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INFLUENCE OF CLIMATE CHANGE ON ENSILING

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Abstract: Climate change can affect the quantity, reliability, and quality of forage production and therefore silage preparation. In the coming decades, crops and forage plants integral to feed conservation will face rising temperatures, higher carbon dioxide levels, and highly variable water availability due to changing rainfall patterns. Contamination with undesirable microbes and chemical agents is often encountered during silage production under climate change conditions. The presence of yeasts and molds can negatively affect the nutritional value and livestock production. Future strategies in feed preparation, processing, and livestock production will focus on achieving carbon neutrality and reducing greenhouse gases in agriculture, including livestock farming, which is a global concern. Ensiling involves microbial activity followed by biochemical reactions. Changes in the silo occur almost immediately after plants are transferred from the field to the silo. The course and severity of these changes depend on various factors, mainly those that promote successful lactic acid fermentation, such as moisture content, an anaerobic environment, carbohydrate levels, and temperature.

Keywords: Silage, Livestock, Nutrition, Feed, Mycotoxins, GHG Emission

INTRODUCTION

Climate change disrupts food, water, and livelihoods by altering temperature, precipitation, and sea levels, and it affects livestock growth, milk production, reproduction, metabolism, and disease rates (Sahoo, 2018). By 2050, global food production must increase by 50% (Hamad and Tayel, 2025), despite climate change threats such as extreme weather and pests, Figure 1. Projections based on population growth and food consumption patterns indicate that by 2050, agricultural production will need to increase by at least 60-70 percent to meet demand (IPPC, 2019). The decarbonization of industrial and agricultural production, including livestock farming, has become a global trend, and many countries are aiming for carbon neutrality by 2050 (Cai, 2025). Meanwhile, total global cultivated land area has not changed since 1991 (O'Mara, 2012), reflecting increased productivity and intensification efforts (Rojas-Downing et al., 2017).

Achieving this requires optimizing land and water use through integrated approaches: enhancing soil health, employing precision agriculture, and promoting biodiversity (Wang, 2025). Climate change can influence the quantity, reliability, and quality of forage production, as well as the water needs of growing forage crops, and the patterns of large-scale rangeland vegetation (Giridhar and Samireddypalle, 2015). The most noticeable effect will be on the primary productivity of forage crops and rangelands. Developing nations are at greater risk from climate change than developed nations due to their reliance on agriculture, warmer baseline climates, and limited resources to adopt new technologies. Over the coming decades, crops and forage plants will face increasing temperatures, higher carbon dioxide levels, and highly variable water availability due to changing rainfall patterns. The combined effects of these factors will determine the actual impact on plant growth and yields. Elevated CO_2 may enhance dry matter production more in C3 plants than in C4 plants, with the response depending on crop type, soil moisture, and nutrient levels (Giridhar and Samireddypalle, 2015). Future efforts in feed preparation, processing, and livestock production will prioritize carbon-neutral research and development (Cai, 2025).

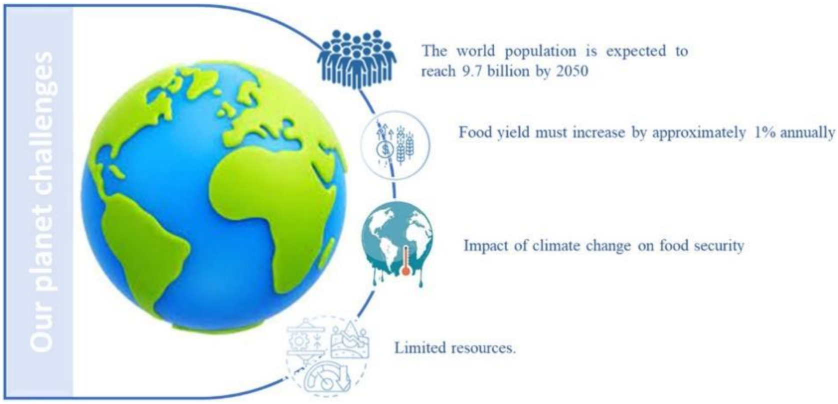

Figure 1. Challenges facing our planet by 2050 (Hamad and Tayel, 2025)

Variations in rainfall during the growing season across many regions are likely to substantially impact forage production. Since agriculture consumes the largest share of freshwater, decreasing water availability will pose a threat to forage crop yields. Nevertheless, adopting suitable adaptation strategies, backed by strong government policies, can mitigate the adverse impacts of climate change and help sustain livestock productivity by securing sufficient forage resources (Giridhar and Samireddypalle, 2015).

Silage

Ensiling is a microbial process used to preserve fresh feed in animal production and in biorefinery (Okoye et al., 2023). In these processes, lactic acid bacteria (LAB) play a key role among silage microorganisms, and the effects of exogenous LAB on silage quality have been widely studied (Wang et al., 2021). Furthermore, LAB are among the microorganisms with GRAS (generally recognized as safe) status (Fabiszewska et al., 2019). Additives are frequently used to speed up the ensiling process, prevent the growth of harmful microorganisms, and improve the silage quality of different crops (Ivetić et al., 2024).

Silage is an excellent method of feed preservation; however, carbon dioxide, methane, and nitrous oxide produced during fermentation are significant sources of agricultural greenhouse gases (Hu et al., 2024). In light of climate change and rising temperatures, understanding the impacts of high-temperature ensiling on microbial communities is crucial, as these conditions may increase the alpha diversity of the resulting silage and enhance heterofermentative fermentation (Hernández-Perea et al., 2025). In many countries, there is a scarcity of forage for ruminant feeding due to climatic conditions and water resource shortages (Sahoo, 2018).

The technology of silage preparation involves several routine techniques, but each step carries a number of possible consequences for the quality of the resulting silage if not implemented correctly (Ivetić, 2017). The main points of risk are selecting the correct stage of plant maturity for ensiling, rapidly removing air from the plant mass in the silo, and ensuring proper covering. Changes in the silo mass occur practically as soon as the plant mass is transferred from the field to the prepared silo object. The course and intensity of these changes depend on a number of factors, but mostly on those that condition the successful development of lactic acid fermentation, such as moisture in the plant mass, an anaerobic environment, carbohydrate content, and temperature. These factors create conditions in which the desired microorganisms will dominate during fermentation of the plant mass and enable the production of quality silage with high nutritional value.

To produce high-quality silage, one must conduct a thorough assessment of the plant, microbial, and environmental factors that influence the fermentation process and, ultimately, the silage's nutrient value. Sahoo (2018) emphasized that the influence of forage characteristics (epiphytic lactic acid bacteria (LAB), buffer capacity, and sugar: buffer capacity ratio) on treatment effectiveness varied with DM content. It is essential to harvest forage at the right time, considering nutritional quality, available quantity, and climatic conditions, and then to store it properly to reduce losses. Silage corn production has significant environmental benefits, including reductions in greenhouse gas emissions, improved fertilizer use efficiency, improved soil health, and reduced environmental pollution (Zhang et al., 2025).

Choosing the right corn hybrid and other plant cultivars affects the nutritional value of silage and milk production. Optimizing harvest maturity, kernel processing, theoretical cut length, and cutting height improve or maintain the nutritive value and milk production of lactating dairy cows (Ferraretto et al., 2018). The authors point out that technological advancements have been developed and made available to dairy producers and corn growers seeking to enhance the fiber and starch digestibility of whole-plant corn silage. However, inconsistencies in silage quality may also be due to climate change.

Impact of Climate Change on Silage Preparation

Greenhouse gas emissions during ensiling are closely linked to microbial activity. Hu et al. (2024) note that studies indicate that Lactobacillus inhibits plant cell respiration and gas-producing bacteria by rapidly lowering the environmental pH in the early phase. Its relative abundance is negatively associated with total gas emissions and CO_2 output (Zheng et al., 2022). Meanwhile, Enterobacteriaceae are active in the initial stages, using sugars to generate CO_2. Their relative abundance correlates positively with CO_2 production (Sun et al., 2023). Where silage microorganisms can recycle CO_2, fermented silage as animal feed has significant potential to reduce emissions, even to the point of serving as a carbon sink, through the application and manipulation of silage bacteria (Kruger et al., 2023).

Where international policy encourages farmers to adopt sustainable farming practices, emissions from silage preservation are not sufficiently documented in the European Union or United States emissions inventories to incentivize good silage preservation practices (Kruger et al., 2023). In fact, emissions from stored silage are excluded from the European inventory (European Environment Agency, 2019), whereas many factors related to silage production are inventoried in non-agricultural sectors.

The increasing frequency of extreme climate events has made the identification of stress-tolerant germplasm essential in crop breeding research (Li et al., 2024). Identifying germplasms with deep root systems enhances drought resistance by facilitating deeper water absorption (Hu et al., 2024).

Krueger et al. (2023) estimated the CO_2 emissions of corn silage based on a meta-analysis review of laboratory experiments to be $1.9 \pm 5.6\%$ (GWP_{20}) and $0.2 \pm 5.5\%$ (GWP_{100}) of silage dry matter. Furthermore, model results demonstrated a precedent for CO_2 recycling by silage microorganisms, which was supported by genome annotation of strains belonging to common silage species. Linear model equations for GWP_{20} and GWP_{100} with inputs and outputs in mg kg^{-1} silage dry matter were developed, where inputs are acetic acid (A), ethanol (E), lactic acid (L), and volatile corrected dry matter loss (DV).

Linear equations are (for GWP20):

$GWP_{20}=-3626.1-0.04343A+0.8011E-0.03173L+1.46573DV$
And for GWP100:
$GWP_{100}=-8526.10-0.22403A-0.11963E-0.03173L+1.46573DV$.

The quality of feed crops and forage may decline due to higher temperatures and dry conditions, which alter water-soluble carbohydrate and nitrogen levels, according to Rojas-Downing et al. (2017). Increased temperatures can raise lignin and cell wall components in plants (Polley et al., 2013), reducing digestibility and nutrient availability for livestock (Polley et al., 2013; Thornton et al., 2009). Conversely, rising CO_2 levels improve forage quality more in C3 plants, which also have higher crude protein and digestibility than C4 plants (Polley et al., 2013; Thornton et al., 2009; Wand et al., 1999).

As climate change challenges plant silage cultivation, adaptation studies are vital. Temperature and precipitation shifts affect growth, development, and yield, highlighting the need for adaptation research, as maize genotypes respond differently to climatic conditions (Zhang et al., 2025).

Drought, heat waves, and groundwater shortages are changing corn cultivation worldwide (Tothi et al., 2022). The authors emphasize that silage crop preparation's sensitivity to climate change. Corn (*Zea mays* L.) silage is a major forage source for ruminants in climates where com is moderate to well adapted, consisting of the high energy, low-protein forage commonly used for growing and finishing beef cattle as supplemental energy for cow and calf production, for growing dairy heifers, and for lactating dairy cows, often in combination with a complementary high-protein forage such as alfalfa (*Medicago sativa* L.), (Allen et al., 2003). Aflatoxins have a significant health, nutritional, and economic impact on the nutritional chain of humans and animals. All participants in the production and food chain such as farmers, grain producers, distributors, crop processors, farmers, and consumers have consequently losses, (Ivetić et al., 2022). Direct effects include increased veterinary care costs, reduced livestock production, and continued endangered food safety for humans and animal feed (Ćosić and Ivetić, 2022).

Contamination with undesirable microbes and chemical agents is one of the major problems in silage production. The presence of yeasts and molds can negatively affect silage's nutritional value (NV) because they produce toxic compounds that are harmful to ruminants (Alonso et al., 2013). These microbes can proliferate massively once the silo is opened due to the presence of oxygen. As a result, increasing yeast and mold populations decrease aerobic stability and reduce silage stability. Mycotoxins are secondary fungal metabolites that have been detected in a variety of feed ingredients and can affect human and animal health, and animal productivity. Consuming the contaminated silage, ruminants are often exposed to mycotoxins, primarily such as aflatoxins, trichothecenes, ochratoxin A, fumonisins, zearalenone, and many others. Mycotoxins in silage can be minimized by preventing fungal growth before and after ensiling, with proper silage management to reduce mycotoxin contamination of feeds, and certain mold-inhibiting chemical additives or microbial inoculants can also reduce the contamination levels, (Ogunade et al., 2018). Apart from mycotoxins, microbial hazards include Clostridium botulinum (associated with cattle botulism), Bacillus cereus, Listeria monocytogenes, Shiga toxin-producing Escherichia coli, Mycobacterium bovis, and various mold species, (Driehuis et al., 2018).

Mycotoxins are secondary products of mold metabolism, which are synthesized by a series of reactions catalyzed by enzymes from a large number of biochemically simple intermediate products of primary metabolism, (Kos, 2015). Mycotoxins are produced by toxic strains of fungi that are found in food for humans and animals, (Chhaya et al., 2023). There is a constant threat to mycotoxins contamination all over the world in the nutritional chain, with a serious impact on human and animal health (Ivetić et al., 2024). Physical factors like pH, light, moisture, temperature, water, relative humidity, and atmospheric gases are responsible for aflatoxin contamination, (Ivetić et al., 2023).

To minimize the aflatoxin contamination in crop plants, various physical, chemical, and biological methods, and various breeding and genetic engineering approaches as well, have been used to minimize the toxicity of aflatoxin and reduce its level below the recommended one. Several approaches have been manifested to reduce the aflatoxin contamination in crops which include various physical, chemical, and biological methods.

Impact of Climate Change on Livestock

Livestock systems are affected by climate change primarily through rising temperatures, changes in precipitation, and increasing atmospheric carbon dioxide (CO_2) concentrations, as well as a combination of these factors (IPCC, 2019). Temperature affects key factors in livestock production, including water availability, animal production and reproduction, and animal health (mostly through heat stress) (Rojas-Downing et al., 2017), as shown in Figure 1. Reduced feed intake is also a response to high environmental temperatures (Cheng et al., 2022).

Climate change significantly affects livestock by impacting agriculture and leading to shortages in feed resources and their quality, which, in turn, can influence growth, milk production, reproduction, metabolic activity, and disease prevalence (Sahoo, 2018). Climate change is already affecting food security. Recent studies in both large-scale and small-holder farming systems document declines in crop productivity due to rising temperatures and changes in precipitation. Evidence of climate change impacts (e.g., declines and stagnation in yields, changes in sowing and harvest dates, increased infestation of pests and diseases, and declining viability of some crop varieties) is emerging from detection and attribution studies and ILK in Australia, Europe, Asia, Africa, North America, and South America (medium evidence, robust, IPPC, 2018) (Figure 2, Table 1).

Indirect effects of climate change on livestock include (i) limited access to water, pasture, and other feed resources, (ii) health issues related to altered or new vector-borne and parasitic diseases, and (iii) competitive environmental interactions with other livestock species, (Sahoo, 2018).

By using a seven-category typology to classify and compare smallholder farmer adaptations across communities, the synthesis shows that in order to reduce their vulnerability, smallholder farmers have mostly taken action on environmental management and diversified their livelihoods through market exchange, and some have engaged in labour migration (Burnham and Ma, 2016).

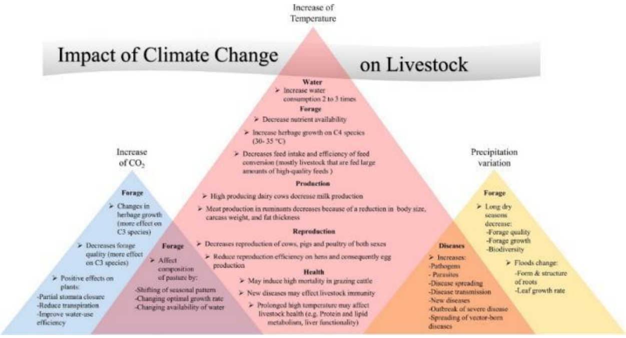

Figure 2. Impacts of Climate Change on Livestock (Rojas-Downing et al., 2017)

The review by Rojas-Downing et al. (2017) outlines key impacts of climate change on livestock: increased heat stress that causes animal mortality and affects product quality; reduced feed quality due to droughts and elevated CO_2 levels; the spread of parasites and vector-borne diseases that threaten livestock health; and the importance of adaptation and mitigation strategies. These include enhanced cooling systems in shelters and modifications to feed. The review also emphasizes the need for research in developing countries to address these challenges. Additionally, Cheng et al. (2022) highlight that implementing adaptation measures is vital to meet the rising demand for livestock products and reduce climate change impacts.

Table 1. Climate change impacts on livestock production (Cheng et al., 2022)

Impact type	**Observed impacts**	**Major influential factors**
Direct impact	Reduced feed intake	Increased temperature (heat stress)
	Decline in animal and meet production	
	Decreased reproductive performance	
	Negatively affected immune functions	
	Increased mortality	
Indirect impact	Changes in feedstuff crop yields	Elevated CO_2 level
	Changes in pasture composition and forage production	
	Changes in forage quality	Increased temperature and elevated CO_2 level
	Shrinking water availability and increasing water use	Increased temperature
	Larger seasonal variation in resource availability	More frequent extreme climate events
	Increased disease, pest, and parasite stress	Increased temperature and changes in the precipitation pattern

Feeds with low quality and digestibility lead to higher enteric emissions per unit of meat or milk, especially in low-productivity systems (Ivetić et al., 2021; Belay 2019). Enhancing feed digestibility and energy content, as well as better matching protein supply to animal needs, can be achieved through improved grazing management, selecting better pasture species, changing forage mixes, and increasing the use of feed supplements to create a balanced diet that includes crop by-products and processed crop residues. These strategies can enhance nutrient uptake, boost animal productivity and fertility, and thus reduce emissions per unit of product. However, it is important to ensure that emissions from off-farm production and processing of supplementary feeds do not exceed on-farm emission reductions (Belay, 2019). Diet adjustments, such as increasing the proportion of concentrates and improving forage quality and digestibility, offer a practical way to lower enteric CH_4 emissions and emission intensity. Nonetheless, the mitigation potential of these practices is typically limited to about 10 to 15% (Hristov, 2024).

Mitigation of enteric methane emissions is necessary to achieve these goals. Many innovative solutions are being tested and considered. Global challenges, such as enteric methane mitigation and its contribution to climate change, cannot be solved by one organization, (Ivetić et al., 2023). Addressing these challenges requires collaboration among many organizations and across different sectors, followed by cross-border and worldwide cooperation, (Ivetić et al., 2023).

Global climate change is affecting temperature, precipitation, and water availability, which directly affects agriculture and livestock productivity (Souza et al., 2023). Therefore, the expected declines in dry matter intake (DMI) and animal productivity, and changes in water intake caused by heat stress, may also affect the environmental costs of production in cattle. Emissions of GHG from livestock (by category) are shown in Figure 3.

The high-efficiency utilization of feed resources and environmental protection are two major challenges in animal husbandry. The goal of carbon neutrality by 2050 is to enhance livestock-rearing technology and contribute to a green, decarbonized society (Cai, 2025). The previously mentioned author emphasizes that this approach not only promotes harmony with nature but also fosters sustainable practices that allow for resource cycling and synergy between farming and livestock operations.

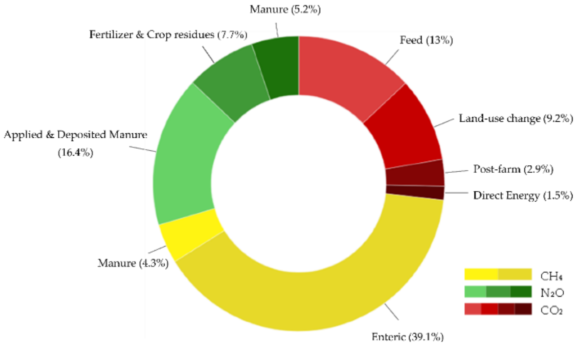

Figure 3. Emissions from livestock (by category), where methane (CH_4) emissions are portrayed in yellow, nitrous oxide (N_2O) in green, and carbon dioxide (CO_2) in red (Cheng et al., 2022) according to the data source of Gerber et al. (2013).

Preserving a greater proportion of food waste for use as livestock feed, especially as silage, would have significant environmental and socioeconomic benefits (Ivetić et al., 2022; Rodriguez et al., 2024). Many experiments have shown that adding food waste as a silage additive to treated silage reduces CH4 emissions and nitrogen losses while decreasing DM digestibility (Zhang et al., 2025). According to Hossain (2025), environmentally, silage production minimizes crop residue waste and lowers greenhouse gas emissions by reducing the need to transport fresh feed. Using silage also helps livestock systems become more resilient to climate change by enabling adaptation to changing feed availability (Hossain, 2025). Although maize silage is widely used in animal agriculture because of its efficiency and nutritional benefits, challenges remain in optimizing quality, managing pathogens, and adapting production processes to climate change (Zhang et al., 2025).

Climate change adaptation refers to adjustments in ecological, social, or economic systems to reduce the negative impacts of climate change or enhance its positive impacts (Cheng et al., 2022). In an agricultural setting, adaptation can occur through ecological change or human action, as previously mentioned, authors noted.

CONCLUSION

By 2050, global food production must increase by 50% despite climate change threats, as projections based on population growth and food consumption patterns indicate a need to meet the population's nutritional demands. On the other hand, there is a growing threat from global climate change and its negative impact on livestock production. These changes affect silage consumption and production patterns, increasing the risk of a decline in silage nutritional value. Many innovative solutions for silage additives are under consideration and being tested. Climate change adaptation refers to adjustments in the ensiling process and in crop cultivation to enhance silage health, safety, and quality.

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