Research Article

Mycotoxins in Silage: Occurrence, Effects, and Management Strategies for Sustainable Livestock Production a Review

Syed Nouman Shah[1], Anees Ur Rahman[1], Abdul Kabir[1,2*], Midrar Ullah[3], Shahab Ahmad Nawaz[1], Muhammad Said[1], Abdul Hafeez Bukero[1], Maaz Ahmad[1] and Muhammad Sadiq[1]

[1]Faculty of Animal Husbandary and Veterinary Science, Sindh Agriculture University Tandojam, Pakistan; [2]Department of Veterinary Microbiology Faculty of Animal Husbandry and Veterinary Sciences Sindh Agriculture University, Tandojam, Pakistan; [3]Livestock and Dairy Development Department Government of Khyber Pakhtunkhwa, Pakistan.

Abstract | Mycotoxins are toxic compounds produced by fungi that contaminate silage, a common livestock feed. Mycotoxin contamination poses significant risks to animal health and performance, affecting various physiological systems and functions. This paper aims to review the current literature on mycotoxin occurrence, effects, and management in silage and identify effective strategies to ensure animal health, productivity, and minimize economic losses. We synthesized evidence from studies on harvest and ensiling techniques, silage additives and preservatives, postharvest management practices, feed management practices, and mycotoxin binders. We found that proper harvest and ensiling techniques; silage additives and preservatives that prevent fungal growth; regular monitoring of storage conditions and feed samples; well-mixed feed formulations with mycotoxin binders; diversified feed ingredients and optimized feed processing techniques can reduce mycotoxin levels in silage and their negative impacts on livestock. We conclude that a comprehensive understanding of mycotoxins in silage and the implementation of effective management strategies are essential for sustainable livestock production. Future research should focus on developing alternative and sustainable feed sources, precision livestock farming techniques, genetic selection for resilience and sustainability, circular economy approaches, and climate change adaptation strategies.

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***Correspondence** | Abdul Kabir, Faculty of Animal Husbandary and Veterinary Science, Sindh Agriculture University Tandojam, Pakistan; **Email:** Kabirvet32@gmail.com
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Introduction

Mycotoxins are secondary metabolites produced by various fungi that can contaminate crops, including silage, during pre- and post-harvest periods (Marroquín *et al*., 2014). Silage is a crucial feed for livestock production, especially in areas with limited access to grazing pastures, and where climate conditions do not support year-round production of fresh forage. It is a fermented feed made by packing and preserving high-moisture crops such as grasses, legumes, and grains under anaerobic conditions. This process facilitates the growth of lactic acid bacteria, which reduce the pH and preserve the feed (Kung *et al*., 2019). While silage is a popular feed among dairy and beef producers, it is also a potential source of mycotoxin contamination. Mycotoxins can affect animal health, productivity, and reproduction, causing economic losses to farmers (Yang et al., 2020). Therefore, the occurrence and impact of mycotoxins in silage is an important topic of research for sustainable livestock production. The complexity and variation of mycotoxin contamination in silage are influenced by many factors, including crop type, harvest practices, storage conditions, and climate (Chhaya et al., 2022). Aflatoxins, ochratoxins, fumonisins, and deoxynivalenol are among the most common mycotoxins found in silage. These toxins have toxic effects on animal and human health (Pitt *et al*., 2016). Fusarium species such as *F. graminearum* and *F. verticillioides* are the most common fungi associated with mycotoxin contamination in silage. Their toxins, such as deoxynivalenol (DON), zearalenone (ZEN), and fumonisins, can cause various health issues in livestock (Durham, 2022). Studies have shown that the levels of DON in silage were positively correlated with the incidence of respiratory disease in dairy cows (Awad *et al*., 2013). Exposure to ZEN in feed has been linked to reproductive problems in sows, such as reduced litter size and abnormal foetal development (Zhu *et al*., 2018). Other fungal species such as Penicillium and Aspergillus can also produce mycotoxins in silage, such as ochratoxin A (OTA), which can accumulate in animal tissues and milk (Fink *et al*., 2008). The impact of mycotoxin contamination in silage extends beyond animal health and productivity and can have broader implications for sustainable livestock production. The use of contaminated silage can lead to increased veterinary costs, reduced feed conversion efficiency, and decreased milk and meat production, resulting in economic losses to farmers. Furthermore, the consumption of mycotoxin-contaminated animal products, such as milk and meat, can pose health risks to consumers (Gallo *et al*., 2018). Despite the potential risks associated with mycotoxin contamination in silage, effective management strategies can reduce the risk of mycotoxin exposure in livestock. Pre-harvest practices such as crop rotation, soil management, and the use of fungicides can prevent the growth of mycogenic fungi and reduce mycotoxin contamination in the crop (Dell'Orto et al., 2015; Driehuis *et al*., 2018). Harvest and post-harvest practices, such as proper ensiling techniques and storage conditions, can also minimize mycotoxin development in silage (Pitt *et al*., 2016). Mycotoxin contamination in silage poses a significant challenge for livestock producers worldwide, as it can have detrimental effects on animal health, productivity, and profitability (Diaz *et al*., 2020). In addition, mycotoxin contamination in silage can lead to reduced feed intake, impaired nutrient absorption, decreased milk production, and increased susceptibility to diseases in animals (Marquardt *et al*., 2017). Moreover, the presence of mycotoxins in animal products derived from contaminated silage can result in economic losses and pose health risks to consumers (Gallo *et al*., 2018). Therefore, effective management strategies are crucial to mitigate the risk of mycotoxin contamination and ensure safe and sustainable livestock production. To address the challenge of mycotoxin contamination in silage, various strategies have been proposed. These strategies encompass improving crop management practices, enhancing storage conditions, using feed additives, and applying biological control agents. For instance, selecting crop varieties with improved resistance to fungal infections, minimizing crop damage during harvest, and ensuring proper packing and sealing of silage are measures that can reduce mycotoxin contamination (Santos *et al*., 2020). Furthermore, the use of feed additives such as activated charcoal and clay minerals has shown promise in binding mycotoxins and reducing their bioavailability to animals (Binder *et al*., 2007). Biological control agents, including lactic acid bacteria and yeasts, offer another avenue for managing mycotoxin contamination in silage. These agents can inhibit the growth of mycogenic fungi and alter the fermentation process, resulting in a decrease in mycotoxin production. Yeasts, in particular, produce organic acids and ethanol that can inhibit the growth of mycotoxigenic fungi and reduce mycotoxin production (Dunière *et al*., 2013). Additionally, certain yeasts have the ability to utilize mycotoxins as a source of carbon, thereby reducing their concentration in the silage (McEniry *et al*., 2008). Given the significant impact of mycotoxin contamination in silage, understanding its occurrence, and implementing effective management strategies are essential. This review paper aims to provide a comprehensive overview of mycotoxins in silage, including their occurrence, effects, and management strategies for sustainable livestock production.

By exploring the complexities of mycotoxin contamination in silage and the various approaches for its control, this review aims to contribute to the development of practical and science-based solutions to ensure the safety and sustainability of livestock production.

Occurrence of mycotoxin in silage during pre- and post-harvest

Preharvest: Mycotoxins produced by various species of Fusarium and Alternaria can contaminate crops, including silage, during the preharvest period. Fusarium species produce trichothecenes, which are sesquiterpenes, with two main types: Type A and type B. Type A trichothecenes, produced by *F. poae, F. sporotrichioides,* and *F. langsethiae*, are considered more toxic than type B trichothecenes, primarily produced by *F. cerealis, F. culmorum,* and *F. graminearum* (Thrane *et al.*, 2001). Deoxynivalenol (DON) is the most common trichothecene found in crops and can cause vomiting, reduced feed intake, and immunosuppression (Zhou et al., 2021; Rotter *et al.*, 1996). Type B-producing Fusarium species also produce zearalenone (ZEA) and its derivatives, α- and β-zearalenol (α- and β-ZOL), which are estrogenic compounds (Storm et al., 2010). Fumonisins, sphinganine analogues with carcinogenic properties, are primarily produced by F. proliferatum and F. verticillioides (Elderblom *et al.*, 1992; Rehman et al., 2022). They are more prevalent in tropical and subtropical areas, leading to higher fumonisin contamination in preharvest crops from these regions (Marasas *et al.*, 2014). Some lactic acid bacteria have the ability to bind to mycotoxins such as DON, ZEA, and fumonisin B1 (Boudra *et al.*, 2008). Plants can also reduce the toxicity of mycotoxins by conjugating them with polar substances such as sugars, amino acids, or sulfate (Schneweis *et al.*, 2002; Berthiller *et al.*, 2005). The Figure 1 shows the different mycotoxin found during preharvest in addition to trichothecenes and fumonisins, other mycotoxins produced by Fusarium and Alternaria species, including moniliformin, fusaproliferin, beauvericin, and enniatins, may be present in cereals and maize preharvest (Battilani *et al.*, 2019). However, their stability in silage is not extensively studied. Alternaria species, such as Alt. arborescens, Alt. alternata, Alt. tenuissima, and Alt. infectoria, can produce various compounds with disputed toxicity, including alter nariols, altertoxins, altenuene, tenuazonic acid, infectopyrones, and novaezelandins (Andersen et al., 2002). Aflatoxins, produced by Aspergillus flavus and Asp. parasiticus, are another major group of mycotoxins that can contaminate silage. Aflatoxins are highly carcinogenic, and their presence in silage can pose a risk to human health as cattle can transform them into hydroxylated derivatives (aflatoxins M1 and M2), which can be found in milk and meat products (Frisvad et al., 2005). Asp. flavus can also produce other mycotoxins, including cyclopiazonic acid and 3-nitropropionic acids (Mansfield and Kaldau, 2007). While aflatoxin B1 has been detected in some surveys of silage, other studies have reported negative results. The occurrence of mycotoxins in silage during the preharvest period raises concerns due to their potential health hazards and impact. Figure 1 displays preharvest mycotoxins categorized into three sections: *Fusarium* spp., *Alternaria* spp., and *Aspergillus* spp. Each section contains drawings of the mycotoxin, pictures of affected plants or crops, and a list of produced toxins. For instance, *Fusarium* spp. affects corn and produces Type A Trichothecene and Type B Toxin (Scribbr, 2021). These fungal metabolites can infect various crops before harvest. *Alternaria* spp. generates alternariol and alternariol monomethyl ether, which are mutagenic and cytotoxic (Scribbr, 2021). Understanding these preharvest mycotoxins is crucial for crop protection and ensuring food safety (Mikula et al., 2013).

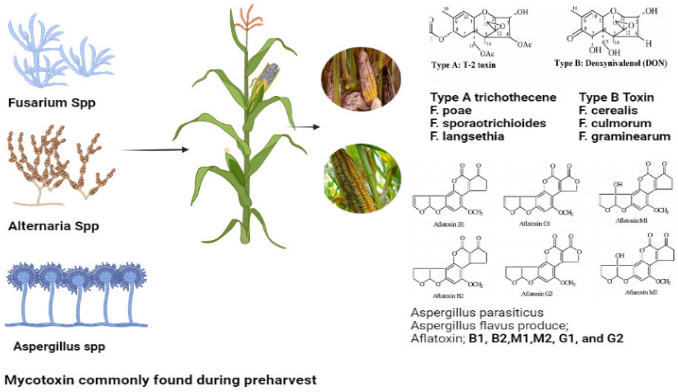

Figure 1: *Different mycotoxin found during preharvest period.*

Postharvest: After harvest, silages can become contaminated by various filamentous fungi, with *Penicillium roqueforti* and *P. paneum* being the most common species. These fungi have been associated with negative effects on cattle herds, including ill-thrift and disease (O'Brien *et al.*, 2006). They produce a range of secondary metabolites, many of which have been detected in silage (Boysen *et al.*, 2000; Sumarah and Miller, 2006). For example, roquefortines produced by *P. roqueforti* have been suspected to cause toxicosis, although no acute toxicity has been observed in feeding experiments with sheep (Häggblom *et al*., 1990; Tüller and Haggblom, 1999). Patulin, produced by *P. paneum* and *B. nivea*, has been found to damage the kidneys and gastrointestinal tract functions in rats and may reduce male fertility (Speijers *et al*., 1978; Selmanoglu and Kockaya, 1990). Aspergillus fumigatus, commonly found in silage, is known to produce over 200 secondary metabolites, including gliotoxin, which is immunosuppressive and may impact the rumen microbiota (Frisvad *et al*., 2008; Niide and Suzuki, 2006). Silage contaminated with *Monascus ruber* may contain citrinin, a nephrotoxic compound (Bouslimi *et al*., 2008). Certain Zygomycetes can also produce bioactive secondary metabolites, although the distribution of toxigenic isolates is not well examined. Rapid growth of Zygomycetes can spoil large amounts of silage quickly, and some species have been known to cause invasive infections, particularly in immunocompromised individuals. The observed effects may be attributed to their secondary metabolites (Jensen and Aalbaek, 1994). For example, Mucor circinelloides can produce various mycotoxins, including zygosporin, which has antifungal properties and may impact animal health (Yiannikouris and Joyany, 2002; Mansfield and Jones, 2008). Proper harvesting and ensiling methods can reduce fungal contamination and mycotoxin production in silage. Mycotoxin levels during ensiling can either increase, decrease, or remain unchanged (Table 1). Effective management is vital for sustainable livestock production. Figure 2 illustrates various sources and types of mycotoxins found in postharvest situations. The left image shows crops being harvested in a field, potentially contaminated by *Fusarium* spp., *Alternaria* spp., and *Aspergillus* spp. The middle image depicts different fungi like *Penicillium* spp., *Aspergillus fumigatus*, *Mucor* spp., and mycotoxins such as aflatoxin, ochratoxin, and patulin. The right image displays moldy silage infected by *Penicillium* spp. and producing patulin, causing gastrointestinal and neurological disorders. This collage highlights the importance of understanding mycotoxins' origins and effects to ensure food quality and safety after harvesting (Frontiers, 2021).

Table 1: *High incidence fungal species and potential mycotoxin at harvest and during ensiling.*

	Survival in silage	Plant type	References
***Fungal* species**			
Alternaria	---	Maize	Mansfield and Kuldau (2007)
Aspergillus spp.	+++	Maize	Mansfield and Kuldau (2007)
Fusarium spp.	---	Ryegrass	Damoglou *et al*. (1984)
		Maize	Lepom *et al*. (1988
		Maize	Mansfield and Kuldau (2007)
Penicillium spp.	+++	Maize	Mansfield and Kuldau (2007)
Mycotoxins			
***Aspergillus* spp. Toxins**			
GT	+	Grass	Boudra and Morgavi (2005)
Fumagallin	---		
Helvolic acid	+++		
Verruculogen	+++		
AFA	-	Maize	Kalac and Woodford (1982), Garon *et al*. (2006)
GT	Slow -	Maize	Garon *et al*. (2006)
***Fusarium* spp. Toxins**			
ZEA	–/+	Maize	Lepom *et al*. (1988)
	nc	Maize	Garon *et al*. (2006)
	+++	Maize	Gonzales Pereyra *et al*. (2008)
DON	+++	Maize	Lepom *et al*. (1988)
	+++	Maize	Mansfield *et al*. (2005)
	---	Maize	Boudra and Morgavi (2008), Gonzales Pereyra *et al*. (2008)
Fumonisins	-	Maize	Garon *et al*. (2006)
	---	Maize	Boudra and Morgavi (2008), Gonzales Pereyra *et al*. (2008)
***Penicillium* spp. Toxins**			
CTN	+++	Maize	Mansfield *et al*. (2008)
	+++	Maize	Garon *et al*. (2006)

AFLA: aflatoxins; CTN: citrinin; DON: deoxynivalenol; GT: gliotoxin; ZEA: zearalenone. +++ Increase; --- decrease; =: no change.

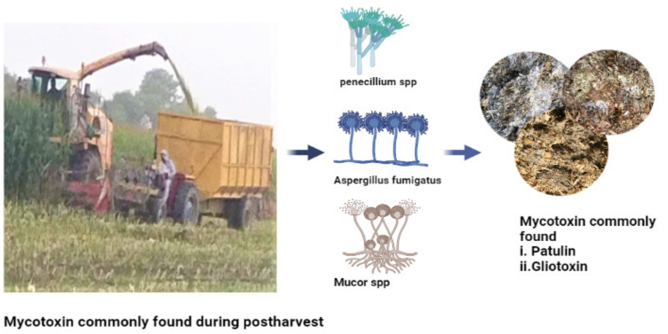

Figure 2: *The commonly found fungal mycotoxin during postharvest time.*

Different levels of mycotoxin in silage

Different levels of mycotoxins in silage can vary depending on factors such as geographical location, climatic conditions, crop type, and storage practices. Accurate assessment of mycotoxin levels in silage requires sensitive analytical methods. LC-MS/MS (liquid chromatography-mass spectrometry) has been recognized as an effective technique for mycotoxin analysis in silage, providing reliable results with low limits of quantification (Grajewski *et al.*, 2012; Zachariasova and Vaclavikova, 2014). Surveys have detected several mycotoxins in both maize and grass silage. Commonly encountered mycotoxins include beauvericin (BEA), deoxynivalenol (DON), HT-2 toxin, enniatins (ENN A, ENN A1, ENN B, ENN B1), nivalenol (NIV), and zearalenone (ZEN). These mycotoxins have been found in a significant proportion of silage samples (Grajewski *et al.*, 2012; Kosicki *et al.*, 2016). In maize silage, DON and ZEN are frequently detected, with average concentrations ranging from 447 μg/kg for DON to 82.4 μg/kg for ZEN. These mycotoxins have been present in a substantial number of samples, with DON detected in 82% and ZEN in 57% of analysed samples (Grajewski *et al.*, 2012; Kosicki *et al.*, 2016). Regarding grass silage, the occurrence of mycotoxins is less studied. However, DON has been detected in grass silage samples at a frequency of 37%, with concentrations up to 167 μg/kg (Skladanka *et al.*, 2013). Additionally, ZEN has been reported in grass silage, with concentrations exceeding 300 μg/kg in some cases (Cavallarin *et al.*, 2004). It is essential to monitor and assess the levels of mycotoxins in silage in comparison to regulatory limits to ensure the safety and well-being of livestock consuming the silage.

Effects of mycotoxin contamination in silage

Health effects on livestock: Mycotoxin contamination in silage can have detrimental effects on the health and performance of livestock, particularly cattle, buffalos, sheep, and goats, which heavily rely on silage in their diets. Mycotoxins can adversely affect various physiological systems in livestock, resulting in a range of health issues. Some commonly reported health effects of mycotoxin contamination in silage Reduced feed intake Mycotoxins can cause a decrease in feed intake, leading to reduced nutrient intake and poor weight gain in animals (Morgavi and Riley, 2007). Digestive disorders Mycotoxins can disrupt the gastrointestinal tract, causing digestive disorders such as diarrhea, constipation, and gastrointestinal inflammation (Morgavi and Riley, 2007). Immunosuppression Mycotoxins particularly gliotoxin can suppress the immune system of livestock, making them more susceptible to infections and diseases (Weaver and See, 2013). Reduced reproductive performance of certain mycotoxins, such as zearalenone (ZEN), can interfere with the reproductive system of animals, resulting in infertility, abortions, and other reproductive disorders (Morgavi and Riley, 2007). Liver damage Mycotoxins, including aflatoxins and fumonisins, can induce liver damage and impair liver function in livestock (Weaver and See, 2013). The severity of these health effects can vary depending on the type and level of mycotoxin contamination, as well as the duration of exposure. It is crucial to minimize mycotoxin contamination in silage to safeguard the health and well-being of livestock.

Economic impact on livestock production: Mycotoxin contamination in silage has significant economic implications for livestock production. The financial losses incurred by livestock producers due to mycotoxin contamination are just one aspect of the overall economic impact (Stoev *et al.*, 2012). Indirect costs related to animal health, productivity, marketability, and farm profitability also need to be considered. The adverse effects of mycotoxins on animal health can result in reduced productivity and increased veterinary costs (Stoev *et al.*, 2012; Gallo *et al.*, 2015). Livestock may experience decreased feed intake, poor weight gain, digestive disorders, immunosuppression, reproductive issues, and liver damage (Morgavi and Riley, 2007; Weaver and See, 2013). These health issues not only affect individual animals but can also have a cumulative impact on the overall productivity of the herd or flock. Mycotoxin-contaminated silage can also lead to feed wastage as animals may refuse or consume less contaminated feed (Piva *et al.*, 2019). This results in additional expenses for livestock producers who must provide alternative feed sources to meet nutritional requirements. Marketability is another significant concern as mycotoxin-contaminated products may not meet quality standards or regulatory limits, leading to decreased market value or even rejection of the livestock or their products (Piva *et al*., 2019; Gallo *et al*., 2015). The costs associated with storage and monitoring of silage to detect and manage mycotoxin contamination add to the economic burden. Regular monitoring of silage quality and implementing preventive measures during harvesting and storage require financial resources and labour investment (Stoev *et al*., 2012). Additionally, the use of toxin-binding additives in animal feed to minimize the impact of mycotoxins also incurs additional costs (Gallo *et al*., 2015). To mitigate the economic risks associated with mycotoxin contamination, livestock producers need to adopt proactive management practices. These include implementing preventive measures such as proper harvesting and storage techniques, regular monitoring, and utilizing toxin-binding additives in animal feed (Piva *et al*., 2019; Gallo *et al*., 2015). Investing in research and development to identify and breed crops with increased resistance to fungal infections and mycotoxin production can also contribute to long-term solutions (Stoev *et al*., 2012).

Food safety concerns for humans consuming animal products

Mycotoxin contamination in silage not only poses health risks to livestock but also raises concerns regarding food safety for humans consuming animal products. Livestock that consume mycotoxin-contaminated silage can accumulate these toxic compounds in their body tissues and products, such as meat, milk, and eggs, which can ultimately enter the human food chain (Stoev *et al*., 2012; Gallo *et al*., 2015). This raises significant concerns as mycotoxins have the potential to cause adverse health effects in humans, including acute toxicity and chronic health problems. One of the major concerns is the presence of aflatoxins, which are potent carcinogens produced by certain Aspergillus species. Aflatoxins can contaminate animal products through the ingestion of aflatoxin-contaminated feed, including silage (Chen *et al*., 2018). Consumption of aflatoxin-contaminated animal products has been associated with an increased risk of liver cancer, immunosuppression, and other health complications (Chen *et al*., 2018). Regulatory limits and monitoring programs have been established to minimize aflatoxin contamination in food and feed, but the risk still remains. Apart from aflatoxins, other mycotoxins such as fumonisins and ochratoxins also raise concerns for food safety. Fumonisins, produced by Fusarium species, can contaminate silage and animal products derived from animals fed with contaminated feed. These mycotoxins have been linked to various health issues, including oesophageal cancer, neural tube defects, and kidney damage in humans (Marin *et al*., 2013). Ochratoxins, produced by Aspergillus and Penicillium species, can also contaminate silage and animal-derived products. Chronic exposure to ochratoxins has been associated with kidney disease and has been classified as a possible human carcinogen (Marin *et al*., 2013). The presence of mycotoxins in animal products highlights the need for effective monitoring and control strategies to ensure food safety. It is essential to establish strict regulatory limits for mycotoxins in animal products, enforce monitoring programs, and implement good agricultural practices to minimize mycotoxin contamination in feed and silage (Gallo *et al*., 2015; Stoev *et al*., 2012). Additionally, implementing pre- and post-harvest interventions, such as proper storage, drying, and processing techniques, can help reduce mycotoxin levels in feed and silage (Chen *et al*., 2018). Regular surveillance and screening of animal products for mycotoxin residues are crucial to identify potential risks to human health. Furthermore, consumer education and awareness regarding mycotoxin risks and proper food handling practices are essential. Proper cooking, processing, and storage of animal products can help minimize mycotoxin exposure. Research efforts should focus on developing innovative strategies to mitigate mycotoxin contamination, such as biological control methods, genetic approaches, and improved storage technologies (Marin *et al*., 2013; Stoev *et al*., 2012). Continuous research and innovation are crucial to develop effective strategies to minimize mycotoxin contamination and safeguard the food chain.

Management strategies for mycotoxin contamination in silage

Management strategies for mycotoxin contamination in silage refer to the practices and interventions employed to prevent, reduce, and control the presence of mycotoxins in silage during the production, storage, and feeding processes (Pitt *et al*., 2013; Gallo *et al*., 2015). These strategies aim to mitigate the negative impact of mycotoxins on animal health, productivity, and overall farm profitability. Key management strategies include implementing good agricultural practices (GAP) to minimize fungal contamination in crops (Pitt *et al*., 2013), optimizing harvesting and ensiling techniques (Gallo *et al*., 2015), using effective silage additives and preservatives (Pitt *et al*., 2013), implementing proper storage and ventilation systems (Gallo *et al*., 2015), monitoring and testing for mycotoxin levels (Pitt *et al*., 2013), and implementing quality control measures (Gallo *et al*., 2015). These strategies aim to minimize fungal growth, mycotoxin production, and subsequent contamination in silage, ensuring the provision of safe and high-quality feed for livestock. Additionally, educational programs, training, and awareness campaigns play a crucial role in promoting the adoption of best management practices and ensuring effective implementation across the entire silage production and utilization chain (Pitt *et al*., 2013; Gallo *et al*., 2015). By employing comprehensive management strategies, livestock producers can reduce the risk of mycotoxin contamination in silage, safeguard animal health, improve productivity, and enhance the safety and quality of animal products. Several preharvest management strategies have been identified and studied to address mycotoxin contamination in silage. These include selecting resistant crop varieties, implementing proper crop rotation, optimizing planting density, timely harvesting, and implementing appropriate agronomic practices to promote healthy crop growth and minimize fungal infection (Pitt *et al*., 2013). Postharvest strategies involve proper handling, drying, and ensiling techniques to minimize fungal growth and mycotoxin production during storage (Gallo *et al*., 2015). Furthermore, the use of effective silage additives and preservatives can help inhibit fungal growth and mycotoxin production. These additives may include organic acids, enzymatic preparations, microbial inoculants, and adsorbent materials, which can bind and detoxify mycotoxins (Pitt *et al*., 2013). Implementing proper storage facilities with adequate ventilation and temperature control can create unfavorable conditions for fungal growth and mycotoxin production (Gallo *et al*., 2015). Regular monitoring and testing of silage samples for mycotoxin levels are essential to detect contamination early and make informed decisions regarding feed management and animal health (Pitt *et al*., 2013). Quality control measures, such as analysing silage for nutritional composition, moisture content, and pH, can help identify potential issues and ensure the production of high-quality silage (Gallo *et al*., 2015).

Preharvest management practices

Preharvest management practices play a crucial role in mitigating mycotoxin contamination in silage. By implementing effective preharvest strategies, livestock producers can minimize the risk of fungal growth and mycotoxin production in crops intended for silage (Binder and Tan, 2014). These practices focus on reducing fungal infection, maintaining crop health, and optimizing harvest conditions.

Harvest timing: Harvest timing is a critical factor in managing mycotoxin contamination in silage. Delaying harvest beyond the optimal maturity stage can increase the risk of fungal infection and mycotoxin accumulation in crops. On the other hand, harvesting crops too early may result in reduced yield and nutritional quality. Therefore, it is important for farmers to determine the appropriate harvest window based on crop maturity, moisture content, and weather conditions to minimize mycotoxin contamination (Bottalico *et al*., 2002).

Crop rotation: Crop rotation is a widely recognized agricultural practice that involves the systematic sequencing of different crops in a specific field over time (Weihrauch *et al*., 2020). It aims to break the life cycle of pathogens and pests, enhance soil health, optimize nutrient utilization, and reduce the risk of mycotoxin contamination. Crop rotation disrupts the build-up of pathogen populations, including mycotoxin-producing fungi, by altering the host plant and depriving them of a continuous food source (Dill-Macky and Jones, 2000). This practice can effectively manage mycotoxin contamination by reducing the inoculum potential and providing an unfavorable environment for fungal proliferation. By diversifying the crop species, crop rotation reduces the risk of mycotoxin contamination and helps maintain a healthy and balanced agroecosystem (Binder and Tan, 2014). Studies have shown that crop rotation can significantly reduce the incidence and severity of mycotoxin contamination in crops such as maize (Bottalico and Perrone, 2002).

Choosing resistant crop varieties: Choosing resistant crop varieties can be an effective preharvest management strategy. Breeding programs focused on developing crop varieties with enhanced resistance to mycotoxin-producing fungi have shown promising results in reducing mycotoxin contamination

(Munkvold and Desjardins, 2016). By selecting crop varieties with inherent resistance or tolerance to specific fungal pathogens, livestock producers can minimize the risk of mycotoxin contamination in silage. Preharvest management practices can significantly reduce the risk of mycotoxin contamination in silage, ensuring the production of safe and high-quality feed for livestock. Proper agronomic practices are essential for minimizing mycotoxin contamination in silage. This includes implementing appropriate fertilization, irrigation, and weed control measures to maintain crop health and vigour. Adequate plant nutrition and irrigation help ensure optimal crop growth and minimize stress, which can make crops more susceptible to fungal infection and mycotoxin production (Munkvold and Desjardins, 2016). Effective weed control is also important as weeds can serve as hosts for mycotoxin-producing fungi and contribute to the spread of contamination to neighbouring crops (Astoreca *et al*., 2017). To further enhance preharvest management the use of effective silage additives and preservatives has gained attention. These additives and preservatives can inhibit fungal growth, reduce mycotoxin production, and enhance silage fermentation. For example, the use of propionic acid-based preservatives has been shown to effectively control the growth of mycotoxin-producing fungi and reduce mycotoxin levels in silage (Pitt *et al*., 2013). Other additives such as biological control agents and microbial inoculants have also shown potential in preventing mycotoxin contamination by competitively excluding or antagonizing mycotoxin-producing fungi (Munkvold and Desjardins, 2016). In addition to physical and chemical management practices, preharvest management practices can also play a crucial role in preventing mycotoxin contamination in livestock feed. The use of resistant crop varieties, crop rotation, and appropriate fertilization practices can help minimize fungal infections and reduce mycotoxin production (Munkvold and Desjardins, 2016; Piva *et al*., 2019). Resistant crop varieties, such as genetically modified corn and soybeans, have been developed to contain specific genes that provide resistance to fungal infections and reduce mycotoxin production (Munkvold and Desjardins, 2016). Crop rotation, or the alternating of crops between seasons, can help reduce fungal infections by interrupting the fungal life cycle and reducing the amount of inoculum present in the soil (Munkvold and Desjardins, 2016). Proper fertilization practices can also help reduce mycotoxin contamination by promoting healthy plant growth and reducing plant stress, which can make crops more susceptible to fungal infections (Piva *et al*., 2019). Another preharvest management strategy is the use of biocontrol agents and microbial inoculants to prevent mycotoxin contamination. Biocontrol agents are natural organisms that can be used to control or eliminate fungal infections in crops (Piva *et al*., 2019). Microbial inoculants are beneficial microorganisms that can be added to crops to enhance their growth and health and to suppress fungal infections (Munkvold and Desjardins, 2016). Both biocontrol agents and microbial inoculants can compete with or antagonize mycotoxin-producing fungi, thus reducing mycotoxin contamination (Munkvold and Desjardins, 2016).

Postharvest management practices: Effective postharvest management strategies involve proper storage, handling, and monitoring techniques to prevent or mitigate the growth of mycotoxin-producing fungi. One important aspect of postharvest management is the implementation of appropriate storage conditions. Proper storage facilities should provide protection against moisture, temperature fluctuations, and pest infestation, as these factors can promote fungal growth and mycotoxin production (Battilani *et al*., 2019). Adequate ventilation and airflow are essential to maintain dry conditions and prevent the accumulation of moisture, which can create a favorable environment for fungal growth (Cantoni *et al*., 2019). Moreover, temperature control within the storage facility is crucial, as high temperatures can accelerate fungal growth and mycotoxin synthesis (Cantoni *et al*., 2019). Regular cleaning and maintenance of storage structures also contribute to reducing fungal contamination and mycotoxin development (Schmidt and Jones, 2018). Monitoring the quality of stored silage is another important postharvest management practice. Regular inspection and sampling of silage for mycotoxin analysis allow for early detection of contamination and prompt implementation of remedial actions. Various analytical methods, such as high-performance liquid chromatography (HPLC) and enzyme-linked immunosorbent assay (ELISA), can be employed for mycotoxin detection and quantification (Streit *et al*., 2013). These monitoring efforts enable livestock producers to assess the level of mycotoxin contamination and make informed decisions regarding feed utilization or disposal. Additionally, postharvest management practices should include appropriate feed-out strategies to minimize the risk of mycotoxin exposure during feeding. It is crucial to adopt a first-in, first-out (FIFO) approach to feed storage, ensuring that older batches of silage are used before fresher ones. This practice helps prevent the accumulation of mycotoxins over time and reduces the risk of exposure to highly contaminated feed (Cantoni *et al*., 2019). Adequate feed-out management also involves minimizing feed exposure to air and moisture, as these conditions can promote fungal growth and mycotoxin production (Driehuis *et al*., 2018). Regular monitoring and timely interventions help prevent economic losses and potential health issues associated with mycotoxin exposure. With proper postharvest management practices, livestock producers can minimize the risk of mycotoxin contamination in stored silage. Ensuring appropriate storage conditions, conducting regular quality monitoring, and implementing proper feed-out strategies are key steps in safeguarding the quality and safety of silage for livestock consumption.

Harvest and ensiling techniques: Harvest and ensiling techniques are critical stages in the production of silage and play a significant role in minimizing mycotoxin contamination. By implementing appropriate harvest and ensiling techniques, including timely harvest, proper drying, effective packing and sealing, and the use of silage additives, the risk of mycotoxin contamination in silage can be significantly reduced. Harvest timing is a crucial factor in minimizing mycotoxin contamination. Delaying harvest beyond the optimal maturity stage can increase the risk of fungal infestation and mycotoxin accumulation in crops (Battilani *et al*., 2019). It is essential to harvest crops at the recommended stage of maturity to ensure proper fermentation and reduce the availability of substrates for mycotoxin-producing fungi. Additionally, avoiding harvesting during wet or humid conditions is vital, as moisture content is a key factor influencing fungal growth and mycotoxin production (Ogunade *et al*., 2018). Proper drying of harvested crops before ensiling is crucial to achieve an optimal moisture level, typically around 65-70%, which inhibits fungal proliferation and mycotoxin synthesis. Ensiling techniques also play a critical role in minimizing mycotoxin contamination. The ensiling process involves packing and sealing the harvested crop in an anaerobic environment to promote fermentation. Proper packing density and compaction are important to exclude oxygen, which can inhibit the growth of aerobic fungi and prevent mycotoxin production (Weinberg and Muck, 1996). Ensuring a tight seal and minimizing exposure to air during the ensiling process is crucial to maintaining anaerobic conditions and preventing the growth of mycotoxin-producing fungi. The use of effective silage additives and preservatives is another important strategy in minimizing mycotoxin contamination during ensiling. These additives can inhibit fungal growth, reduce spoilage, and enhance fermentation processes. Effective silage additives and preservatives such as acids, enzymes, inoculants, and absorbents can help create unfavorable conditions for mycotoxin-producing fungi (Pitt *et al*., 2013). For example, propionic acid and its derivatives have been shown to effectively inhibit fungal growth and mycotoxin production in silage (Driehuis *et al*., 2018). Microbial inoculants containing lactic acid bacteria can enhance fermentation and inhibit the growth of undesirable microorganisms, including mycotoxin-producing fungi (Tabacco and Righi, 2011). Furthermore, absorbents such as clay minerals and activated carbon can bind mycotoxins and reduce their bioavailability in silage (Yitbarek and Tamir, 2020). These practices contribute to the production of high-quality, safe silage that supports livestock health and performance while minimizing economic losses associated with mycotoxin-related issues. Proper implementation of harvest and ensiling techniques, combined with the use of appropriate silage additives and preservatives, is essential for effectively managing mycotoxin contamination in silage production.

Feed management strategies for livestock

Livestock producers need to implement effective feed management practices to reduce the impact of mycotoxin-contaminated silage on animal health and productivity. One crucial aspect of feed management is feed sorting and quality control. Livestock should be provided with well-mixed feed to ensure uniform distribution of nutrients and mycotoxins throughout the ration. Sorting of feed can lead to the selective consumption of certain feed components, potentially increasing the exposure to mycotoxins present in the feed (Streit *et al*., 2013). Regular monitoring and analysis of feed samples for mycotoxin content allow for timely identification of contaminated batches and appropriate adjustments in feed formulations (Schmidt and Jones, 2018). Another important feed management strategy is the inclusion of mycotoxin binders or adsorbents in the animal's diet. These additives, such as clay minerals, activated carbon, and yeast cell walls, have the ability to bind mycotoxins in the gastrointestinal

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tract, preventing their absorption and reducing their toxic effects (Dänicke *et al*., 2011). Mycotoxin binders should be carefully selected and incorporated into the animal's diet based on their efficacy against specific mycotoxins and their compatibility with other feed components (Papaioannou *et al*., 2005). Diversification of feed refers to the practice of incorporating a variety of feed ingredients in the animal's diet to reduce the concentration and impact of mycotoxins. Including a variety of feed ingredients in the animal's diet can dilute the concentration of mycotoxins and reduce the risk of adverse effects (Streit *et al*., 2013). Livestock producers can incorporate alternative forages, grains, or by-products with lower mycotoxin contamination levels to mitigate the impact of mycotoxins on animal health. Additionally, optimizing feed processing techniques can contribute to reducing mycotoxin levels in feed. Proper grinding, pelleting, or heat treatment of feed ingredients can help inactivate or destroy mycotoxins, improving the safety and quality of the feed (Dänicke *et al*., 2011). Regular monitoring of animal health, performance, and production parameters is crucial in evaluating the effectiveness of feed management strategies. Monitoring allows for the early detection of any deviations from normal values, which may indicate mycotoxin-related issues (Driehuis *et al*., 2018). Livestock producers should collaborate with veterinarians and nutritionists to develop and implement tailored feed management plans based on the specific needs and challenges of their livestock operation. By implementing these feed management strategies, livestock producers can minimize the negative effects of mycotoxin-contaminated feed on animal health and productivity. Ensuring proper feed sorting, quality control, mycotoxin binding, feed diversification, and optimized feed processing are essential steps in safeguarding the well-being and performance of livestock.

Future research directions for sustainable livestock production

Future research directions for sustainable livestock production are critical for addressing the challenges and ensuring the long-term viability of the industry. Here, we outline several key areas that require further investigation and innovation.

Sustainable feed production

Developing sustainable feed sources is essential for reducing the environmental impact of livestock production. Future research should focus on exploring alternative feed ingredients, such as insect-based protein, algae, and co-products from the food and agriculture industries (Bhatt *et al*., 2020). Additionally, optimizing feed formulations to improve nutrient utilization and reduce waste will contribute to sustainable and efficient livestock production systems (Huang *et al*., 2018).

Precision livestock farming

Advancements in technology and data analytics offer great potential for optimizing livestock management. Future research should explore the application of precision livestock farming techniques, such as sensor-based monitoring, automated systems, and machine learning algorithms, to improve animal welfare, productivity, and resource efficiency (Viazzi, 2014). This includes real-time monitoring of health, behavior, and environmental parameters to enable timely interventions and decision-making (Wathes, 2008).

Genetic selection for resilience and sustainability

Breeding animals for improved resilience to environmental stressors, disease resistance, and efficient resource utilization is crucial for sustainable livestock production. Future research should focus on identifying genetic markers associated with these traits and incorporating them into breeding programs (Rosen, 2018). Furthermore, exploring the potential of novel breeding techniques, such as gene editing, can accelerate the development of resilient and sustainable livestock breeds (Tait-Burkard, 2018).

Circular economy approaches

Implementing circular economy principles can enhance resource efficiency and reduce waste in livestock production systems. Future research should investigate innovative strategies for nutrient recycling, such as anaerobic digestion of manure, composting, and bioconversion technologies (Liu *et al*., 2020). Exploring the potential of integrated farming systems, where the waste from one component becomes a resource for another, can maximize resource utilization and minimize environmental impact (Mertenat and Nemecek, 2019).

Climate change adaptation

Climate change poses significant challenges to livestock production, including heat stress, water scarcity, and changes in disease patterns. Future research should focus on developing adaptive strategies to mitigate the impacts of climate change on livestock. This includes exploring heat stress-tolerant breeds, improving water management practices, and implementing disease surveillance and control measures that account for changing climatic conditions (Herrero *et al*., 2016).

By prioritizing research in these areas, sustainable livestock production can be achieved, promoting environmental stewardship, animal welfare, and economic viability in the industry.

Conclusions and Recommendations

The management of mycotoxin contamination in silage is an urgent and critical challenge in livestock production. It is crucial for livestock producers to implement comprehensive management strategies to mitigate the risks associated with mycotoxins in silage. Preharvest, harvest, and postharvest management practices, as well as feed management strategies, play important roles in reducing mycotoxin contamination and ensuring livestock health and productivity. While significant progress has been made in understanding and addressing mycotoxin contamination in silage, there are several areas that require further research. First, there is a need to enhance our knowledge of the factors influencing mycotoxin production in silage, including the interactions between different fungal species, environmental conditions, and agronomic practices. Future research should focus on exploring the mechanisms underlying mycotoxin production and the development of predictive models to assess mycotoxin contamination risks. The development of rapid and reliable methods for mycotoxin detection and monitoring in silage is crucial for effective management. Future research should aim to identify biomarkers and novel analytical techniques that allow for real-time monitoring of mycotoxin levels. This will enable early detection and timely interventions to minimize the impact of mycotoxin contamination. Furthermore, exploring the potential of emerging technologies, such as genetic modification and biocontrol agents, in preventing mycotoxin contamination in silage warrants further investigation. Future research should evaluate the efficacy and safety of these approaches and their potential for practical application in livestock production systems. Economic assessments of mycotoxin contamination in silage are essential for evaluating the cost-effectiveness of different management strategies. Future research should conduct comprehensive cost-benefit analyses to guide decision-making and investment in mycotoxin management practices. Moreover, understanding the transfer of mycotoxins from contaminated silage to animal products, such as meat, milk, and eggs, is essential for assessing the potential risks to human health. Future research should investigate the fate of mycotoxins in the animal body and their impact on the quality and safety of animal-derived food products. Addressing the current research gaps and educating livestock producers about mycotoxin contamination can lead to more effective management strategies that safeguard livestock health, improve productivity, and ensure food safety. Future research should focus on exploring sustainable and eco-friendly approaches to managing mycotoxin contamination, studying the impact of changing climatic conditions, and fostering collaboration among researchers, industry professionals, and policymakers. By focusing on these future research directions, we can enhance our knowledge, improve management practices, and ultimately minimize the impact of mycotoxins on livestock production, animal health, and food safety. Through continuous research and innovation, we can strive towards sustainable and resilient agricultural systems that contribute to the well-being of both animals and humans.

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Novelty Statement

Mycotoxins are harmful substances that can affect the health and performance of livestock that consume silage, a fermented feed made from forage crops. In this paper, we review the latest research on how to prevent and control mycotoxin contamination in silage and its impact on animal production. We summarize the best practices for harvesting, ensiling, storing, and feeding silage, as well as the use of additives and binders that can reduce mycotoxin levels and effects. We also discuss the future challenges and opportunities for sustainable livestock production in the context of mycotoxins, climate change, and circular economy.

Author's Contribution

Abdul Kabir, Shahab Ahmad Nawaz, AUS: Conceptualization of the study.
Abdul Kabir, Shahab Ahmad Nawaz: Literature review.
Abdul Kabir and Anees Ur Rahman: Writing the original paper.
Abdul Kabir, Muhammad Sadiq, Maaz Ahmad, Abdul Hafeez Bukero: Review and editing.
Midrar Ullah and Muhammad Sadiq: Supervision.
All authors have read and approved the manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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