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Review

Mitigating Ammonia Deposition Derived from Open-Lot Livestock Facilities into Colorado's Rocky Mountain National Park: State of the Science

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Abstract: Northeast Colorado's livestock operations have been identified as a major contributor to reactive nitrogen deposition in the Rocky Mountains National Park (RMNP). We present a review on the state of knowledge concerning the emission, transport, deposition, and mitigation of gaseous ammonia (NH_3) from open-lot cattle feeding facilities located east of the Northern Front Range of the Rocky Mountains. Gaseous NH_3 mitigation strategies discussed are related to diet manipulation and management practices. Crude protein content of 11% and condensed tannins of 8% reduced the NH_3 emission by 43% and 57%, respectively. Ambiguous results for NH_3 mitigation by using water sprinklers have been reported—an increase in NH_3 emission by 27% and decrease of 27 to 56%. Manure harvesting should be evaluated in terms of maintaining proper moisture content, and not necessarily as a mitigation option. The use of chemical and physical manure amendments has shown a wide range in NH_3 mitigation effectiveness, ranging from 19 to 98% for chemical and 0 to 43% for physical amendments, respectively. The review outlined the scientific basis, practicality, and expected efficacy of each management practice. The most plausible management practices to reduce NH_3 emissions from corral surfaces in cattle feedyards are presented.

Keywords: air quality; ammonia emissions; confined animal feeding operations; CAFO; animal agriculture; feedlot management; beef cattle

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1. Introduction

Colorado's Front Range of the Rocky Mountains lies along the Great Plains' western edge, a classic rural–urban interface between the fast-growing cities of the Interstate 25 corridor and the agriculture-dominated land uses of eastern Colorado. That narrow interface is also an imaginary boundary between the sensitive, alpine ecosystems of the Front Range and the anthropogenically modified air masses along and east of the foothills. Among the many and varied land uses characteristic of the plains adjacent to and east of Interstate 25 are intensive animal agricultural production systems, prominently including concentrated animal feeding operations (CAFOs) such as open-lot cattle feedyards and

dairies. Those livestock operations have been identified as a major contributor to reactive nitrogen deposition in Rocky Mountains National Park (RMNP).

The ruminant population of the Great Plains has not changed over the last 300–400 years although bison (*Bison bison*) have been replaced by beef and dairy cattle (*Bos taurus* and *B. indicus)*. The primary differences between bison and cattle include characteristic adult liveweights (2600 vs. 1300 lbs per head for bison and cattle, respectively), characteristic diets (lower-protein, lower-energy grasses and forbs for bison vs. higher-energy, higher-protein diets for cattle), rumen adaptation to (and feed-to-gain conversion efficiency of) those diets, and characteristic management intensity (free-ranging and extensive vs. a combination of controlled-extensive and intensive production, respectively). We cannot yet document the extent to which any differences exist between the two genera in magnitude, location, and/or duration of ruminant-derived ammonia (NH_3) emissions and their implications for NH_3 deposition in RMNP, but it is reasonable to suppose that such differences exist and may be significant.

The meteorology of this region is complex due to the local topography (principally the South Platte River Valley and the high mountain ranges) and the consequent predominance of orographic influences, which include diurnal, thermally driven, and upslope/downslope conditions as well as less frequent, synoptic-scale, deeper, and upslope flows [1–3].

Superimposed on the regional meteorology are the fugitive, airborne emissions of NH_3 from a wide variety of anthropogenic sources, in animal agriculture and beyond—and the subsequent transport and deposition of that NH_3 into RMNP under 'upslope' conditions. The ecological significance of NH_3 deposition in the RMNP is amplified, especially in the high elevations east of the Continental Divide, because the soils are thin and rocky; soluble nitrogen compounds accumulate and concentrate in snowpack and are released on short timescales during the spring melt; and the length of the growing season is greatly attenuated. Consequently, the RMNP ecosystem is quite sensitive to changes in macronutrient inputs from the atmosphere [4].

The increased wet and dry NH_3 deposition and its effects on RMNP ecosystems have been studied for over three decades [5–12]. Wet deposition of reduced N comprises fine particulate ammonium (NH_4^+) salts or aerosols of acidic gases. These components have a relatively long atmospheric residence time, 4 to 15 days, and when removed by precipitation contribute to N deposition after long-range transport in remote ecosystems [13]. Dry deposition is the removal of N pollutants by sedimentation under gravity, diffusion processes, or turbulent transfer that results in interception [14]. Field measurement and modeling studies have shown that eastern Colorado annually has contributed more to the wet deposition of gaseous ammonia (NH_3^0) and ammonium aqueous (NH_4^+) (61%) in RMNP than NH_3 sources west of the Continental Divide (26–30%); sources within the park contributed to the remaining 9–13% [8,12]. According to modeling studies [9,12], sources west of the State of Colorado contribute about 30% of measured NH_3, with California contributing approximately 13%, eastern Utah 10%, and the Snake River Valley of southern Idaho 7%. Regional contributions to dry N deposition into RMNP are still lacking. The larger, easterly contribution to N deposition in RMNP is apparently due to source proximity and relatively high aggregate emissions [12,15]; eastern Colorado hosts the fourth highest NH_3 emission "hot spot" in the U.S. [16,17]. However, the larger eastern Colorado contributions are episodic, depending on meteorological conditions that lead air masses from this region into the RMNP. As a result, emissions transport from eastern Colorado into RMNP is correlated with the occurrence of upslope events (Figure 1) [12].

According to the Rocky Mountains Atmospheric Nitrogen and Sulfur Study (RoMANS) [18], wet N deposition is the major deposition process in RMNP during both spring and summer. The total dry deposition flux was significantly less than wet deposition flux for all species measured during spring and summer at the RoMANS's core site. Wet deposition fluxes increased from spring to summer, specifically 135.6% for nitrate, 101.9% for NH_4^+, 48.9% for organic N, and 61.6% for sulfate. Dry deposition fluxes of nitric acid, ammonia, and sulfur dioxide also increased by 101.6%, 141.0%, and 16.5%, respectively,

during the summer. Contrarily, dry deposition fluxes of particulate nitrate, NH_4^+, and sulfate decreased by 62.1%, 10.0%, and 16.1%, respectively [18].

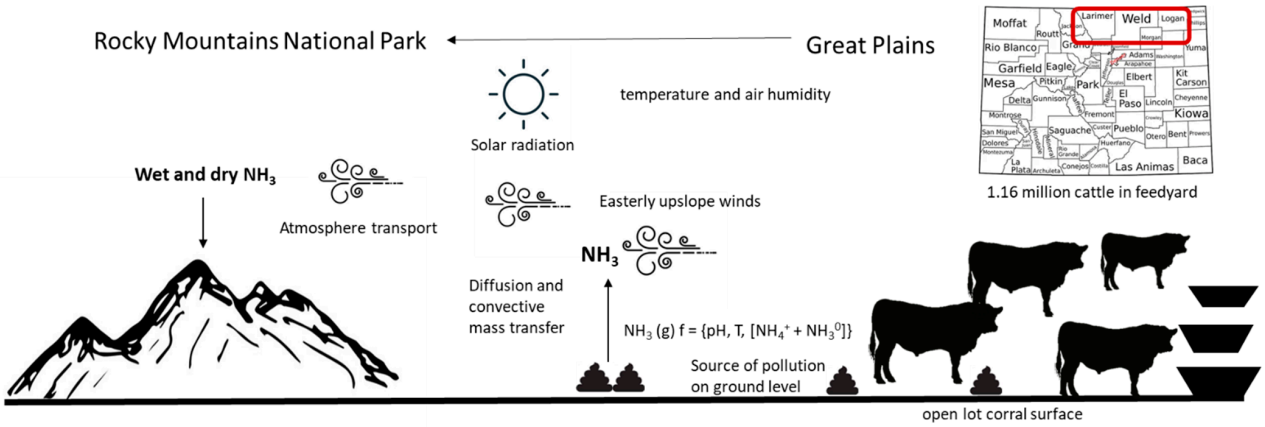


Figure 1. Main drivers influencing NH_3 transport from Colorado's eastern plains into Rocky Mountain National Park (RMNP), followed by both wet and dry deposition. Increased air temperature and solar radiation heat the NH_3-enriched manure on the corral surface, accelerating NH_3 emissions at ground level; diffusion and convective mass transfer bring the NH_3 into the atmospheric boundary layer; easterly (upslope) winds move NH_3-laden air masses into RMNP. Colorado's map shows the region of interest/concern highlighted in red.

There are roughly 2.6 million head of cattle in Colorado, including beef and dairy cattle (cows and calves) [19]. On average, the region of concern in this paper (northeast Colorado; specifically, Morgan, Logan, Larimer, and Weld Counties) has approximately 1,100,000 animals on feed in feedyards at any one time, and the majority of which are fed ~80 km east of RMNP in Weld County, the leading animal and agricultural producing county in Colorado [20].

The manure (feces plus urine) deposited continuously on a feedyard's corral surface is a primary source of fugitive NH_3 emissions, and the process of NH_3 formation and volatilization begins immediately after urine and feces are excreted. Ammonia is produced by the urease-mediated (present in the feces) hydrolysis of nitrogenous compounds (urea and protein) in the urine. Urea in urine is the predominant, fast-hydrolyzing NH_3 source in manure; more complex compounds, such as proteins and amino acids, are decomposed more slowly by microbes [21]. Once emitted into the atmosphere, in the presence of water and suitable anionic species (primarily oxides of S and N), NH_3 enters rapidly into ionic reactions that form secondary aerosols as precipitates. The dynamics of those reactions, however, are complex and depend on environmental conditions and the relative concentrations of reactants, being extremely sensitive to temperature, moisture, pH [22,23], air pollutants (e.g., dust) [24], and wind as well as to the aerodynamic mechanisms that modulate NH_3 emissions from different source classifications [12].

Some 70–90% of N fed to beef cattle is excreted in feces and urine [25]. Because protein sources are relatively expensive components of the mixed feed, the cattle-feeding industry has long sought research-based management practices to decrease NH_3 emissions, first via dietary manipulations and growth-promoting technologies to increase nutrient- use efficiency by cattle (e.g., crude protein (CP), β-adrenergic agonists (β-AA), and condensed tannins (CT)), and from pen surfaces and the broader production system, such as amending pen-surface chemistry (alum or gypsum) and more frequent manure-harvesting operations. Only recently [26] has the use of sprinkler dust-control systems been proposed as a means of reducing NH_3 emissions from the pen surface.

Few field-measured NH_3 emissions studies have been conducted to date in Colorado's cattle-feeding regions [26,27]. Most studies have been conducted in other cattle-feeding areas, such as Canada, United Kingdom, and especially the Texas Panhandle and the

surrounding Southern High Plains in the United States (Figure 2). Because of regional differences (edaphic and climatic, animal density, dietary feedstocks, and proximity to RMNP) between Texas and Colorado's Front Range, more research data from representative Colorado feedyards would enhance the regional understanding of NH_3 dynamics in RMNP's immediate source areas, thereby reducing the uncertainty associated with modeling results derived from assumptions imported from other cattle-feeding regions [28].

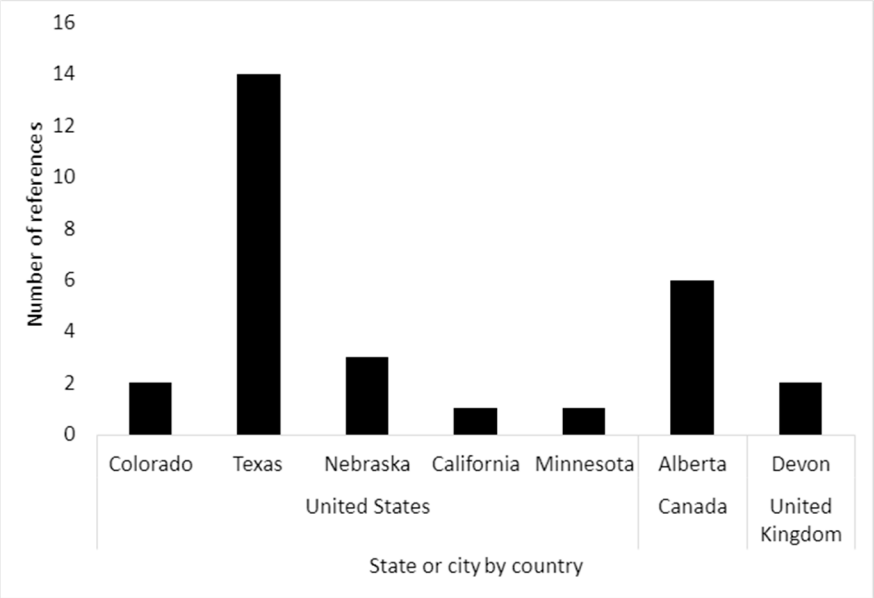


Figure 2. Number of journal articles on in situ NH_3 emissions studies conducted in cattle-feeding regions in the U.S., Canada, and United Kingdom from 1982 to 2022.

In 2007, the cattle-feeding industry committed (along with the broader agricultural and agribusiness sector in eastern Colorado) to support the RMNP Nitrogen Deposition Reduction Plan (NDRP), the goal of which is to reduce the 5-y average deposition flux of inorganic N into RMNP by 50% as compared to 2004 levels. The targeted wet-deposition flux into RMNP is 1.5 kg N ha^{-1} y^{-1} by 2032. This flux threshold, established through "hindcasting" by previous research, is the estimated critical load of wet-deposited N that can be assimilated by sensitive ecosystems within RMNP without irreversible changes to the Park's flora and fauna [5]. The downward trajectory in deposition flux from 2004 to 2032 that is expected to result from the NDRP is known colloquially as the "glidepath" [11]. The Natural Resources Report (NDRP) [10,11] showed annual wet N deposition in 2018 and 2019 to be about 2.5 kg N ha^{-1} y^{-1}, decreasing from 3.2 in 2017. However, the 5-y average (2.7 $\pm$ 0.22 kg N ha^{-1} y^{-1}) remained 0.3 kg N ha^{-1} y^{-1} above the glidepath (2.4 kg N ha^{-1} y^{-1}).

Gauging feedyards' implementation of management practices to reduce NH_3 emissions would be difficult. But the scientific community has identified important knowledge needs and gaps. Understanding the emission mechanisms and atmospheric-transport dynamics associated with NH_3 deposition in RMNP will inform the selection and implementation of both tactics and strategies to reduce NH_3 emissions from cattle feedyards in response to short- and long-range weather forecasts. Given the importance of ensuring that feedyard management recommendations are both affordable and demonstrably effective, with financial support from the USDA Natural Resources Conservation Service (NRCS) and the Colorado Livestock Association (CLA), we present herein the most recent state of the science on the dynamics of NH_3 emissions in open-lot livestock facilities, the influence of diurnal and synoptic weather events on NH_3 emission, transport, and deposition into RMNP, and the most plausible management practices to reduce fugitive NH_3 emissions

from corral surfaces in cattle feedyards. We outline the scientific basis, practicality, and expected efficacy of each candidate mitigation method.

Our literature review seeks to answer the overarching question "how might theoretically plausible methods to reduce NH_3 emissions from open-lot cattle feedyards be practically applied in northeastern Colorado to reduce the delivery of atmospheric NH_3 into RMNP during transient, upslope conditions?" That question presents four major objectives:

1. Understand the dynamics of NH_3 emissions from pen surfaces in open-lot CAFOs characteristic of northeastern Colorado;
2. Describe the meteorological influences on NH_3 emissions mechanisms from open-lot cattle feedyards, including both seasonal and daily components;
3. Describe the meteorological influences on the transport mechanisms from Colorado's Front Range into RMNP, including both synoptic meteorological patterns and upslope conditions;
4. Evaluate recommended management practices to decrease NH_3 emission in open-lot livestock facilities during upslope conditions, based on the USDA-NRCS list of best management practices, such as diet manipulation (CP, CT), growth-promoting technologies (β-AA, implants), feed additives (monensin), phase feeding, manure harvesting, water sprinkling, and pen surface amendments.

2. Materials and Methods

2.1. Literature Review Approach

We searched Google Scholar and Web of Science for the most relevant published literature on NH_3 emission in feedyards. Initially, the topic "ammonia (emission)" yielded over 3,300,000 (1,600,000) documents. After adding the search terms "Cattle (beef)", over 100,000 documents remained; adding the search terms "Feedlot (CAFO, AFO, feedyard)" and identifying papers pertaining to (a) feedlot NH_3 emissions or (b) management practices to mitigate NH_3, our search yielded ~150 papers that were clearly within the scope of this review topic. The data were summarized in tables according to the major management practices adopted by feedyards.

2.2. Relevance and Screening

We used data exclusively from primary research evaluating the following: (1) NH_3 emissions from open-lot cattle feedyards, (2) the seasonality or temporality of those emissions, and (3) the effects of management practices to mitigate them. Data were considered eligible when published in refereed journal articles (132), dissertations and theses (1), and conference articles (6). Our primary focus was research conducted in the United States cattle-feeding sector.

3. Literature Review

3.1. NH_3 Emission Dynamics in Open-Lot Surfaces

Ammonia is a colorless gas with a distinct pungent smell. It occurs naturally and is normally found in trace amounts in the atmosphere, where it is the dominant alkaline gas, combining readily with acidic compounds. It is produced by the decomposition or fermentation of animal and plant residues containing N, including livestock manure (urine and feces) [29]. The primary sources of livestock-derived NH_3 emissions into the atmosphere are manure in CAFOs [30–32] and the associated waste management systems, including open manure storage and land application of manure products.

Bovines use dietary N less efficiently than most other species [33]. In open-lot cattle feedyards, between 70 and 90% of fed N is excreted in feces and urine [25]. Once excreted, urea is enzymatically hydrolyzed to CO_2 and NH_4^+ and then volatilized to gaseous NH_3 via well-documented reactions given below (Equations (1)–(3)):

$$CO(NH_2)_2 + 2H_2O + (\text{Urease}) \rightarrow (NH_4)_2CO_3^- \quad (1)$$

$$(NH_4)_2CO_3 + 2H^+ \rightarrow 2NH_4^+ + CO_2 \uparrow + H_2O \quad (2)$$

$$NH_4^+ + OH^- \leftrightarrow NH_3 \uparrow + H_2O \quad (3)$$

A significant fraction of cattle manure N, primarily from urinary urea ($CO(NH_2)_2$), is converted to NH_4^+ and eventually lost to the atmosphere as NH_3. Up to 90% of feedyard NH_3 originates from urine deposited in animal pens [22,23], but the instantaneous magnitude of that loss depends strongly on weather conditions (temperature, precipitation, humidity, and wind), soil properties, pH, microbiological activities (e.g., urease activity), and management practices (Tables 1 and 2). Ammonia volatilization increases linearly with total ammoniacal nitrogen concentration (TAN), and curvilinearly with temperature, wind speed, and slurry pH [24,34,35]. Temperature and pH have been reported to be the most important factors influencing NH_3 volatilization [24], as the NH_3/NH_4^+ ratio is equilibrium dependent (Figures 3–5).

Table 1. Percent NH_3-N loss as a percentage of nitrogen fed to beef cattle confined in feedyards.

Location of Study	Summer	Winter % of N fed	Annual	Reference
Texas Panhandle	68–71	42–44	52–59	Todd et al. (2011) [36]
Texas Panhandle	46–55	31–51	49	Rhoades et al. (2010) [37]
Nebraska	56–64	36–64		Erickson and Klopfenstein (2010) [38]
Texas Panhandle	50	28		Cole and Todd (2009) [39]
Texas Panhandle	68	36	53	Todd et al. (2008) [40]
Texas Panhandle	63			Flesch et al. (2007) [41]
Texas Panhandle	51–65			Cole et al. (2006) [42]
Texas Panhandle	55	27	41	Todd et al. (2005) [43]
Nebraska	54	31		Erickson et al. (2000) [44]
Nebraska	57–67			Bierman et al. (1999) [45]
Average	58	39	52	
Range	46–71	27–51	41–59	

NH_3-N refers to the percentage of N related to the entire ammonia molecule (NH_3).

Table 2. Seasonal NH_3-N emissions reported for cattle feedyards.

Location of Study	Reference	NH_3-N Emission (g head^{-1}day^{-1})				
		Spring	Summer	Fall	Winter	Annual
Colorado	Hutchinson et al. (1982) [27]					50
Texas Panhandle	Todd et al. (2005) [43]		74 *		44 *	
Texas Panhandle	Cole et al. (2005) [46]	108			66	
Texas Panhandle	Baek et al. (2006) [47]		167 *		13 *	
Alberta, Canada	McGinn et al. (2007) [48]			140		
Texas Panhandle	Flesch et al. (2007) [41]	150				
Narrabri, Australia	Denmead et al. (2008) [49]				46	
Alberta, Canada	van Haarlem et al. (2008) [50]			164–318		
Texas Panhandle	Rhoades et al. (2008) [51]	89 (58–123)	78 (72–86)			
Texas Panhandle	Todd et al. (2008) [40]	118	131		68	97
Alberta, Canada	Staebler et al. (2009) [52]			245		
Texas Panhandle	Rhoades et al. (2010) [37]	97.5 (69–128) *	88 (82–96) *	70 (47–103) *	61 (47–76) *	79 *
Texas Panhandle	Todd et al. (2011) [36]		135–207		78–93	105–150
Texas Panhandle	Waldrip et al. (2013) [53]					90–167
Alberta, Canada	McGinn et al. (2016) [54]					85
Alberta, Canada	McGinn et al. (2018) [55]					100–117
Average		113	130	187	59	104
Range		108–150	74–207	140–318	13–93	50–167

* Indicates the estimated NH_3 emission using the given NH_3 flux and stocking density. If stocking density was not given, an average value of 20.9 m^2 head^{-1} [56] was used.

During winter, mineralization of organic N to NH_3 is limited by low temperature, but as pen surfaces warm in spring and summer, the mineralization rate increases rapidly [57]. Increasing manure temperature (Equation (1)) accelerates microbial activity and favors the production of gaseous NH_3 (Equation (2)) [12,58]. In summary, there are three major factors associated with an increase in NH_3 volatilization as temperature increases: (1) a decrease in solubility of aqueous NH_3, (2) an increase in ratio of aqueous NH_3 to NH_4^+ in solution (NH_4^+/NH_3 equilibrium), and (3) an increase mineralization rate of organic matter via biological activity [24].

The percentage of NH_3-N loss from fed N during the summer was around 58%, and 39% in winter, which reflected an average annual loss of 52% (Table 1). On an annual basis, one beef cattle (animal unit) fed in confinement emits 104 g NH_3-N per day (Table 2), which represents 52% higher NH_3 emissions on average than what was previously reported for Colorado [27] in the early 1980s (50 g head^{-1} day^{-1}). It is important to highlight the lack of current information related to NH_3 emissions from Colorado's feedyards, especially considering the evolution of the beef cattle industry.

In addition, at a constant temperature, higher pH favors the formation of NH_3 over NH_4^+ and increases the potential for NH_3 volatilization (Figure 3) [59,60]. The proportion of NH_3 increases rapidly as pH exceeds 7, and at pH 10, virtually all of the total ammoniacal N exists as NH_3 [23]. Manure's buffering capacity is strong, especially due to the presence of bicarbonates and organic acids, which result in an increase in pH when in acidic systems (manure–soil–water; open-lot surface). Thus, maintaining manure with a low pH to mitigate NH_3 emission is challenging. Increasing pH (Figure 3) and temperature (Figure 4) move the NH_4^+/NH_3 equilibrium towards NH_3 formation. Thus, the higher temperatures reached during summer enhance the NH_3 volatilization in feedlots (Table 2). The drying process itself increases aqueous NH_4^+ concentrations, thereby enhancing NH_3 volatilization; however, that may be temporarily reduced under optimum water content/corral surface moisture. The optimum water content for manure composting, for example, ranges between 50–70%, which allows maintenance of highly soluble NH_3 in a dissolved state [61,62]. However, to reach an optimum moisture level in open-lot surface is challenge (if not impossible) as a dynamic environment is constantly receiving new fresh manure deposition and evaporating existing moisture.

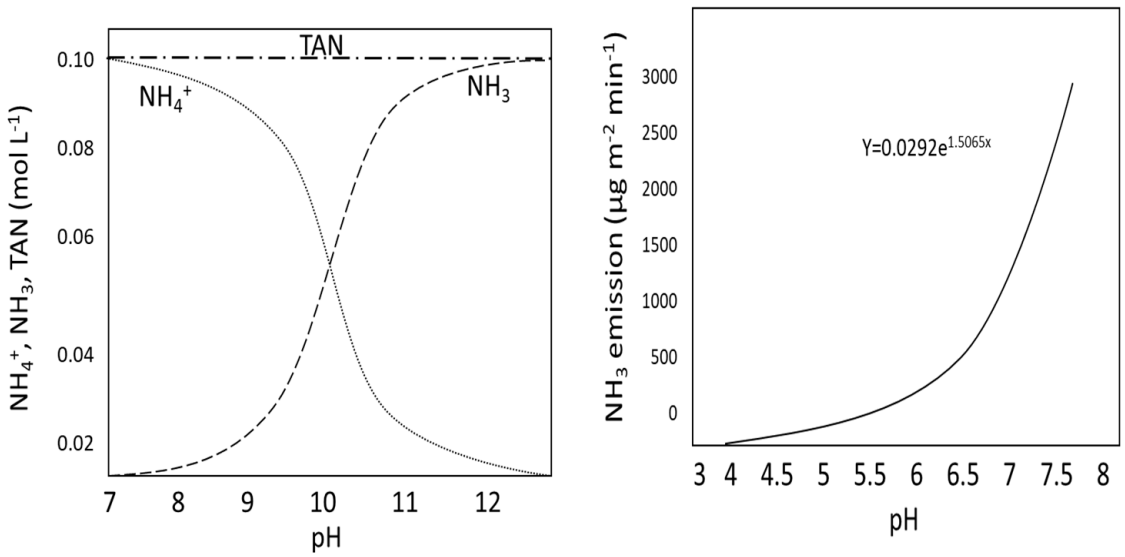


Figure 3. NH_4^+, NH_3, and TAN equilibrium as a function of pH, and the relationship between NH_3 emission flux and pH for the simulated beef cattle feedyard data.

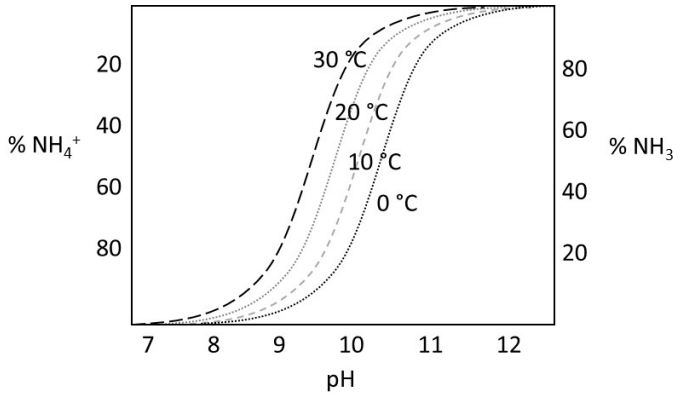


Figure 4. Ammonium and ammonia equilibrium as a function of temperature and pH (adapted from [61]).

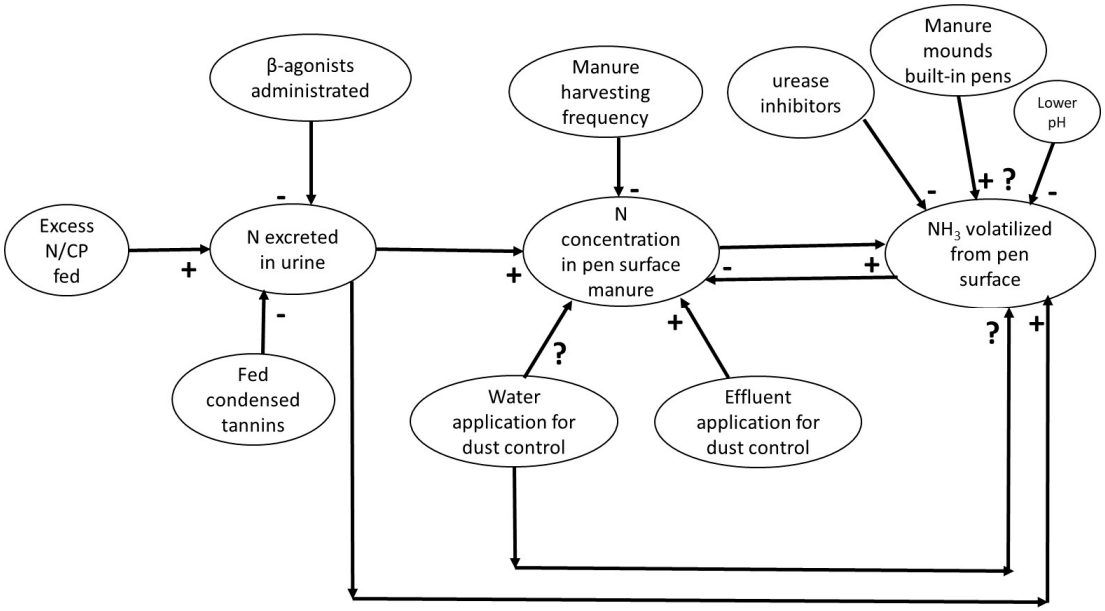


Figure 5. NH_3 emissions mechanisms and management levers available to alter those emissions. If a given arrow starts at variable A and points to variable B, then the sign (+ or −) on the tip of the arrow designates the direction that variable B moves if variable A increases.

3.2. Meteorological Impacts on NH_3 Emission and Transport Characteristics from Colorado's Front Range into the Rocky Mountains

3.2.1. Synoptic Meteorological Pattern and Upslope Conditions

Colorado's Front Range and the adjacent east slopes of the Rocky Mountains, including RMNP, are characterized by prevailing westerly (downslope) winds during much of the year. However, easterly upslope winds resulting from either synoptic-scale storm systems or diurnal, orogenic circulations are known to contribute to gas and particulate transport from eastern Colorado's livestock facilities into the RMNP, where atmospheric deposition then enriches sensitive alpine ecosystems with reactive nitrogen [1,12,15].

The easterly transport mechanisms associated with various meteorological flow patterns are variable and complex due to many factors, such as the unique meteorological situation, mountain–valley circulation effects, high elevation, and varied terrain [63]. However, these meteorological effects vary seasonally and temporally and can be mostly predicted in advance by numerical weather prediction models. This has raised interest in combining short-term weather forecasts (e.g., Early Warning System; [1]) with the understanding

of NH_3 emission dynamics from open-lot corral surface [22,23] to improve management practices to reduce NH_3 emission.

Two primary easterly transport processes are documented in the literature as mostly responsible for maintaining the N enrichment process of the RMNP. One of these process is the synoptic meteorological pattern that brings notable cool-season (particularly in the spring) rain and snowstorms to the Colorado Front Range, and the other process is the summertime mountain–plains circulation that occurs when the jet stream is too far north for its associated large-scale westerly winds to influence Colorado [1]. The most common period (40% of hours of the day) of upslope conditions in RMNP associated with synoptic-scale storm systems is in April, and least frequent in December (20% of hours of the day; [18]). Although easterly conditions are important, their association with precipitation events is fundamental for N deposition in RMNP. The coincidence of upslope conditions and precipitation events is most likely to occur in the winter and spring, whereas summer precipitation events are more prone to be associated with westerly winds [18]. However, unexpectedly high precipitable water values associated with cold fronts play also significant roles in the N deposition into the RMNP [1].

Boreal summers in Colorado promote fewer synoptic weather systems, which allows the diurnal cycle to exert a dominant control on meteorological flows along the mountain–plain interface. The weak synoptic conditions in the warm season have unique consequences for the transport, mixing (dilution), and photochemical processing of local emissions [3,64,65]. As the land surface cools during the evening, downslope drainage flows extend from the Continental Divide onto the eastern plains and are most pronounced in the canyons and river valleys [65]. As solar radiation heats the ground during the morning hours, upslope flows are formed, starting a few hours after sunrise in the foothills and slowly extending to the eastern plains about 3 h later. The upslope flows can reach the top of the Continental Divide by mid-afternoon on days with strong upslope. Flow reversal starts at the top of the Continental Divide in the late afternoon, which forms the convergence line that moves east in the evening hours. Downslope winds then dominate the entire region again around midnight [63,65]. Thus, vertical and horizontal dispersion associated with these cyclical mesoscale mountain circulations, driven by differential heating of mountains and plains, are considered a primary driver of the eastward convective transport towards mountains in the absence of large-scale synoptic weather systems [1].

There remains some uncertainty in the depth and relative magnitude of the easterly upslope transport associated with both synoptic storm systems and mountain–plains circulations into the RMNP, and the need to more accurately model the easterly flows in the complex terrain has been noted [15,66]. For example, Clow et al. (2015) [67] found higher summer dissolved inorganic nitrogen concentrations in the eastern portions of RMNP, presumably because local flow patterns result in greater easterly transport from the Front Range in these areas than in locales further to the west.

3.2.2. Major Meteorological Factors Influencing Local Surface NH_3 Emission

To represent accurate weather processes and simulate potential scenarios of high NH_3 deposition into the RMNP, it is also important to understand how variations in meteorological quantities associated with synoptic weather regimes, season, and time of day affect the local NH_3 emissions and chemistry at ground level at the various emission sources in eastern Colorado. The soil and air temperatures, humidity/precipitation, and wind/atmosphere turbulence (Figure 1) strongly influence the emission and dispersion processes of NH_3. Diurnal temperature change is considered one of the major weather factors influencing NH_3 flux in Colorado because of the direct effect on the volatilization of TAN [18,28,63,68,69]. On an annual scale, NH_3 mixing ratios in northeastern Colorado typically achieve a maximum in warmer summer months when the volatility of NH_3 increases due to higher temperatures and to conditions that suppress partitioning to particle NH_4^+ [68–70]. Air temperature for this period ranges from 10.0 to 36.6 °C, with an overall mean of 24.9 °C [18,68]. Golston et al. [68] reported enhanced emissions from

0.08 to 0.55 mol NH_3/mol^{-1} of air (10^6 ppm) in this region during summertime conditions, with the lowest and highest temperature reflecting the minimum NH_3 emission from 12:00 a.m. to 6:00 a.m. and maximum around 12:00 p.m., respectively [18]. Evaluating NH_3 mixing ratios at different heights during the summer, Tevlin et al. [2] observed at higher altitudes; specifically at 100 ± 5 approximately 8 to 22 ppb, and at 280 ± 5 m 6 to 11 ppb, which represented a gradual maximum between 9:00 a.m. and 4:00 p.m. local time, and at 10 ± 5 m (lower altitudes), the maximum was achieved earlier at 7:00 a.m., followed by a sharper increase at 9:00 a.m.; approximately ranging from 6 to 16 ppb.

Although summer is characterized by the highest NH_3 emission fluxes, a slight increase in winter season NH_3 concentrations at surface of observing sites (urban and rural area) in northeastern Colorado has been noticed as compared to fall and spring [69,70], which is attributed to the low-level temperature inversions that trap NH_3 emissions closer to the surface within a shallower nocturnal and less well-ventilated winter boundary layer [2,69,70].

The difference in concentration between manure and atmosphere drives NH_3 emission first through diffusive transfer from the ground surface, followed by convective mass transfer in the atmospheric boundary layer, where wind and atmospheric turbulence transport the NH_3 according to the prevailing wind direction [71]. Overall, Colorado's diurnal, orographically driven, evening winds are usually from the northwest (downslope), while during daytime (7:00 to 18:00) winds change to southeasterly (upslope), suggesting transport from the Front Range to the RMNP during the daytime [18]. The highest NH_3 mixing ratios measured at multiple altitudes were observed when the wind arrives from the north and east, and the lowest ratios were observed when westerly and southwesterly winds were coming from the direction of the Rocky Mountains and cities along the foothills [2].

Li et al. [68] and Tevlin et al. [2,69] evaluated the vertical scale/profile (0–300 m) NH_3 mixing ratios at the Boulder Atmospheric Observatory (BAO) Tower throughout the year of 2012 and during the summer of 2014, respectively. Overall, both studies observed comparable results with an increase in NH_3 mixing ratios at the lower heights (4.69 μg m^{-3} (89%) during the day and 2.73 μg m^{-3} (141%) at night [2], and 4.63 μg m^{-3} at 10 m height through the year) [69]. However, the highest NH_3 concentration at the vertical profile evaluated by Li et al. [69] was always observed at the 10 m height instead of closer to the surface, which decreased towards the surface (4.35 μg m^{-3}) and towards higher altitudes (1.93 μg m^{-3}), with the minimum concentration observed at the 300 m height.

Having measured those data year-round, Li et al. [69] could conclude that the highest concentrations across the profile were observed in summer, when the volatility of NH_3 increases due to higher temperatures and vertical mixing is enhanced, which also may reflect a shift in the thermodynamic equilibrium of particulate-phase NH_4NO_3 toward its gas-phase precursors, NH_3 and HNO_3. Although higher NH_3 ratios were observed during the summer, the greatest vertical concentration differences were observed in winter with a decrease of approximately 75%, with the average concentration near the surface higher than 4 μg m^{-3} and approximately 1 μg m^{-3} at 300 m, followed by autumn, with average of 1.9 μg m^{-3} near the surface and 4.5 μg m^{-3} at 300 m). Authors concluded that low-level temperature inversions which trap NH3 emissions closer to the surface (shallow winter boundary layer) are common in both seasons (autumn and winter) that can produce elevated surface concentrations. They also stated that is usual a gradient of decreasing concentration near the surface at this location, where local emissions are expected to be small, and the net local flux represents surface deposition.

To summarize, high values of wet N deposition in RMNP require elevated NH_3 emissions, easterly winds transporting fugitive emissions toward RMNP, and conditions that favor precipitation followed by deposition, especially in the leeside of the park [1]. As easterly winds advect and lift pollutants up the east slope of the RMNP, the air cools and condenses to form clouds in the presence of moisture. Precipitation maxima in northern Colorado are associated with easterly winds and occur most frequently in spring and

summer [6,7]. During precipitation events, clouds entrain Front Range pollution and deposit the pollutants over the mountains with precipitation [1].

3.3. Feeding and Management Practices to Mitigate NH_3 Emissions from Open-Lot Livestock Facilities

The digestion of dietary proteins and other nitrogenous compounds is complex in ruminants because of ruminal fermentation [72]. The ruminal microorganisms can degrade some of the dietary nitrogen (also known as rumen-degradable protein, or RDP) and use the products for their own growth. According to Owens and Zinn [73], ruminal microbes themselves produce between 20 and 60% of their dry matter as CP. Accordingly, rumen microorganisms can use both dietary protein and non-protein nitrogen, as well as nitrogen recycled to the rumen. A portion of the NH_3 produced in the rumen by the deamination of amino acids not used for microbial protein synthesis will be absorbed across the ruminal epithelium into the portal vein and converted mostly to urea by the liver [74]. Firkins and Reynolds (2005) [75] found that the net NH_3 absorption was 42% of dietary nitrogen intake across 304 measurements in lactating dairy cows. The urea produced by the liver is partly excreted in the urine (20–60%), with the remainder recycled back to the gastrointestinal tract, and of this, 27–60% of the urea enters the rumen [76]. Feeding excess N results in increased NH_3 absorption, increased urea production, and increased urea excretion in urine [74]. In fact, as N intake increases urine N excretion increases at a much greater rate than fecal N excretion [77]. The NH_3 emissions from open-lot livestock facilities is primarily produced via the hydrolysis of urinary urea to NH_4^+ and CO_2 that occurs on the feedlot pen surface [23,39].

Aiming to mitigate NH_3-N deposition into RMNP, the USDA-NRCS has listed several recommended management practices for crops, dairy, and beef production. Because our primary objective is to evaluate recommended management practices to decrease NH_3 emission in open-lot livestock facilities, we have used the USDA-NRCS's list of best management practices (Table 3) to search the literature for scientific evidence of the most common/conventional management practices on NH_3 abatement (Tables 4–8).

Table 3. Best management practices (BMP) for open-lot livestock facilities to decrease NH_3 deposition into RMNP (USDA-NRCS; conservation management practices [78]) in Colorado.

Category	NRCS Code	Management Practices
Feed management	592	Diet manipulation CP CT Growth-promoting technologies β-AA Implants Feed additives (monensin), Phase feeding
Pen maintenance	N/A	Manure harvesting and pen drainage
Dust control	375	Water sprinkler
Manure amendment	632	Surface amendment and manure separation

NH_3 mitigation through feeding management ultimately aims to improve the efficiency of dietary N use by beef and dairy cattle, decreasing the amount of N compounds excreted, more specifically decreasing urinary excretion of urea-N. According to NASEM [72], in beef cattle, 40 to 80% of non-retained N is excreted in the urine, increasing as the dietary CP and/or RDP concentration increases in the diet. For that reason, NH_3 emissions generally increase with increased N intake in protein-adequate diets. Decreasing CP concentration in the diet can potentially decrease NH_3 emissions, but it also decreases average daily gain, which can increase days on feed, the amount of manure deposited in the pens, and consequent NH_3 emissions.

Phase feeding is a nutritional management strategy in which the ingredients and chemical composition of the diet is modified over the growth stage of the animal so that the nutrient composition of the diet more closely meets the nutrient requirements of the animal [42]. The purpose of phase feeding is to supply a more accurate quantity of nutrients for each animal's stage to decrease nutrient excretion and subsequent losses of these nutrients, especially N and P, to groundwater, surface, or to the atmosphere. As beef cattle grow and mature, many of their nutrient requirements as a percentage of the diet decrease, most notably protein [79]. However, according to NASEM [72], the practicality of phase feeding under the current feeding and management situations is equivocal because of potential logistic (additional supplements, diets, and feed truck scheduling), economic, and animal health obstacles. Clearly, more scientific discussions on the technoeconomic of phase feeding are still needed.

Including some feed additives (e.g., monensin and CT) and growth-promoting technologies, such as β-AA and implants, have shown benefits to the feedlot industry, including increased feed-to-gain performance and meat quality and reduced environmental impact through reduced NH_3 and CH_4 emissions. In addition, other management practices such as manure harvesting, dust control using water sprinklers or other irrigation systems, and surface manure amendments have also been evaluated, although results are still uncertain (Figure 5).

3.3.1. Feeding Management—Diet Manipulation: CP and CT

NH_3 emissions from feedlot operations are sensitive to dietary CP concentrations [36,46,80]. When beef cattle are fed enough CP to meet their physiological and growth needs, about 25 to 50% of N intake is subsequently lost to the atmosphere as NH_3 [22]. When CP exceeds cattle needs, the excess N is excreted, primarily as urea in the urine, thereby increasing NH_3 emissions [81]. Kissinger et al. [82] found that 12% of the feed N is retained by cattle, and the remaining was assumed to be excreted to the pen surface, representing 67% of excreted N, which were lost as NH_3 volatilized, as dissolved or suspended N in feedlot runoff, or retained in manure not removed from pens. One way to mitigate NH_3 emissions from open-lot livestock facilities is by manipulating dietary CP. By reducing dietary CP content to match animal needs more closely, more urea recycling is stimulated, overall feed efficiency improves, and N losses are minimized [26]. According to previous studies, when CP in the feed was adjusted to around 11%, the NH_3 emission due to the volatilization of the excreted N could be reduced by 42.8% (Table 4).

Table 4. NH_3 mitigation by manipulating CP in feeding beef cattle in open-lot livestock facilities.

Study Location	CP Range Value (%)	NH_3 or N Excretion Mitigation Result	Rate (%)	*p* Value	Reference
Nebraska	13.4 to phase-fed (10.5–12.0)	N volatilization from N excretion: 158 to 108 g/head/d	32	0.01	Erickson et al. (2000) [44]
Texas	13.0 to 10	Urine N excretion: 5.2 to 1.7 g/head/d	67	<0.01	Cole et al. (2006) [42]
Texas	16.3 to 12.2	NH_3 emission: 149 to 82 g/head/day	45	<0.05	Todd et al. (2009) [83]
Texas	13.0 to phase-fed (10.9–12.1%)	N volatilization from N excretion: 101 to 86 g/head/day	15	0.32	Erickson and Klopfenstein (2010) [38]
Texas	16.0, 13.5, and 11	Estimated NH_3 emission: 169.9, 104.4 to 90.1 g/head/d	47	N/A	Todd et al. (2013) [81]
Michigan	13.0 to 10.0	NH_3 emission: 32.4 to 11.8 g/head/d	64	<0.01	Chiavegato et al. (2015) [84]
Texas	13.0 to 11.0	NH_3 flux: 1.69 to 0.79 g/m^2/d	53	<0.05	Pandrangi et al. (2003) [85]
Texas	13.0 to 11.5	NH_3-N flux from excretion: 1.95 to 1.24 g/m^2/d	37	<0.01	Cole et al. (2005) [46]
Texas	13.0 to 11.5	NH_3 flux (Lab): 0.18 to 0.10 g/m^2/d NH_3 flux (Field): 0.49 to 0.33 g/m^2/d	32–44	<0.01 (Lab) >0.05 (Field)	Todd et al. (2006) [80]
Colorado	13.5 to 11.6	NH_3 flux: 7.2 to 6.3 g/m^2/d	13	<0.05	Galles et al. (2011) [26]

Another way to mitigate NH_3 emission is by including CT in the diets. CT are polyphenolic compounds synthesized by plants that bind and precipitate proteins [86]. Herbaceous plants such as alfalfa and cottonseed have CT present in their seed coats and hulls [87]. Phenolic hydroxyl groups of CT form complexes with macromolecules (primarily proteins), reducing degradation in the rumen [86]. CT are thought to increase the efficiency of urea recycled to the rumen, which lowers the ruminal production of NH_3 [88]. It occurs because CT reduces N excretion in urine by shifting the excreted N from urine to feces [89]. For example, when a mixture of condensed and hydrolysable tannins was provided to dairy heifers at 0.15% of dry matter, urine N excretion was reduced by 12% [90]. Since volatilized NH_3 is mainly from urine, significant mitigation of NH_3 has been reported with CT feeding (0 to 57% NH_3 mitigation rate; Table 5).

Table 5. NH_3 mitigation from including CT in beef cattle feeding.

Study Location	CT Source	CT Dose	NH_3 or N Excretion Mitigation Result	Rate (%)	Feeding Description	*p* Value	Reference
Colombia	Quebracho, acacia, and chestnut	0, 2, 4, and 8% dry weight.	Quebracho (0 to 8%): 68 to 50 NH_3 concentration mg/dL Acacia (0 to 8%): 68 to 48 mg/dL Chestnut (0 to 8%): 69 to 30 mg/dL	26–57	CT (Quebracho, acacia, and chestnut) was added to soybean meal at levels of 0, 2, 4, and 8% of dry weight.	<0.05	Gonzalez et al. (2002) [91]
Texas	Not identified	CT rates of 0, 0.5 and 1.0% on a dry matter basis.	0 to 0.5% CT: 64 to 33 ppm 0 to 1% CT: 64 to 37 ppm	42–47	-	<0.01	Campbell et al. (2016) [92]
Texas	Not identified	CT extract at 0, 0.5, and 1.0% of diet, DM basis	Urinary N excretion was not different among treatment. 0 to 1% CT: 82 (139) to 74 (136) g/d	Not significant	Top-dressing a steam-flaked corn–based finishing diet (14.4% CP and NEg 1.47 Mcal/kg)	≥0.39	Ebert et al. (2017) [93]
Canada	*Acacia mearnsii*	Feeding 2.5% CT extract with high protein diets containing corn dried distillers' grains and solubles (DG)	Feeding 40% DG with CT decreased the excretion of total urinary N and urea N in urine by 17 and 21%, respectively.	17–21	-	<0.01	Koenig & Beauchemin (2018) [94]
Italy	Mimosa and Gambier Chestnut and Tara (hydrolysable CT)	Two CT (Mimosa and Gambier) and two hydrolysable CT (Chestnut and Tara) were added (4 g/100 g DM) to a basal feed.	NH_3 emission was mitigated with hydrolysable CT (control 249 to CT 179 mg/L rumen fluid)	28	-	<0.01	Cappucci et al. (2020) [95]

3.3.2. Growth-Promoting Technologies: β-AA and Implants

β-AA, such as ractopamine and zilpaterol hydrochloride, are catabolic hormones that indirectly lead to decreased lipogenesis and increased lipolysis [96]. This feed additive is used by the feedlot industry to enhance the efficiency of gain and modify the carcass characteristics and meat quality [96]. Ractopamine also affects protein metabolism by increasing protein synthesis and decreasing protein degradation. β-AA activates adenylate cyclase, increases cyclic adenosine monophosphate (cAMP), and thereby activates protein kinase A (PKA) and other protein kinases. Thus, β-AA was thought to promote protein degradation and inhibit protein synthesis. However, previous studies have found that β-AA is attributed to elevated myofibrillar protein synthesis [97,98] and depressed myofibrillar protein degradation [99]. β-AA promotes protein synthesis in livestock, reducing N excretion. The reduced N excretion mitigated NH_3 emission (11 to 17%) from β-AA feeding [100]. Ross [100] conducted an experiment to determine the efficacy of feeding ractopamine hydrochloride (RAC) for the last 42 days of the finishing period to reduce NH_3 emissions and improve animal performance. Steers fed RAC vs. control rations showed lower NH_3 emission by 17.21% from d 0 to 28 ($p = 0.032$) and a trend for lower emissions from d 0 to 42 by 11.07% ($p = 0.070$). Ractopamine simultaneously increased beef cattle performance reduced NH_3 emissions [100].

A relatively new β-AA, called lubabegron (Experior; Elanco, Greenfield, IN, USA), was approved by the U.S. Food and Drug Administration in 2018 to be fed to finishing cattle during the last 14 to 91 days on feed, with the label to reduce NH_3 emissions. To our knowledge, lubabegron is the first feed additive approved by the FDA with a label to reduce NH_3 emissions. When fed at a dose of 1.5, 3.5, or 5.5 mg per kg DM, lubabegron increased average daily gain by 11.3%, 16.2%, and 14.2%; feed efficiency by 9%, 12%, and 11.4%; and hot carcass weight by 2.8%, 3.9%, and 4.2% during the last 56-d on feed compared with the control, respectively. Further, NH_3 emissions were reduced by 1.3%, 6.0%, and 11.0% compared with the control when lubabegron was fed to cattle at 1.5, 3.5, or 5.5 mg per kg DM, respectively [101,102].

Previous studies demonstrated decreased NH_3 and amino acid concentration when ractopamine was added to in vitro incubations of ruminal fluid, suggesting a decrease in proteolysis and deamination, and the potential need for greater ruminally degraded protein, although effects varied with protein source and method of grain processing [103].

Growth promoting implants are known as an anabolic hormone product. The active ingredients contained in implants belong to three major categories of endogenously produced hormones: androgens (male hormones), estrogens (female), progestins (pregnancy), progesterone (female), and estradiol (female). Implants increase the circulating levels of somatotropin (ST) and insulin-like growth factor-1 (IGF-1) [104,105], which in skeletal muscle are important for the proliferation and differentiation of bovine satellite cell needed to support the DNA to protein unit throughout growth [106]. Both of ST and IGF-1 are produced by the animal and have a marked effect on how nutrients are used by the animal to produce muscle, bone, and fat [105]. In addition, the mechanisms of the implant to increase growth performance of cattle include modification of priorities for nutrient use for protein vs. fat deposition, alteration of tissue turnover, modification of daily tissue deposition limits, and modification of nutrient supply [107,108].

It was reported that implants enhance both ADG and feed conversion; however, implanted cattle often have less marbling and lower quality grades [109–111]. An increase in protein synthesis with an implant would be expected to reduce N excretion, but no studies have been found to prove that hypothesis. The use of conventional productivity-enhancing technologies (monensin, tylosin, β-AA, and others) mitigate NH_3 emissions by 11–13% [112,113], but the effect of implants alone has not been investigated.

3.3.3. Feed Additive: Monensin

Monensin is an ionophore that increases overall energy yield from feed, improves animal growth performance, and prevents *Coccidiosis* caused by ssp. in beef and dairy cattle. Monensin alters the volatile fatty-acid profile by changing the dominant bacterial species in the rumen from gram-positive bacteria, which favor acetate production, to gram-negative bacteria, which favor propionate production [114–118]. Monensin increases the ratio of propionate to acetate [117,119] and decreased the deamination of amino acids [117].

Monensin decreased NH_3 concentration in ruminal fluid and increased bacterial protein [120]. By decreasing amino acid-fermenting bacteria, monensin has an amino acid-sparing effect, which results in decreased deamination of amino acids and NH_3 concentration in the rumen, leading to increased flow of dietary amino acids to the abomasum [117,121,122].

Providing monensin in feedlot diets decreases DMI and improves feed efficiency of feedlot cattle [119,121,123,124]. In addition, monensin improves N metabolism of rumen bacteria andthe animal, and reduces ruminal degradation of peptides and amino acids, while increasing the flow of dietary protein origin to the small intestine [122,125,126]. Muntifering et al. [126] reported that the amount of N retained in beef steers fed a diet with monensin (33 mg kg^{-1}) was increased from 19 to 24 g/d (+27%) as compared to a monensin-free control diet.

Although the reported effects of monesin seem to increase N availability and decrease N excretion, some studies did not determine a subsequent increase in animal perfor-

mance [127] or a reduction in N excretion in manure [128]. In addition, the isolated effect of monensin on NH_3 emission has not yet been reported, but, only, the mitigation of NH_3 emissions through combination of monensin, tylosin, and β-AA.

3.3.4. Manure Harvesting

The purpose of manure harvesting is to prevent an increase in the production of odorous gases and dust control due to moisture saturation of the open corral surface, which receives constant manure excretion, and to avoid impairing the productivity and welfare of livestock from muddy conditions. If the moisture content of the pen surface is high due to the infrequency of manure harvesting, an environment is formed wherein the NH_4^+ in the manure (especially urine) is easily evaporated as NH_3 into the atmosphere rather than absorbed into soil or bedding. It was reported that moisture content management through periodic manure harvesting reduced NH_3 emissions by 14 to 44% [38,129] (Table 6). In addition, wet conditions foster negative health and well-being outcomes as the wet environment promotes microorganisms' development and creates an uncomfortable environment for livestock to rest and move.

Table 6. Manure harvesting effectiveness in decreasing NH_3 emissions in open-lot livestock facilities.

Study Location	Study Scale	Pen Cleaning Frequency	Result	Rate	*p* Value	Reference
Nebraska	Field	Monthly cleaning (28 days) vs. cleaning after marketing	N loss with monthly cleaning: 12–17 kg/head; N loss with cleaning after marketing: 15–21 kg/head	Monthly cleaning reduced the total N loss by an average of 14%.	<0.01	Wilson et al. (2004) [129]
Nebraska	Field	Monthly cleaning (28 days) vs. cleaning after marketing (135 days)	Monthly cleaning N loss: 12–17 kg/head N loss from cleaning end: 15–21 kg/head	19–44%	<0.01	Erickson and Klopfenstein (2010) [38] *
Iowa	Field	Beef bedded pack barn vs. cleaned and re-bedded one to two times per week (transition)	Bedded pack: 68 mmol/L Transition: 64 mmol/L	Not significant	Not significant	Spiehs et al. (2011) [130]

* Erickson et al. (2010) [38] used the measured data from Wilson et al. (2004) [129].

3.3.5. Manure Handling

Management of livestock manure has a direct impact on NH_3 loss to air [131]. The management of livestock manure and the way it is stored affect manure decomposition, with a direct impact on NH_3 [131] and greenhouse gas (GHG) emissions [132]. Manure is often stockpiled or composted prior to land application [21,22]. Stockpiles heap manure into stacks with no active management of the pile [23], while composted manure piles are turned periodically, entraining oxygen (O_2) into the piles. Overall, it is expected that composted manure emits more aerobically produced gases, such as carbon dioxide (CO_2) and NH_3 [23,26], while stockpiled manure emits more anaerobically produced gases such as CH_4 [25]. Manure composting reduces pathogenic microbes and weed seeds, reduces moisture content, reduces odor, stabilizes nutrients, and improves physical properties of manure that add value to manure as a soil amendment and organic fertilizer [133]. The impact of composting beef manure, although perhaps a means of reducing NH_3 losses during land application, is associated with higher emission losses prior to the field application [131]. The end-product differs from raw manure due to the minimal N loss in storage or after land application [133]. It is estimated that more than 50% of the total N fed is lost as NH_3 from the manure that accumulates within the feedlot [43,134]. Overall, 56 to 75% of the N content of beef cattle manure can be lost between the time it is excreted by the animal and when it is field applied [134]. Piled manure that was applied to the land lost 27% less NH_3 than did manure taken directly from the pen. There was little NH_3 lost from compost that was applied to land since the applied available-N was very low relative to the pen and piled manure [131]. Nitrogen loss during composting ranged from 19 to 42% related to the initial manure N content. Ammonia volatilization (calculated by difference)

accounted for >92% of the N loss whereas combined runoff nitrate and ammonium loss was <0.5% [135].

The influence of handling treatment (fresh, stockpiled, or composted) on nutrient levels and mass balance estimates of feedlot manure was evaluated at Lethbridge, Alberta, and Brandon, Manitoba, in Canada, which showed that total nitrogen (TN) concentration was not affected by handling treatment but the percent of inorganic N was lower ($p < 0.01$) for compost (5.1%) than both fresh (24.7%) and stockpiled (28.9%) manure [136].

The N lost as NH_3 and N_2O emissions represented 26.4 and 3.8% of the initial N in windrow (turning), and 5.3 and 0.8% of that in the stockpile (non-turning), respectively, in a commercial feedyard in Australia [137].

Cumulative GHGs (except N_2O) and NH_3 emissions were higher from composted compared to stockpiled manure (all $p < 0.01$) from cattle fed a typical finishing diet and 3-NOP (125–200 mg kg^{-1} dry matter (DM) feed), or both 3-NOP (125–200 mg kg^{-1} DM) and monensin (33 mg kg^{-1} DM) together, compared to a control (no supplements). NH_3 fluxes averaged 2.9 g N m^{-2} d^{-1} and 2.2 g N m^{-2} d^{-1} from the composted and stockpiled manure for the first 104 days, respectively, which drastically decreased to 0.1 g N m^{-2} d^{-1} at 105 and 202 days for both practices evaluated. Within the respective handling methods, cumulative NH_3 emissions extrapolated over the initial surface area of the piles (kg $pile^{-1}$) averaged over all additives were 158% higher from the composted compared to the stockpiled manure ($p < 0.001$). Compared to the stockpiled manure, the NH_3 kg N t^{-1} initial N was 142% higher ($p < 0.001$) from the composted manure [132].

3.3.6. Dust Control—Water Sprinklers/Irrigation System

Fugitive dust emissions are a high-profile environmental concern for open-lot cattle feedyards. Feedyard dust includes particles from manure, soil, hair, plant material, and insects [138]. It is composed of organic dust (proteins, complex carbohydrates), microorganisms (viruses, bacteria, and fungi), and cellular components like endotoxins [139,140]; it also carries odorous volatile organic compounds [141]. Dust from feedyard surfaces may create nuisance conditions, health hazards, and traffic hazards on adjacent highways [142,143]. Offensive odors are often associated with high dust concentrations [144] and can lead to an increase in neighbor complaints and a decrease in property values [145]. Therefore, NH_3 emission in feedyards correlates with dust control, but the relationship between the two remains somewhat ambiguous.

Water sprinklers are recognized to decrease dust emissions and are thought to mitigate heat stress, but they have not been used in large scale with the aim to mitigate NH_3 from open-lot corral surfaces. While the mechanism of NH_3 volatilization suggests that adding water could increase the rate of N loss, other studies suggest that water has a depressive effect on volatilization rates [26]. The phenomenon of decreasing NH_3 emission following a precipitation event could relate to simple leaching of aqueous NH_4^+ away from the surface layers where it is less susceptible to volatilization. Hutchinson et al. [27] suggested that precipitation events cause a dramatic increase in the size of the reservoir available for NH_3 to exist in solution—diluting the NH_4^+ concentration and effectively decreasing the area of the air/water interface in the manure, the boundary at which volatilization occurs. A modeling exercise by Wu et al. [146] suggests that both mechanistic explanations are at work.

Contradictory results for NH_3 mitigation by using water sprinklers have been reported (Table 7). Some studies evaluating water sprinklers in feedyards have reported an increase in NH_3 generation by ~27% [85,147] after water application, but other studies have reported the mitigation of NH_3 emissions ranging from 27 to 56% [26,148–150]. In view of the lack of consensus on the use of this management practice, there is a concern that the NH_3 mitigation due to water sprinkler is temporary and causes more NH_3 generation during the evaporation process, especially when a rapid evaporation of water due to the hot weather and windy climate in the feedyards is expected.

To fill this knowledge gap, we need:

- More studies on the use of water sprinklers in open corral surface;
- Elucidate short-term NH_3 dynamics in open-lot feedyard;
- Understand those dynamics in different soil and weather conditions;
- Evaluate the major factors influencing short-term NH_3 dynamics, such as sprinklers height, depth of water applied, and frequency of application, and
- A deeper understanding of those dynamics will help livestock producers respond effectively to the Rocky Mountain National Park Early Warning System.

Table 7. Use of water sprinklers to decrease NH_3 emissions in open-lot livestock facilities.

Study Location	Study Scale	Treatment	NH_3 Mitigation		*p* Value	Reference
			Water Applied	Rate (%)		
UK	In vitro	2 mm and 12 mm as layers of water applied after the urine application	2 mm 12 mm [(1)]	+15 +81 [(3)]	N/A	Whitehead et al. (1991) [150]
Texas	In vitro	Day 7 (control) Day 9 (270 mL water added)	270 mL (at 9 d)	−1 to −27%	N/A	Pandrangi et al. (2003) [85]
Maaninka, Finland	In vitro	(1) no irrigation (control), (2) 5 + 5 mm irrigation (3) 20 mm irrigation	NH_3 flux at control: 0.01~0.1 $g/m^2/h$ NH_3 flux with 20 mm irrigation: 0 to 0.04 NH_3-N $g/m^2/h$). [(2)]	~+56	N/A	Saarijärvi et al. (2006) [149]
Colorado	In vitro	Water layer application of 5 mm	5 mm	+27	<0.01	Galles (2011) [26]

[(1)] after urine application, [(2)] rainfall along with irrigation, [(3)] means more NH_3 was emitted to the atmosphere, and + means NH_3 was mitigated/less emission.

3.3.7. Manure Amendments

Manure amendments include both chemical and physical amendments. The mechanism for mitigating NH_3 for each specific amendment is different in detail. Chemical amendments primarily suppress urea decomposition or the formation of aqueous NH_3^0. Physical amendments act to block NH_3 emission or absorb it prior to release from the pen surface.

Most of the proposed amendments for mitigating NH_3 are chemicals applied to the pen surface. Much of the N excreted in the urine is in the form of urea, which is rapidly hydrolyzed to NH_4^+ and eventually NH_3 gas by the urease enzyme produced by soil and fecal microbes [130]. Urease inhibitors can block the hydrolysis of urea to NH_4^+ [131,132] and thereby decrease NH_3 production. Studies evaluating application of chemical amendment on open corral surfaces to mitigate NH_3 emission have shown a wide range (19 to 98%) of effectiveness, which included urease inhibitors [130,132–134] and chemical compounds such as calcium chloride, humate, aluminum sulfate, and CT [135] (Table 8). The urease inhibitor reduced emissions between 26 and 66% in the laboratory and at the pilot scale but did not show significant mitigation in a farm-scale experiment. The manure amendments calcium chloride, humate, aluminum sulfate, and commercial NH_3 inhibitors, lower the pH and thereby inhibit urease hydrolysis which reduce in vitro NH_3 emission by 32 to 71% [135].

Widespread adoption of chemical amendments is low due to their high cost and the negligible financial benefit of NH_3 suppression.

As physical amendments, biochar, bentonite, vermiculite, and zeolites have been used on pen surfaces to mitigate emissions by absorbing NH_3 generated from beef, dairy, and swine manure.

Biochar is defined by Lehmann and Joseph [151] as a carbon-rich product derived from the pyrolysis of organic material at 300 to 800 °C. Biochar's total surface charge and total concentration of functional groups act on the adsorption of NH_3 or organic-N into biochar, cation or anion exchange reactions, and enhanced immobilization of N as a consequence of labile C addition in the biochar. The action of zeolite is based on its tetrahedral crystals containing silicon and aluminum in various proportions, forming a skeletal structure with unique ion-exchange properties enabling the removal of pollutants. The efficiency of this process depends mainly on the type of pollutant, the presence of oxygen, and the reaction temperature [152].

Several studies evaluating the effects of biochar and CT have shown significant results on mitigating NH_3 emission from swine and dairy manure [137–139]. However, only Sepperer et al. [136] evaluated the effects on beef manure amended with CT, observing mitigation of NH_3 emission from 75 to 95%. Szymula et al. [153] evaluated different sorbents to decrease NH_3 emissions from fecal samples collected from dairy cows and found that the most effective reduction in NH_3 was achieved using 3% biochar (42.56% of reduction), 3% bentonite, with zeolite in a 1:1 ratio (24.56% of reduction), and 3% addition of zeolite (10% of reduction) relative to the control.

Table 8. Effectiveness of manure amendments on decreasing NH_3 emissions in feedyards.

Study Location	Study Scale	Type of Amendment	Amendment Dose	NH_3 Mitigation Rate (%)	*p* Value	Reference
Nebraska	Field	Urease inhibitor: N-(n-butyl) thiophosphoric triamide (NBPT)	22.8 kg/ha once per week for 42 d	45	N/A	Varel et al. (1999) [154]
Texas	In vitro	NBPT	1 kg/ha for 21 d	65	<0.05	Shi et al. (2001) [155]
		NBPT	2 kg/ha for 21 d	66	<0.05	
		Calcium chloride	4500 kg/ha	71	<0.05	
		Humate	9000 kg/ha	68	<0.05	
		Aluminum sulfate	9000 kg/ha	98	<0.05	
		Commercial product (Ammonia Hold, Lonoke, AR)	750 kg/ha	32	<0.05	
Texas	In vitro	NBPT	1 kg/ha once per 8 d for 38 d	49	<0.05	Parker et al. (2004) [156]
		NBPT	2 kg/ha once per 8 days for 38 d	66	<0.05	
Texas	In vitro	NBPT	5 kg/ha once per 4 d + 6 mm rainfall once per 4 d	26	<0.05	Parker al. (2011) [157]
		NBPT	5 kg/ha once per 4 d	33	<0.05	
Texas	Field	NBPT	1, 2, 4, 8, and 40 kg/ha for 42 d	Not significant		Parker al. (2016) [158]
Austria	In vitro	CT	1 mL of manure was added with 1%, 5%, and 10% by weight of tannins adsorbent	75–95	Not significant	Sepperer et al. (2020) [159]

4. Conclusions

Our review combines the state of knowledge concerning the emission, transport, and deposition, and mitigation strategies of gaseous NH_3 from open-lot cattle feeding facilities located east of the northern Front Range of the Rocky Mountains. Overall, up to 90% of feedyard NH_3 originates from urine deposited in animal pens, but the instantaneous magnitude of that loss depends strongly on weather conditions (temperature, precipitation, humidity, and wind), soil properties, pH, microbiological activities (e.g., urease activity), and management practices. As easterly winds advect and lift pollutants up the eastern slope of RMNP, the air cools and condenses to form clouds. Precipitation maxima in northern Colorado are associated with easterly winds and occur most frequently in spring and summer. During precipitation events, clouds entrain Front Range pollution and deposit the pollutants over the mountains in the precipitation. Among dietary manipulation practices, CP and CT were the most effective in reducing NH_3 emission (43 and 57%, respectively). However, more information is needed on the effectiveness of implants and monensin

on NH_3 mitigation. Manure moisture content management through periodic manure harvesting reduced NH_3 emissions by 14 to 44%. The impact of water sprinklers has been ambiguous, showing both increases and decreases in NH_3 emissions. Pen-surface amendments are promising but costly NH_3 mitigators whose effectiveness at scale has not been conclusively demonstrated.

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Abbreviations

Definitions of key acronyms used in this paper.

ADG	average daily gain
AFO	animal feeding operations
BAO	Boulder Atmospheric Observatory Tower
BMP	best management practices
BSC	bovine satellite cell
CAFOs	concentrated animal feeding operations
CAMP	cyclic adenosine monophosphate
CLA	Colorado Livestock Association
CP	crude protein
CT	condensed tannins
DMI	dry matter intake
IGF-1	insulin-like growth factor-1
NASEM	National Academies of Sciences, Engineering, and Medicine
NBPT	urease
NDRP	Nitrogen Deposition Reduction Plan
NRCS	Natural Resources Conservation Service
PKA	protein kinase A
RAC	ractopamine hydrochloride
RDP	rumen degradable protein
RMNP	Rocky Mountains National Park
RoMANS	Rocky Mountains Atmospheric Nitrogen and Sulfur Study
RUP	rumen undegradable protein
ß-AA	ß-adrenergic agonists
ST	somatotropin
TAN	total ammoniacal nitrogen

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