15,000 and 25,000 seeds annually (Paliwal et al., 2011; Su and Chen, 2020; Amad and Zentek, 2022) depending on the variety. *Moringa oleifera* can be propagated by direct seedlings, cuttings, or by seeds under minimal care and with a wide range of management practices (Paliwal et al., 2011). *Moringa* trees grown from seeds start producing pods (fruit) in the first year. Similarly, trees grown from large cuttings typically begin producing fruit 12–18 months after planting. *Moringa oleifera* can be harvested several times during the growing season and has a high biomass yield ranging from 43 to 115 t/hectare annually (Makkar and Becker, 1996; Makkar and Becker, 1997; Kholif et al., 2016).

Nutrients and phytochemical compounds in *M. oleifera*

Nutrients

Moringa oleifera is known for its nutritional potential; therefore, all parts of *M. oleifera* are a storehouse of important and essential nutrients such as proteins, fats, carbohydrates, vitamins, and essential amino acids (Stadtlander and Becker, 2017). Previous studies reported the concentrations of organic nutrients and minerals in different parts of this plant (Table 1). It must be emphasized that stems and immature pods of *M. oleifera* have lower nutrient levels compared to leaves. The leaves of *Moringa* contain approximately 27–30% or slightly more protein on a dry matter (DM) basis, with significant quantities of all the essential amino acids (Amad and Zentek, 2022). The protein content of *Moringa* leaf meal is higher than that of other forage plants such as *Medicago sativa* (Alfalfa) and many commonly consumed green leafy vegetables (spinach and mint). In addition, it is equivalent to many pulses such as soybeans, which contain 22–24% protein DM (Joshi and Mehta, 2010). The leaves have high contents of calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), chloride (Cl), and iron (Fe) among other minerals (Mulyaningsih and Yusuf, 2018). The crude fat content of *Moringa* leaves reaches an average of up to 9% on a dry matter basis, with polyunsaturated omega-3 and omega-6 fatty acids, in particular linoleic, linolenic, and oleic acid dominating. *Moringa oleifera* leaves have a high concentration of crude fiber (4.8–27.6% DM). The seeds of the *Moringa* plant have high levels of protein and lipids (Table 1). Dry seeds contain 18–25% protein and thus have approximately twice the content in cereals (Paliwal et al., 2011). An early study by Makkar and Becker (1997) mentioned that the protein content in untreated kernels reached 36.7% DM. The seeds of *M. oleifera* are rich in oil, with even higher contents than soybeans, ranging between 30–40%. The oil is highly resistant to rancidity and is similar to olive oil in its fatty acid profile (Fahey, 2005; Ben Salem and Makkar, 2009; Paliwal et al., 2011; Leone et al., 2015). In addition, *Moringa* flowers are rich in proteins, lipids, dietary fiber, carbohydrates, and minerals. The pods of *Moringa* contain high levels of dietary fiber but are low in crude protein and fat (Rizwan et al., 2022). The leaves, flowers, and pods of the *Moringa* tree are rich in provitamins A (ß-caroten), vitamin D, vitamin E, vitamin B (thiamine, riboflavin, niacin, pantothenic acid, vitamin B6, and folate B9), and vitamin C (Gopalakrishnan et al., 2016; Abbas et al., 2018). In fact, the *Moringa* tree is a source of highly digestible nutrients and every part of the *Moringa* is suitable and important for nutritional or therapeutic use in many tropical countries, as shown by Fahey (2005); Paliwal et al. (2011) and Su and Chen (2020).

TABLE 1 Approximate nutrient content in *M. oleifera* leaves and seeds*.

Nutrients	Leaves	Seeds
Protein (%)	26.8–30.3	29–38
Total fat (%)	6.4–13.4	23.0–41.2
Carbohydrate (%)	36.0–50.1	30.0–41.0
Crude fiber (%)	4.8–27.6	20.0–22.9
Crude ash (%)	8–14.8	3.6–5.0
Calcium (g/100 g)	1.6–2.3	0.15–0.26
Phosphorus (g/100 g)	0.25–0.6	0.075
Iron (mg/100 g)	25.6–49.0	44.8
Copper (mg/100 g)	0.7–1.1	1.3
Zinc (mg/100 g)	0.82–5.9	7.3
Vitamin (A µg)	4000–8000	–
Vitamin C (mg)	15.0–100.0	14.4
Vitamin E (mg)	80.0–150	751

*Amad and Zentek (2022); Horn et al. (2022); Oluwaniyi et al. (2020); Sonkar et al. (2020); Singh et al. (2019); Igwilo et al. (2017); Sodamade et al. (2017); Godinez-Oviedo et al. (2016) - unavailable.

Phytochemicals and antinutrients

Moringa oleifera is also a reservoir of functional phytochemicals or bioactive compounds, such as alkaloids, flavonoids, phenolics, glucosinolates, carotenoids, sterols, saponins, phenolic acids, tannins, and isothiocyanates, which are present in significant concentrations in various parts of the plant (Verma et al., 2009; Meireles et al., 2020; Mohanty et al., 2020). The diversity of these phytochemicals contributes to many functional traits, including pharmacological and therapeutic properties. Therefore, *M. oleifera* has been widely used in traditional medicine in tropical and subtropical regions for centuries. Scientific reports mentioned that the leaves of *M. oleifera* contain a total of 35 bioactive compounds, including high concentrations of flavonoids (21.8%), followed by tannins (14.3%), saponins (12.6%), and alkaloids (2.4%) (Maqsood et al., 2017). Flavonoids, glycosides, terpenoids, and phenols in the leaf extract of *M. oleifera* showed potent antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*, as well as antifungal effects and antioxidant activities (Elangovan et al., 2015; Malhotra and Mandal, 2018). Anwar and Bhanger (2003) stated that *Moringa* leaves also contain flavonoids such as kaempferol and quercetin, which have higher antioxidant activities than ascorbic acid. *Moringa oleifera* leaves and seed meals act as valuable sources of vitamins, selenium, flavonoids, phenolics, and carotenoids, which makes them suitable as a nutritionally valuable and healthy ingredient, valuable for preventive medicine (Williams, 2013). Carotenoids play an important role in animal nutrition due to their strong antioxidant properties (Bhaskarachary et al., 1995). The flowers and roots of this plant also contain the antimicrobial compound Pterygospermin, which showed a potential effect against microbial species such as

Fusarium solani, *Bacillus subtilis*, *Staphylococcus aureus*, and *Pseudomonas areogunosa* (Pandey, 2012). Aqueous extracts of mature and premature flowers studied by chromatographic analysis showed the presence of free sugar, D-galactose, D-glucose, O-mannose, polysaccharide, amino acids, alkaloids, and flavonoids such as rhamnetin, isoquercitrin, and kaempferitrin. The pods contained isothiocyanates, thiocarbamates, and nitriles. The fruits contained cytokines, whereas seeds contained high concentrations of benzylglucosinolate (Faizi et al., 1998; Pramanik and Islam, 1998; Bhattacharya et al., 2018).

On the other hand, *M. oleifera* tree has numerous antinutritional factors or antinutrients including tannins, alkaloids, phytate, saponins, oxalates, cyanide hydrogen, and enzyme inhibitors (Table 2). The types and concentrations of these anti-nutritional factors seem to differ from one part of the plant to another, and also depend on growth conditions and cultivars (Stevens et al., 2015; Sultana et al., 2015b). The seeds tend to show lower concentrations of antinutrients than the leaves (Fayis, 2017). These anti-nutritional factors are responsible for the reduction in feed intake, digestibility, absorption, and utilization, and may produce other adverse effects that impact the health and productivity of animals (Akande and Fabiyi, 2010). Early reports from Noonan and Savage (1999) and Radek and Savage (2008) indicated that the levels of anti-nutritional factors found in *M. oleifera* are lower compared with those found in some other leafy vegetables. Oxalates and phytates are present in *Moringa* leaves at 10.5 and 21 g/kg DM, respectively (Rizwan et al., 2022). Oxalates are insoluble and not harmful to animals. Trypsin inhibitors are found at relatively low levels (Ogbe and Affiku, 2011) or are not present (Makkar and Becker, 1997; Balami et al., 2018). Hydrogen cyanide (HCN) does not exist or is present in low concentrations in leaves and has no harmful effects (Teixeira et al., 2014). Saponins and tannins also exist in *Moringa* leaves at high concentrations of approximately 4.7–5 g/kg and 12–20.6 g/kg DM, respectively (Moyo et al., 2011; Teixeira et al., 2014; Su and Chen, 2020). An increase in tannins and phytates can negatively affect digestibility and metabolism by reducing the rate of utilization of dietary nutrients, and this could lead to a negative growth rate in animals (Amad and Zentek, 2022). The seeds of *Moringa* contain 479 mg/kg DM tannins and 2.5 g/kg DM saponins (Fayis, 2017). Igwilo et al. (2014) reported that *M. oleifera* roots were rich in anti-nutritional factors, with higher concentrations of tannins and oxalates (450 mg/kg and 171 mg/kg, respectively), while those of saponins, phytates, and cyanogenic glycosides were lower (42 mg/kg, 0.7 mg/kg, and 27.2 mg/kg, respectively).

TABLE 2 Concentrations of antinutrients in *M. oleifera* leaves and seeds* (mg/100g).

Antinutrients	Leaves	Seeds
Alkaloids	1.56	0.291
Phytates	2.23–8.9	0.175–1.381
Tannins	1.63–6.3	0.13–0.63
Saponins	2.06–4.04	0.033–0.16
Oxalates	1.42–2.9	0.110

*El-Anoos et al. (2022); León-López et al. (2020); Olagbemide and Philip (2014); Auwal et al. (2019); Ndubuaku et al. (2015).

Use of *Moringa oleifera* in ruminant feeding

In developing countries, the use of *Moringa* tree leaves is common as a cheap and valuable alternative feedstuff and as a source of nutrients, aiming to overcome the limitations of other feed sources. The relatively low cost of feed helps farmers to maintain and improve animal production (Kholif et al., 2016). Ruminants can digest fibers such as cellulose, hemicelluloses, and other cell wall constituents because of their rumen microorganisms, which contain the necessary enzymes for breaking down these macromolecular substances. The high nutritional and bioactive composition of *M. oleifera* along with its low amounts of anti-nutrient compounds makes it suitable for ruminant nutrition. Debela and Tolera (2013) reported that *Moringa* fed as fresh forage or leaf meal can be considered a good potential source of supplementary protein in the diets of ruminant animals; moreover, it can be fed either as an extract or as dried forage.

Use in cattle feeding

The leaf, seed, and bark of *Moringa* are readily eaten by cattle as a constituent of their daily ration. Reports mentioned that supplementation with *M. oleifera* enhanced milk yield and milk composition (Babiker et al., 2017; Kholif et al., 2018; Brar et al., 2022). In one study, dairy cows (second lactation) fed a *Moringa* leaf supplement at a rate of 0 to 1.7 kg DM/d increased their milk production compared to those not fed. This increase in milk yield may be due to the positive effect of *Moringa* on the rumen environment, which leads to an increase in microbial production in the rumen. The protein in *Moringa* also has good rumen bypass properties (Sarwatt et al., 2004). Feeding dairy cows 2 kg or 3 kg DM of *M. oleifera* increased milk yield (4.9 and 5.1 kg/day) compared to cows fed only Brachiaria brizantha hay; this improvement was related to an increase in feed intake and in the digestibility of nutrients (dry matter, organic matter, crude protein, and dietary fiber) in *M. oleifera* (Sanchez et al., 2006). Moreover, it was concluded that ensiled *Moringa* can be fed in large quantities (10.40 kg DM/day) to dairy cows without any adverse effect on nutrient intake or digestibility, due to the high content of protein and fiber (Mendieta-Araica et al., 2011). Cows fed with *M. oleifera* (40 and 20% DM) had higher milk yields compared to those fed with alfalfa ration (40%). The milk constituents, including total solids, fat, protein, and ash, were significantly higher when *Moringa* forage was used, which correlated to higher nutrient digestibility levels, better nitrogen utilization, increased levels of rumen volatile fatty acids, microbial yield, and acetic acid concentration (Khalel et al., 2014). Similar results were obtained by Cohen-Zinder et al. (2016), who showed an increase in milk yield, milk fat, and protein content in lactating cows fed ensiled *M. oleifera* supplementation at 180 g/kg total mixed ration (TMR) DM. Likewise, the addition of

Moringa (6% rachis and twig) to the diet of lactating multiparous cows improved milk production by 4.7% due to increased feed intake, nutrient digestibility, and ruminal fermentation (Zhang et al., 2018). In this study, increased milk fatty acid profiles, including mono-unsaturated and polyunsaturated fatty acids, were observed; however, the protein, glucose, and total solids in the milk were not affected, probably because the basal diet was high in fiber. Complete replacement of Berseem hay in the ration of lactating cows with 20% *M. oleifera* stems showed the best feed conversion and nutrient digestibility, leading to superior milk yield and composition (El-Esawy et al., 2018). Malik et al. (2019) concluded that the consumption and digestibility of dry matter and organic matter were improved by supplementation with *M. oleifera* in Bali cows. Shankhpal et al. (2019) found a similar tendency, and stated that cows fed 15 kg *Moringa* green fodder had higher milk yields, significantly more milk fat, lactose, and β-Carotene, but reduced cholesterol content compared to the control group (Figure 1). The authors showed that the b-carotene levels improved by 37%, while the level of cholesterol decreased by 17.6% in cows fed *Moringa* as green fodder. Kekana et al. (2019) mentioned that supplementation with *M. oleifera* at 60 g/cow/day markedly reduced oxidative stress in milk, measured with a modified Trolox equivalent antioxidant capacity (TEAC).

On the other hand, Mendieta-Araica et al. (2011) reported that when soybean meal was replaced with a *Moringa* leaf meal in dairy cow feed, a decrease in milk yield occurred, with no effect on milk composition, which was probably linked to increases in protein and energy intake in the soybean meal feed. Other studies showed that different levels of *M. oleifera* (0, 3, 6, and 9% DM of rachis and branch) in the diet resulted in similar feed intake, leading to the same milk production (Dong et al., 2019). *Moringa* leaf meal supplementation (0, 30, and 60 g/cow/day DM) had no effect on body weight or milk yield (Kekana et al., 2019). A recent study by Kekana et al. (2022) showed that supplementation with *M. oleifera* leaf meal at 16.6 g/100 kg body weight had no effect on the dry matter intake and body weight of cows, calf birth weight, or colostrum yield. In another experiment, the replacement of conventional concentrate ingredients (particularly ground corn, soybean meal, and wheat bran) with up to 50% mixtures of *Moringa* mash (leaves, twigs, and branches of *Moringa*) did not affect the DM intake or live weight gain of bulls (Sultana et al., 2021). The body weight, weight gain, and height at withers of crossbred calves fed TMR without and with 5% DM of *M. oleifera* meal were not affected (Sherasiya et al., 2022).

Based on the above, it can be stated that providing *Moringa* as green fodder, silage, or supplementary feed to cows in different proportions increases milk production and its components. It should be noted that the differences between the milk production results in different studies may be mainly due to breed type, age, production stage, parts of *Moringa* used (leaves, stem, seed, flowers, or a mix of these), and environmental and management conditions. The positive effects of *Moringa* on milk yield and higher milk fat could be attributed to a higher feed intake, apparent nutrient digestibility, and increased fermentation efficiency, which were enhanced by phytochemical-rich *Moringa* in conjunction with amino acids and minerals such as P, Ca, and Mg in *M. oleifera* leaves that are essential for high milk synthesis, as observed for other forage plants. It was shown that a small amount of tree leaves (leucaena hay) affected the rumen environment, leading to improved utilization of a low-quality roughage diet (Kabatange and Shayo, 1991). Moreover, moderate levels of phenols and tannins in *M. oleifera* (especially in the leaves) provide antioxidant and antimicrobial properties, which positively affect ruminant production (Verma et al., 2009; Cohen-Zinder et al., 2016). Moreover, rumen methanogenesis could be inhibited by phenols and tannins, resulting in inhibition of rumen CH_4 production, as reflected in the improved fat yield and efficiency of milk production (Shaani et al., 2016; Dong et al., 2019). In addition, *Moringa* foliage is a good source of protein and amino acids, which can enhance the utilization of dietary N (Figure 2), boosting the productivity of dairy and beef cattle (Bashar et al., 2020; Sultana et al., 2021).

Use in sheep feeding

In an experiment replacing cottonseed cake with *M. oleifera* leaf meal (20% DM) in the diet of growing sheep (based on maize bran), an improvement in the digestibility of DM and an increased growth rate (20%) were observed; however, the feed conversion was poor (Murro et al., 2003). Feeding lambs with defatted *M. oleifera* seed meal at 2, 4, and 6 g DM/lamb/day had no effect on hay intake, diet digestibility, or N-balance; however, the highest daily gains were obtained for lambs fed intermediate levels of defatted *M. oleifera* seed meal (Ben Salem and Makkar, 2009). This was possibly due to the fact that 4 g/day of defatted *M. oleifera* seed meal in the diet increased the energy value of the diet. Lambs fed *M. oleifera* stems had higher feed efficiency; however, no significant difference was observed in the average daily and total body weight gain between animals in the control group fed clover hay and the experimental animals, which was due to the fact that clover hay had the highest nutrient digestibility and nutritive value (Mahmoud, 2013). In addition, a *Moringa* diet increased the average daily weight gain and milk yield of Najdi ewes compared to those fed alfalfa diets (Babiker et al., 2016; Babiker et al., 2017) (Figure 3). Lambs fed 75% and 100% *Moringa* foliage in a rice straw diet exhibited a positive growth performance, good carcass traits, and reduced subcutaneous fat (Sultana et al., 2017), similar to results obtained by Allam et al. (2015), who found that rations containing *Moringa* leaves improved the feed conversion and growth performance. Lambs fed 0, 25, and 50 g/kg DM *M. oleifera* root bark exhibited improvements in feed efficiency and body N retention, ultimately increasing the mean daily gain of these lambs (Soltan et al., 2018). Supplementation of male Barki sheep with *Moringa* seeds (4 g DM per day/head) significantly increased their final body weight and daily gain (EL-Hedainy et al., 2020). Moreover, a study on Deccani lambs showed a significantly higher body condition score when they were fed *M. oleifera* leaf meal at 25% in the concentrate mixture (Bhokre et al., 2020). These results and benefits were based on the excellent protein levels in *Moringa* forage and its positive effect on microbial protein formation in the rumen.

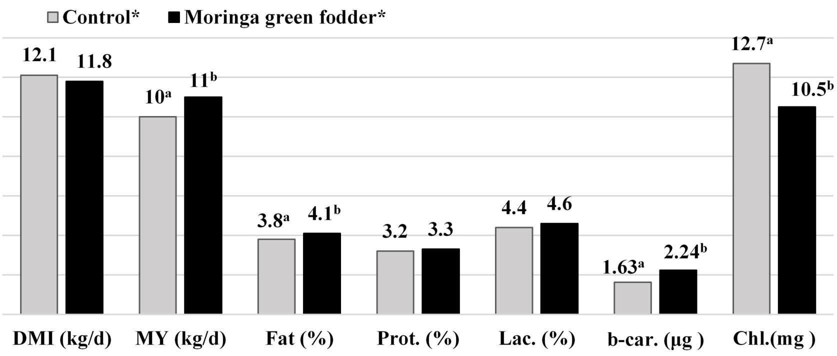

FIGURE 1
Effect of feeding *Moringa oleifera* on milk yield and its composition in crossbred cows (Shankhpal et al., 2019. Modified). DMI, Dry matter intake; MY, Milk yield; Prot, Protein; Lac, Lactose; B-Car, B-Carotene; Chl, Cholseterol. *15.0kg Moringa green fodder by replacing 15.0 kg hybrid Napier.
[ab] Mean bearing different superscripts differ significantly (P < 0.01).

Feeding Najdi ewes with 25% *M. oleifera* in their daily ration increased the milk yield compared to those fed alfalfa diets (40%), and there was a slight increase in milk fat, lactose, and energy output. An *M. oleifera* diet improved the milk yield due to its lower neutral detergent fiber (NDF) and acid detergent fiber (ADF), higher metabolizable energy contents, and excellent rumen bypass characteristics (Sarwatt et al., 2004; Babiker et al., 2016). In contrast, dietary supplementation with hydroalcoholic extracts of *M. oleifera* leaves at doses of 20, 40, or 60 mL/ewes/day in lactating ewes had no effect on milk yield and composition. Also, in this study there was no effect on ewe weaning efficiency, average daily gain, or litter weaning weight of lambs (Olvera-Aguirre et al., 2020). Early experiments indicated lower malondialdehyde values in the milk and serum of ewes fed *M. oleifera* and this might be attributed to the high total phenolic content and antioxidant capacity of an *M. oleifera* diet (Babiker et al., 2016; Babiker et al., 2017). In general, the improved milk yield and composition (fat, lactose, total energy, and energy output) is due to the lower NDF and ADF, high mineral contents (especially P, Ca, and Mg), high metabolizable energy, undegradable rumen protein, and adequate amino acid profile in *M. oleifera* feed (Zarkadas et al., 1995; Sarwatt et al., 2004; Babiker et al., 2016; El-Naggar et al., 2017), which led to improved nutrient utilization and body weight.

Use in goat feeding

Regarding feeding goats with *M. oleifera*, data indicated that dietary replacement of sunflower seed cake with 25, 75, and 100% *Moringa* meal did not significantly affect goat body weight gain (g/d) (Sarwatt et al., 2002). However, in the same study, goats that were fed 75 and 100% *Moringa* meal had greater dry matter intake compared to those that were not fed *Moringa*. Goats fed 20 and 50% *Moringa* leaves showed increased digestibility of dry matter, crude protein, and organic matter, resulting in an improvement in live weight gain (Aregheore, 2002). Similarly, results showed higher feed intake with improved mean daily weight gain in goats fed 200 g of dried *M. oleifera* (Moyo et al., 2011). The average animal weight gain improved and reached an average of 20.8 g/animal/day in African dwarf goats that were supplemented with *Moringa* compared to those fed a mixed

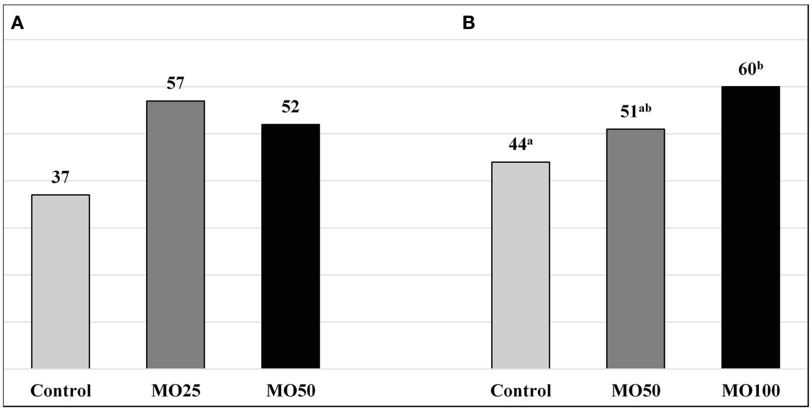

FIGURE 2
Effect of feeding *Moringa oleifera* on N-utilization in bull **(A)** (Sultana et al., 2021) and dairy cows **(B)** (Bashar et al., 2020) (in %). MO, *Moringa oleifera*; replacing concentrate mixture 25% or 50% **(A)** and 50 or 100% of concentrate mixture **(B)**. [ab] Mean bearing different superscripts differ significantly (P < 0.05).

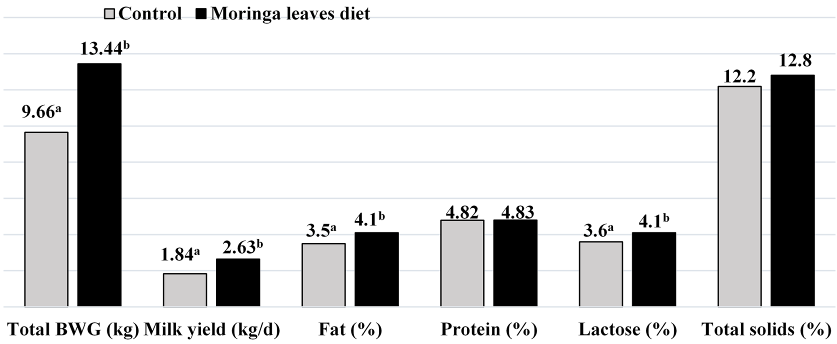

FIGURE 3
Effect of *Moringa oleifera* feeding on total live body weight gain, milk yield and composition Najdi ewes (Babiker et al., 2017). [ab] Mean bearing different superscripts differ significantly ($P < 0.05$).

concentrate, which can be attributed to the improvement in feed conversion and protein efficiency ratios (Asaolu et al., 2012). Goats fed a concentrate diet with 15% *M. oleifera* leaf meal had significantly higher rates of growth than those fed 5% and 10% *M. oleifera* (Tona et al., 2014). This indicated that a higher *M. oleifera* leaf content (15%) resulted in better feed utilization and nutrient digestibility, improving growth performance. Sultana et al. (2015b) found that the crude protein digestibility and final body live weight of experimental male goats increased linearly with increasing dietary *Moringa* leaf supplement content (25, 50, 75, and 100%). In addition, the replacement of a conventional concentrate mixture with 50 and 100% dried *M. oleifera* leaves improved the body weight and average daily body weight gain, without affecting the feed intake of Mehsana goat kids (Damor et al., 2017). One study indicated that kid goats fed 20 and 25% *Moringa* forage, included leaves, petioles, stems, and soft rachis, achieved a significantly superior final weight, total weight gain, and daily gain, which were linked to the better feed efficiency and higher digestibility of most nutrients (Ahmed and Shaarawy, 2019). Moreover, the daily supplementation of *M. oleifera* at 40, 60 and 80 g/day/head in goats on natural pasture had a significant impact on the overall body weight gain and final body weight of bucks; however, there was no significant difference among goats supplemented with *leuceane Leucacephala* and *M. oleifera*. The results also showed a significant improvement in all measured female reproduction efficiency parameters such as birth rate, twinning rate, and birth and weaning weight compared to control goats (Mataveia et al., 2019). Another study showed that supplementing the diet of goats with *M. oleifera* extract at different concentrations (30 and 60 ml extract/animal) improved the dry matter intake and feed conversion efficiency, which was reflected in a higher body weight and daily weight gain (Pedraza-Hernández et al., 2021). As shown in Figure 4A, *Moringa oleifera* supplementation improved the daily weight gain (g/day) and N-retention (%) in goat kids compared to both the control and 25% cowpea feed mixture groups (Wankhede et al., 2022). On the contrary, 75 and 100% *M. oleifera* leaf used as a replacement for concentrates had a negative impact on the final body weight and mean daily gain. These negative influences on growth rate parameters could be due to a reduction of crude protein digestibility, which is probably caused by the high content of anti-nutrient compounds such as phytates, tannins, and oxalate in *M. oleifera* (Zaher et al., 2020). Replacing a commercial concentrate mixture with 25 and 50% *M. oleifera* meal did not affect the overall body weight or biometry (body length and heart girth) of Surti kids, which may be due to the same protein content in all experimental groups (Pandey et al., 2022).

Regarding milk production, a previous study mentioned that replacing sesame meal with *M. oleifera* leaf meal in the goat diet increased the milk yield by 10 to 15%, which was attributed to an increased feed intake, improved nutrient digestibility, and ruminal fermentation (Kholif et al., 2015). Other results showed that replacing alfalfa with air-dried *M. oleifera* leaves (25%) positively affected the milk yield of goats and improved the oxidative status of milk and serum (Babiker et al., 2017). The administration of an oral dose of *M. oleifera* leaf extract to lactating Nubian goats increased the milk production and composition as a result of improved feed intake (Kholif et al., 2019). Moreover, the replacement of a concentrate feed mixture with a mixture of *M. oleifera* (20 and 40 DM basis) improved the nutrient digestion, ruminal fermentation characteristics, milk yield, and milk composition, concentrations of milk fat and lactose, and feed efficiency compared to the control treatment in lactating goats (Kholif et al., 2022; Morsy et al., 2022) (Figure 4B). Other findings have shown that milk yield, weight gain (by kids), and reproductive performance were high in goats that were fed 2 and 3.5% *M. oleifera* leaf powder in comparison to the control group. The supplementation of *M. oleifera* leaf powder improved the plasma flavonoids ($p < 0.05$) and the total antioxidant capacity (TAC) by suppressing the malondialdehyde concentration and the total oxidant status values, which could be due to the synergistic effects of flavonoids, phenolics, selenium, and vitamin C present in *M. oleifera* leaves (Afzal et al., 2022). The positive effects of supplementation with *M. oleifera* on growth, milk performance, and reproduction (ovulation rate) in goats was due to the supply of high-quality energy and protein and greater palatability, digestion, and utilization of nutrients in these feed sources (Asaolu et al., 2012; Sultana et al., 2015a; Moyo et al., 2016; Damor et al., 2017; Kholif et al., 2018; Kholif et al., 2019; Mataveia et al., 2019). Furthermore, these positive effects could be linked to the beneficial effects on ruminal function (better rumen bypass characteristics) and digestibility resulting from the consumption of vital micronutrients in *M. oleifera* such as vitamins A, B, and C as well

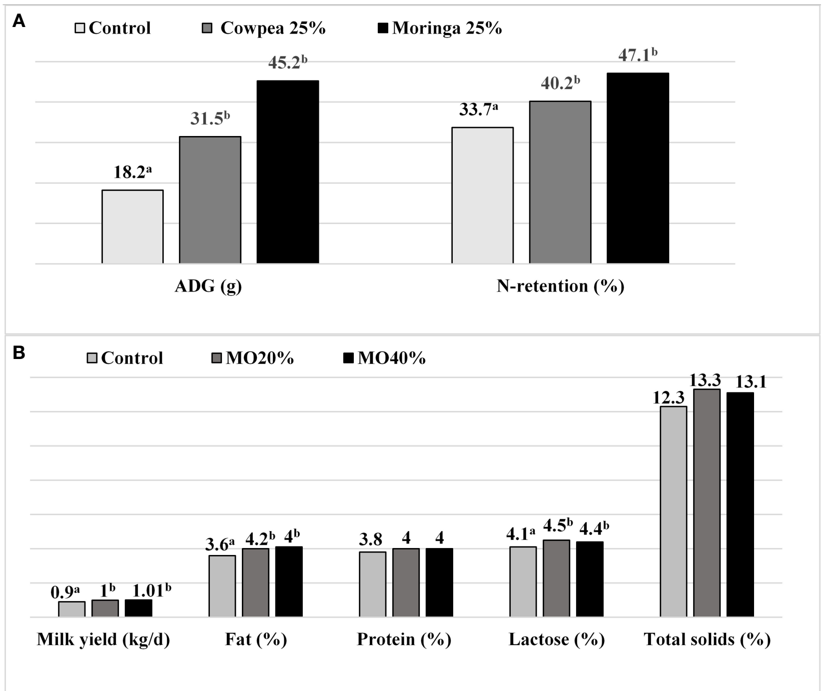

FIGURE 4
Effect of Moringa oleifera feeding on goats' performance: **(A)** average daily body weight gain (ADG) and N-retention in goats kids, adapted from Wankhede et al. (2022); **(B)** milk yield and composition of Damascus Goats, adapted from Kholif et al. (2022). [ab] Mean bearing different superscripts differ significantly (P < 0.05).

as amino acids (Kholif et al., 2015; Sayed-Ahmed et al., 2018; Ahmed and Shaarawy, 2019). Moreover, the bioactive compounds or secondary metabolites in *Moringa* might have enhanced the anthelmintic activity and improved the nutrient digestibility, which led to better growth performances in goats (Pedraza-Hernández et al., 2021; Kholif et al., 2022).

Contribution of *M. oleifera* to climate change mitigation

Climate change is primarily caused by greenhouse gas (GHG) emissions, resulting in warming of the atmosphere (Stocker et al., 2014), to which livestock farming, particularly ruminant meat and dairy, is a major contributor of global methane production and global warming (Palangi and Lackner, 2022). Global warming has led to increased land desertification, air and water pollution, and reduced biodiversity and agricultural productivity (Thornton and Gerber, 2010; Bellarby et al., 2013; Gerber et al., 2013). Climate change is expected to have severe consequences on small farms practicing animal production, which dominate the agriculture sector in developing countries (Verchot et al., 2005; Daba, 2016). Therefore, many adaptive measures are required, including agroforestry and improved feeding practices, to mitigate the climatic effects of animal husbandry. Agroforestry is an efficient and integrated land use system that creates and maximizes the use of feed crops, tree crops, and livestock on the same unit of land. The roles of agroforestry systems (trees and shrubs) are well known in the mitigation of and adaptation strategies for global climate change (Toppo and Raj, 2018; Horn et al., 2022). Trees and shrubs can modify a local climate by impacting the temperature, wind speed, humidity, water balance, and nutrient cycling. Trees and shrubs can further contribute to global carbon sequestration *via* carbon dioxide absorption from the atmosphere and the subsequent release of oxygen, with the type of tree planted having a significant influence on the environmental outcome (Betts et al., 2007; Jose, 2009; Smith et al., 2012). Improved feeding practices include the incorporation of agroforest plants as high-quality forages into animal diets (Thornton and Herrero, 2010a). An alternative is dietary modification to reduce methane production in cattle (Rendón-Huerta et al., 2018; Mangar et al., 2022). The forage intake of plants with high digestibility will generally reduce GHG emissions arising from rumen fermentation and stored manure (Hristov et al., 2013). Dietary manipulation offers dual benefits: the improvement of animal production and the reduction of GHG emissions (Haque, 2018). An early report stated that the utilization of deep-rooted plants can sequester more carbon than natural rangeland vegetation (Fisher et al., 1994). *Moringa oleifera* is a suitable plant in terms of climate protection because of its high adaptability and numerous nutritional, agricultural, medicinal, domestic, industrial, and environmental benefits (Ndubuaku et al., 2015; Daba, 2016). *Moringa oleifera* trees have deep roots that are well adapted to harsh environmental and soil conditions. They do not require much maintenance and can easily grow and yield high amount of biomass in different agro-ecological zones. Therefore, they are often considered as ideal and beneficial trees for agroforestry (Devkota and Bhusal, 2020; Horn et al., 2022). Desertification is a major problem caused by climate change, and the *Moringa* tree can play a role in combating this phenomenon. *Moringa* trees can grow quickly and efficiently in dry areas, and, due to their deep roots, can withstand prolonged drought as well as protecting the soil from erosion. Furthermore, *M. oleifera* trees could be used as a dual solution, providing an alternative source of food and feed, while also mitigating the impacts of climate change (Trigo et al., 2021). *M. oleifera* can sequester more atmospheric carbon dioxide through all its different parts (Gedefaw, 2015; Sahoo et al., 2020). This plant yields high biomass even during the dry season and acts as a good sink for carbon dioxide, thus reducing the level of carbon dioxide in the atmosphere, which is one of the main causes of ozone layer depletion and global warming (Ndubuaku et al., 2015; Daba, 2016; Sahoo et al., 2020). An early report showed that the capacity of the *Moringa* tree to absorb carbon dioxide was fifty times higher than that of the Japanese cedar tree and twenty times higher than that of general vegetation (Villafuerte and Villafurte-Abonal, 2009). In addition, an evaluation of the physiological parameters of three drought-tolerant tree species (*Moringa oleifera*, *Colophospermum mopane*, and *Sclerocarya birrea*), to determine their potential to mitigate climate change through carbon sequestration under semi-arid conditions, showed that *M. oleifera* was among the species with the highest capacity for carbon sequestration (Mabapa et al., 2018). The replacement of soybean meal with *Moringa* leaf meal decreased CH_4 production in goats and steers (Elghandour et al., 2017). Other results asserted that the use of *M. oleifera* supplementation in the diet of dairy cows not only improved dairy production (milk yield) and quality of milk but also helped to regulate the microbial metabolic function and methane emissions (Dong et al., 2019). In *in-vitro* experiments, rumen emissions were significantly reduced when leaves or extracts of *Moringa* were used, through active modulation of the rumen microbiome (Sarkar et al., 2016; Akanmu and Hassen, 2018; Ebeid et al., 2020). Lins et al. (2019) examined the effects of increasing concentrations of raw, ground *Moringa* seeds on rumen fermentation and CH_4 production, using the rumen stimulation technique (Rusitec). The results of this study indicated that methane production linearly decreased as the inclusion of *Moringa* seeds increased (0, 100, 200, and 400 g/kg concentrate dry matter). Increasing *Moringa* by 1 g/kg DM decreased CH_4 emission by 6 g/kg gain and absorbed nitrogen loss by 0.069%, possibly due to improved energy efficiency (Sultana et al., 2021). Using *M. oleifera* extract as feed supplement reduced CH_4 and CO_2 production in goats (Pedraza-Hernández et al., 2019). Further studies provided evidence that *M. oleifera* can help to mitigate methane emissions in cattle (Soliva et al., 2005; Soltan et al., 2019; Mangar et al., 2022). Additionally, other results showed that feeding lambs *Moringa oleifera* root bark reduced the estimated CH_4 produced per unit of body weight gain (Soltan et al., 2018). Supplementing diets with alternative protein sources from trees and shrubs increased the dry matter intake and improved microbial protein synthesis in the rumen and the efficiency of rumen fermentation, with a shift in fermentation towards propionate (Halmemies-Beauchet-Filleau et al., 2018). The Recent study by Kholif et al. (2023) showed that replacing a concentrate feed mixture with up to 30% *M. oleifera* silage positively impacted the ruminal fermentation, with an inhibition of CH_4 production. The methane inhibitory effects of these foliage plants might be induced by secondary metabolites such as alkaloids, flavonoids, and tannins, which are capable of interacting with rumen microbes and influencing ruminal fermentation patterns, leading to inhibition of methanogen activity (Akanmu and Hassen, 2018; Dong et al., 2019; Akanmu et al., 2020; Ku-Vera et al., 2020). Extracts from leaves of diverse plants with increased flavonoids and tannins levels reduced CH_4 emission and increased microbiota counts (Broudiscou et al., 2002). Tannin-rich forages can effectively reduce CH_4 emission (Ramirez-Restrepo and Barry, 2005; Palangi et al., 2022), while higher concentrations of saponins could suppress CH_4-producing microbes (Bodas et al., 2012). In addition, highly nutritious forage can reduce ruminant methane production since feed moves through the digestive system more rapidly (Knapp et al., 2014; Khusro et al., 2021).

Conclusion

In the tropics, leaves from forage trees and shrubs are good protein supplements for ruminants and have the potential to improve nutrient digestibility and reduce enteric methane emissions. *Moringa oleifera* is widespread in tropical and subtropical regions and possesses promising traits such as rapid growth, increased biomass, drought resistance, and minimal care requirements. Due to its high content of nutrients, especially proteins and bioactive compounds, it can be used as an alternative to conventional ruminant feed materials. Various results showed that using *M. oleifera* either individually or in combination with other feedstuff improved the production performance (growth rate, milk yield, and milk quality) in cattle, sheep, and goats. All parts of *Moringa oleifera* can sequester more atmospheric carbon dioxide, and, by feeding it to ruminants, can also reduce rumen methane emissions. This indicates that this plant can be used in agroforestry systems, which can supply animals with high value feed supplements and contribute to the adaptation and mitigation of climate change. Finally, future research should focus on the effects of different supplements of *M. oleifera* feed and extracts (leaves, seeds, flowers, roots, and bark) on ruminant performance and CH_4 emission.

Author contributions

Both authors have made a substantial and direct contribution to this scientific article and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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