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Feedborne biological hazards in hydroponic and conventional fodder production: a comparative risk assessment

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Abstract

Animal nutrition is a cornerstone of modern livestock production, as feed represents both the largest input cost and the primary determinant of animal growth, health, and productivity. Ensuring feed safety is therefore fundamental to the broader food safety chain, reflecting the principles of the One Health framework, which emphasizes the interconnection between animal, human, and environmental health.

In this context, conventional fodder production systems (pasture, hay, silage) remain the backbone of ruminant nutrition but are inherently vulnerable to contamination. Soil contact, climatic variability, and suboptimal storage practices may result in microbial pathogens, parasites, mycotoxins, and physical or chemical hazards entering the feed chain. Well-documented examples include silage-associated *Listeria monocytogenes*, *Salmonella* contamination from manure and soil, and productivity losses linked to aflatoxins, fumonisins, and zearalenone. Additional risks such as pesticide residues, heavy metals, and foreign objects further highlight the multifactorial nature of fodder-related hazards, with significant repercussions for animal health, farm economics, and public health through zoonotic transmission and carry-over into food products.

In recent decades, hydroponic fodder production has emerged as an innovative alternative. This technology, based on sprouting cereal grains in controlled, soil-free environments, enables rapid biomass production within 7–10 days, continuous year-round availability, and reduced land requirements. Moreover, the adoption of hydroponic systems fundamentally alter the relevance of different hazard types, with potential implications for feed safety.

The present thesis applies a qualitative risk assessment framework to systematically identify and compare the risk associated to different hazards in conventional and hydroponic fodder production. Each hazard was evaluated in terms of severity and likelihood of occurrence, and comparative risk matrices were developed to visualize differences between systems. The results indicate that while hydroponic systems reduce the risk associated with most hazards, particularly parasites, soil pathogens, and heavy metals, specific vulnerabilities linked to moisture, microbial ecology, and water management are also introduced, with implications for mold growth and mycotoxin accumulation, biofilm-associated opportunistic bacteria, and chemical residues from disinfectants or seed treatments.

These findings provide a scientific basis for developing tailored risk management strategies and addressing critical control points for each production system. By combining hazard identification through literature review with comparative risk rating, the study contributes to improved understanding of fodder safety, offering practical insights for safer, more sustainable, and resilient livestock production.

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1 INTRODUCTION

1.1 Fodder in Animal Production Systems

Fodder has historically been one of the cornerstones of animal agriculture and remains one of the most critical factors determining the efficiency, sustainability, and profitability of livestock production systems worldwide. In the context of animal nutrition, fodder is broadly defined as plant-derived feed materials — whether fresh, dried, or conserved — that are harvested, grazed, or cultivated specifically to supply the bulk of the diet for domesticated animals, particularly ruminants. Unlike concentrates or feed additives, which are generally designed to provide dense sources of protein or energy, fodder constitutes the structural and volumetric basis of the ration. It plays a dual role: first, as the principal supplier of nutrients such as carbohydrates, proteins, minerals, and vitamins; and second, as the irreplaceable source of dietary fiber, which is essential for the maintenance of ruminal function, microbial activity, and overall digestive health. The quality, availability, and balance of fodder resources thus directly affect not only animal performance but also the economic viability of entire production systems and the safety of food products of animal origin [1, 2].

Fodder resources are highly diverse and traditionally classified into several categories. Green forages include pasture grasses, forage legumes, and cultivated green crops, which are consumed either directly by grazing animals or by cut-and-carry methods. Dry forages consist primarily of hay, straw, and crop residues, harvested and preserved through drying to reduce moisture and enhance storage stability. Conserved forages, such as silage and haylage, represent fermented or partially fermented plant materials produced under anaerobic conditions, allowing farmers to ensure feed availability during periods of seasonal scarcity. More recently, a fourth category of innovative or non-traditional fodder systems has emerged, including hydroponically sprouted grains and other soilless methods of biomass production, which are attracting attention in regions with limited arable land or water resources [3, 4]. Each of these categories has distinct nutritional profiles, preservation characteristics, and economic implications, making the choice of fodder source a strategic decision in farm management.

The role of fodder within animal production systems varies according to species, production objectives, and regional agroecological conditions. In dairy and beef cattle production, fodder generally contributes between 50 % and 70 % of the total dry matter intake, providing structural fiber that stimulates rumination and saliva flow, stabilizes rumen pH, and supports the growth of cellulolytic microorganisms. The adequacy of fodder not only prevents digestive disorders such as subacute ruminal acidosis but also determines milk yield, carcass composition, reproductive performance, and disease resistance [5, 6]. In small ruminants such as sheep and goats, fodder plays an equally vital role by supplying digestible energy and protein required for wool growth, meat quality, and lactation. For monogastric animals, the inclusion of fodder in diets is limited due to lower fiber tolerance; however, small proportions of fresh green feeds are often incorporated to provide natural antioxidants, pigments, and vitamins that enhance animal health and product quality [7]. In integrated crop–livestock systems, fodder crops also contribute to soil fertility, reduce erosion, and enhance nutrient cycling, thereby supporting both agricultural sustainability and resilience to climate variability [8].

Nutritional properties of fodder are extremely heterogeneous and depend on plant species, stage of maturity, cultivation practices, and preservation methods. The crude protein (CP) content of grasses typically ranges from 8 % to 15 %, while legumes such as alfalfa and clover can reach values of 18–22 %, making them superior protein sources [9]. Fiber fractions, expressed as neutral detergent fiber (NDF) and acid detergent fiber (ADF), are critical indicators of fodder quality, as they influence voluntary feed intake and digestibility. High NDF reduces the amount of feed animals can consume, while high ADF corresponds to indigestible fractions, limiting energy supply. Non-structural carbohydrates (NSC) — starches, sugars, and soluble carbohydrates — serve as rapidly fermentable energy sources, while vitamins and minerals present in forages, including calcium, phosphorus, magnesium, zinc, selenium, and vitamins A, E, and K, contribute to metabolic regulation, bone development, and immune function [10, 11]. At the same time, many fodder species contain secondary metabolites, such as tannins, saponins, or phenolics, which may exert both beneficial and adverse effects. At moderate levels, they can reduce methane emissions and improve protein utilization in the rumen, whereas at high concentrations they may impair palatability or cause toxicity [12].

Despite its central importance, fodder production faces multiple challenges worldwide. Seasonal variability remains one of the most significant issues, as climatic fluctuations and prolonged droughts frequently result in feed deficits, particularly in arid and semi-arid regions [13]. Land competition between food crops and fodder production further constrains availability, while inadequate harvesting, drying, or ensiling practices lead to significant nutrient losses and, in some cases, the proliferation of molds and production of mycotoxins that compromise both animal health and food safety [14]. High costs of transportation and storage add to the economic burden, especially in regions where farms are geographically dispersed. Addressing these challenges requires technological and managerial innovations, including the adoption of precision agriculture tools for monitoring fodder growth, the development of dual-purpose crop varieties, optimized silage inoculants, and the introduction of non-soil-based systems such as hydroponics to ensure continuous feed supply [15–17].

In summary, fodder is not merely a feed component but a strategic resource that underpins animal health, productivity, economic performance, and food security. Its efficient production, preservation, and utilization are increasingly recognized as critical levers for sustainable livestock development. Against the backdrop of growing global demand for animal products, constrained natural resources, and climate change, the search for resilient and innovative fodder systems — including hydroponic approaches — is intensifying, making the comparative evaluation of conventional and alternative systems both timely and essential.

1.2 Hydroponic Fodder Production

Hydroponic fodder production represents an alternative and increasingly popular approach to overcome the limitations of conventional forage systems, particularly in regions facing land scarcity, water limitations, or climatic variability. By definition, hydroponics refers to the practice of growing plants without soil, using nutrient-rich water solutions or inert substrates to provide roots with essential elements under controlled environmental conditions [18]. In the case of animal nutrition, hydroponic fodder typically involves sprouting cereal grains such as barley, wheat, maize, or oats in specially designed trays or growth chambers over short periods of 6–10 days. The system produces a dense mat of green shoots and roots, often referred to as “sprouted grain fodder” or “hydroponic green fodder,” which can be fed directly to animals. Unlike field-based forage, which requires months of growth and is subject to environmental uncertainties, hydroponic fodder ensures rapid, consistent, and year-round production of fresh biomass [19].

The principle of hydroponic fodder production is relatively simple but technologically demanding. Grains are first soaked in clean water to initiate germination and then spread in shallow trays where they are irrigated several times a day with water or a diluted nutrient solution. No soil is required, and the seeds rely on their endogenous reserves during the early stages of sprouting. Controlled conditions — including temperature (20–25 °C), humidity (60–75 %), and light (natural or artificial) — are maintained to optimize growth and minimize contamination risks. Within 7–8 days, one kilogram of dry grain can yield 6–10 kilograms of fresh green fodder, depending on the cereal type and management practices [20, 21].

Globally, hydroponic fodder production has been adopted in diverse contexts ranging from smallholder dairy farms in Asia and Africa to intensive livestock operations in the Middle East, Australia, and Latin America. Its popularity stems from several distinct advantages. First, hydroponic systems drastically reduce land requirements, as production can be carried out vertically in racks within greenhouses or indoor units, making it feasible even in urban or peri-urban settings [22]. Second, water use efficiency is significantly higher than in field-grown fodder: estimates suggest that hydroponics can save up to 80–90 % of irrigation water through recirculation systems, with minimal losses to evaporation or runoff [23]. Third, nutrient dynamics during the sprouting process make hydroponic fodder particularly attractive from a nutritional standpoint. During germination, enzymatic hydrolysis of starches, proteins, and lipids leads to the accumulation of simple sugars, amino acids, and fatty acids, which are more readily digestible for ruminants and monogastrics alike [24]. Studies report an increase in crude protein concentration, a decline in structural fiber fractions, and higher levels of vitamins such as tocopherols, folates, and β-carotene compared to the original grain [25, 26]. Although dry matter yield per kilogram of grain may not increase — in fact, some losses occur due to respiration — the improved nutrient bioavailability and digestibility often justify the inclusion of hydroponic fodder in balanced rations [27].

Animal performance trials across species have demonstrated promising results. In dairy cattle, supplementation with hydroponic barley fodder has been associated with improved feed conversion, higher milk yields, and better reproductive performance, although outcomes vary depending on inclusion levels and baseline diets [28]. Beef cattle and small ruminants show enhanced growth rates, carcass quality, and nitrogen retention when hydroponic fodder is integrated into feeding regimes [29]. Poultry and pigs also benefit from sprouted grains in terms of gut health, antioxidant capacity, and overall productivity [30]. However, the magnitude of these benefits often depends on management quality, as poorly controlled hydroponic units may suffer from mold, bacterial contamination, or nutrient imbalances that compromise both animal health and feed safety [31].

Despite its potential, hydroponic fodder production is not without limitations. The high moisture content of the product (~80–85 %) reduces its dry matter yield relative to conventional preserved forages, meaning that large volumes are required to meet animal nutrient demands. Capital investment for infrastructure — including trays, pumps, lighting, and climate control — may be prohibitive for resource-poor farmers, although innovations in low-cost hydroponic systems are gradually improving accessibility [32]. Furthermore, the risk of microbial contamination in warm, humid environments is significant [33], requiring strict adherence to hygiene, disinfection protocols, and rapid utilization of harvested biomass.

1.3 Case Study of Hydroponic Fodder Production in Kazakhstan

The application of hydroponic fodder production in Kazakhstan has been tested and adapted within local agricultural settings over the past several years. In particular, practical trials were conducted in the Zhetysu Region (Kerbulak district) between 2018 and 2023, focusing on the cultivation of barley and wheat sprouts under controlled conditions. The aim was not to generate experimental results but to observe and document the practical aspects of system operation in real farm environments.

The production cycle in the observed facilities typically lasted 7–10 days, starting from grain soaking and germination to the harvesting of a full biomass mat composed of shoots, roots, and residual grains. On average, 1 kilogram of dry cereal grain produced 7–10 kilograms of fresh hydroponic fodder, provided that optimal conditions were maintained: temperature of 22–25 °C, relative humidity of 70–80 %, and adequate ventilation. The resulting biomass was characterized by bright green shoots and a dense root mat, which could be fed directly to cattle, sheep, and goats without additional processing.

One of the key advantages observed was the system's independence from soil and climate conditions. While conventional forage production in the region is heavily dependent on seasonal rainfall and soil fertility, hydroponic systems provided a consistent year-round supply of green feed. This feature was particularly relevant in years of drought or poor pasture productivity, when farmers experienced severe feed shortages.

Nutritional evaluations carried out in local laboratories revealed that hydroponic barley and wheat sprouts contained 14–16 % crude protein, 17–19 % crude fiber, as well as elevated concentrations of vitamins such as vitamin E, folic acid, and biotin. Essential minerals including calcium, phosphorus, magnesium, iron, zinc, manganese, and selenium were also present in higher proportions compared to field-grown analogues. Farmers who participated in the trials noted that animals readily consumed the hydroponic fodder and showed no signs of refusal, which emphasized its high palatability.

At the same time, several practical challenges were identified. Storage of the harvested sprouts beyond 48 hours without sufficient ventilation led to rapid spoilage and visible mold growth. Microbiological testing confirmed the presence of opportunistic fungal species in spoiled biomass. Another recurrent issue was the contamination of nutrient solutions and trays when disinfection protocols were not rigorously followed. Biofilm formation in irrigation pipes was observed, which increased the risk of bacterial proliferation. These challenges highlighted the importance of strict hygiene management and rapid utilization of the product after harvest.

From an economic perspective, farmers noted that the system required initial investment in infrastructure (trays, racks, irrigation, and climate control equipment), but once operational, it significantly reduced dependence on external feed markets and mitigated risks of seasonal shortages. The ability to produce green fodder within a closed and controlled environment was seen as a strategic advantage for small and medium-sized livestock farms in the region.

This case study demonstrates that hydroponic fodder production is a practical and adaptable solution to the challenges of conventional forage production in Kazakhstan. While it is not without limitations, particularly in terms of storage and sanitation, the technology offers a consistent and nutritionally valuable source of animal feed that aligns with the country's priorities in strengthening food security and livestock productivity.

1.4. Importance of Feed Safety

Feed safety is an essential aspect of livestock production systems and has profound implications for animal health, productivity, and the safety of food of animal origin. While feed represents the fundamental source of nutrients required to sustain growth, reproduction, and metabolic functions in farm animals, it also constitutes a major entry point for hazards that can compromise both animal and human health. These hazards are diverse in nature and are typically classified into biological, chemical, and physical categories, each presenting different modes of action and consequences [34]. The risks pertaining feed safety are particularly relevant in countries such as Kazakhstan, where traditional fodder production systems (silage, hay, pasture) dominate but are often constrained by climatic variability, storage conditions, and limited access to quality control technologies.

Biological hazards remain the most widespread and consequential group. Among these, bacteria such as *Salmonella* spp., *Listeria monocytogenes, Clostridium botulinum*, and pathogenic *E. coli* are frequent contaminants of feed resources. Poorly fermented silage is a well-recognized source of listeriosis, presenting with neurological disease, abortions, and septicemia in ruminants, and representing a zoonotic risk to humans through contaminated dairy products [35]. Botulism, caused by clostridial neurotoxins produced under anaerobic conditions, is another catastrophic feedborne hazard. Outbreaks linked to silage contaminated with carcasses or poultry litter have been associated with sudden deaths and high fatality rates in cattle herds [36]. *Salmonella enterica* and enterohemorrhagic *E. coli* may enter the feed chain through contaminated ingredients, water, or vectors in feed mills, causing diarrhea, septicemia, and growth retardation in calves, with strong zoonotic relevance [37]. Parasitic hazards, particularly nematode larvae and protozoan oocysts in pasture-based systems, contribute to chronic production losses. Viral hazards, though less common, can be disseminated indirectly through contaminated feed or fomites, as in the case of foot-and-mouth disease or African swine fever [38].

Fungal hazards and mycotoxins represent a particularly critical dimension of feed safety due to their high prevalence, chronic effects, and direct carry-over into milk and meat products. Field fungi such as *Aspergillus*, *Fusarium*, and *Penicillium* readily colonize cereals, hay, and silage, especially under conditions of delayed harvest, high humidity, and poor storage. These fungi produce a wide range of mycotoxins with severe implications for animal and human health. Aflatoxins, especially aflatoxin B1 (AFB1), are potent hepatotoxins and carcinogens. In dairy cows, ingested AFB1 is metabolized to aflatoxin M1 (AFM1), which appears in milk at rates of 1–2 % of intake, with reported maxima of up to 6 % in high-yielding animals, thereby creating a direct food safety hazard [39]. Fumonisins, primarily produced by *Fusarium verticillioides*, impair liver and kidney function, reduce feed intake, and are associated with pulmonary edema in swine and leukoencephalomalacia in horses [40]. Zearalenone (ZEN) acts as an estrogenic mycotoxin, disrupting fertility and causing reproductive syndromes in cattle and pigs. Deoxynivalenol (DON), commonly referred to as vomitoxin, reduces palatability, suppresses immunity, and is frequently detected in total mixed rations (TMR). Surveys in European and Kazakh dairy farms consistently confirm multi-mycotoxin co-occurrence, with synergistic interactions contributing to chronic immunosuppression, reduced productivity, and increased susceptibility to infectious disease [41, 42]. Importantly, mycotoxin contamination is not limited to conventional systems. Although hydroponic fodder reduces exposure to field fungi, post-harvest storage of moist sprouts under high humidity can promote opportunistic mold growth and subsequent toxin formation, posing risks if sprouts are fed beyond recommended time frames [43].

Chemical hazards in feed include pesticide residues, heavy metals, and residues of veterinary drugs or industrial pollutants. In conventional systems, the use of pesticides on fodder crops often results in measurable residues in feed, which may accumulate in animal tissues and products, posing risks for human consumers [44]. Heavy metals such as lead, cadmium, and mercury, introduced through contaminated soils or irrigation water, are persistent hazards that can impair organ function and accumulate in the food chain. These contaminants not only compromise animal performance but also raise public health concerns through biomagnification.

Physical hazards, while less frequent, also represent an important aspect of feed safety. Stones, plastic, glass, and metallic fragments can enter feed during harvesting, transport, or processing, leading to traumatic injuries in animals. In cattle, the ingestion of metallic objects may cause “hardware disease” (traumatic reticuloperitonitis), resulting in severe economic and welfare consequences [45].

The consequences of unsafe feed extend across multiple dimensions. At the farm level, contaminated feed reduces productivity through decreased growth rates, lower milk yields, reproductive failure, and increased veterinary costs. At the food chain level, pathogens and toxins carried over from feed to animal-derived products may directly endanger consumer safety. At the societal level, outbreaks of feedborne zoonoses undermine consumer confidence and can result in trade restrictions. Recognizing these broad implications, feed safety has been formally integrated into the global One Health agenda, linking livestock nutrition to public health and ecosystem sustainability [51].

2. AIM OF STUDY

The aim of this thesis is to systematically assess the health risks posed by fodder consumption in livestock and to understand how these risks are influenced by different fodder production systems. Relevant hazards may include pathogenic bacteria, parasites, fungi and their mycotoxins, chemical residues such as pesticides or heavy metals, and physical contaminants that may be introduced during harvesting, processing, or storage. If not properly managed, such hazards can lead to diseases, reduced productivity, reproductive problems, or even death in animals, while also introducing risks into the human food chain through milk, meat, and other animal-derived products.

Understanding these risks requires careful comparison of different fodder production systems. Conventional methods — including pasture, hay, and silage — are widely used and well established but remain vulnerable to environmental contamination, seasonal fluctuations, and quality deterioration during storage. Hydroponic systems, by contrast, offer year-round availability of fresh green feed, independence from soil and weather conditions, and often improved digestibility, but the high humidity in growth chambers and short shelf life can pose additional challenges linked to biological hazards.

By focusing on the relationship between production systems and feed safety and using a qualitative risk assessment approach with comparative risk rating, this thesis aims to provide a comprehensive understanding of how the method of fodder cultivation shapes the type, frequency, and severity of health risks. The goal is not only to highlight potential hazards but also to underline the implications for animal performance, food safety, and public health. In this way, the study seeks to contribute to the development of feeding strategies that maximize the nutritional benefits of fodder while minimizing the risks, ensuring that livestock production remains both productive and safe within the broader context of sustainable agriculture.

3. MATERIALS AND METHODS

3.1 Identification of Relevant Hazards Associated to Fodder Consumption

The purpose of this review was to collect, compare, and synthesize scientific evidence on the biological, chemical, and physical risks linked to the use of fodder in animal production systems, with a particular emphasis on the comparison between conventional (pasture, hay, silage) and hydroponic production methods.

The identification of relevant hazards associated with fodder consumption was carried out through a literature review, following a structured approach:

1. Databases consulted: Peer-reviewed articles, reports, and reviews were retrieved from international scientific databases including Scopus, Web of Science, PubMed, and ScienceDirect. In addition, official documents from FAO, WHO, OIE, and EFSA were consulted to include regulatory and risk assessment perspectives.
2. Keywords and search strings: The search strategy was based on a combination of keywords related to both the feed (i.e., fodder, silage, etc.) and hazard (i.e., bacteria, *Salmonella*, mycotoxins,etc.), using boolean operators (AND, OR) to refine the searches.
3. Inclusion criteria: Only peer-reviewed articles, reviews, and official reports addressing hazards associated with fodder consumption and published between 2000 and 2025 were included. Earlier publications were considered when they represented foundational studies (e.g., classic works on silage microbiology or mycotoxin toxicology).
4. Exclusion criteria: Studies focused exclusively on crop agronomy without a link to feed use, non-peer-reviewed sources, or publications not available in English were excluded.
5. Data extraction and classification: Identified hazards were grouped into biological (bacteria, fungi, parasites, viruses), chemical (pesticides, heavy metals, drug residues), and physical (foreign materials, mechanical contaminants). Further subdivisions were made based on the available evidence regarding specific hazards.

This structured strategy ensured that the literature review captured the full spectrum of fodder-related hazards, providing a comprehensive basis for the comparative analysis of risk between production systems.

3.2. Qualitative risk assessment

3.2.1. Risk rating criteria

After defining key hazard types related to fodder consumption, a qualitative risk assessment approach was used to systematically rate them and obtain comparable risk scores. The framework was developed according to internationally accepted practice in food/feed safety risk analysis (FAO/WHO risk analysis, Codex Good Animal Feeding, ISO 31000 risk management) [46-50] and was tailored to fodder safety. Specifically, each "hazard × system" pair (e.g., Aflatoxin B1 × hydroponic production; Chemical hazards × conventional production) was rated separately, then compared.

The risk assessment considered two parameters, considered as the minimum recommended dimensions for qualitative risk assessment in feed/food safety [46-50]:

- Severity (S) — the magnitude of adverse effects if exposure occurs;
- Likelihood (L) — the probability of occurrence and exposure.

Both parameters were defined with feed-specific descriptors to reduce subjectivity. The Severity component captured animal health impact, herd-level productivity loss, zoonotic/carry-over potential, regulatory/economic consequences, and reversibility. The most adequate descriptor had to be chosen from the ones contained in Table 1, yielding the respective score.

Table 1 – Severity scale and feed-specific consequence descriptors.

Level	Label	Description
S1	Negligible	No clinical disease; no measurable productivity loss; no carry-over; fully reversible without treatment.
S2	Minor	Mild/subclinical effects (e.g., transient diarrhea; ≤1–3% milk or growth loss); no human exposure; reversible with routine care.
S3	Moderate	Clear clinical disease in some animals; productivity losses ~3–10%; sporadic abortions/need for treatments; possible residues < legal limits; limited recalls.
S4	Major	Multi-animal outbreaks; ≥10–20% productivity loss; carry-over likely (e.g., AFM1 near limits); culling/large recalls; regulatory non-compliance.
S5	Severe	High morbidity/mortality or long-term reproductive failure; confirmed zoonotic transmission or widespread residue violations; trade restrictions/farm closure.

The Likelihood component was evaluated by considering factors such as the baseline prevalence in inputs, seasonality, growth/toxin formation potential, and exposure/transfer potential, yielding a score from L1 to L5 according to Table 2 descriptors.

Table 2 – Likelihood scale and practical interpretation.

Level	Label	Description
L1	Rare	≤1% of batches; ≤1 event/10y under current controls.
L2	Unlikely	Sporadic; atypical conditions needed.
L3	Possible	Known problem 1–2× per 1–5y; seasonal/management dependent.
L4	Likely	Several times per year without additional controls.
L5	Almost certain	Routine unless targeted controls exist.

Risk scores were then calculated as R = S × L, and qualitatively categorized into the following bands:

- Very Low (1–3);
- Low (4–7);
- Moderate (8–14);
- High (15–19);
- Very High (20-25).

3.2.2. Comparative risk rating in traditional and hydroponic production systems

A qualitative risk assessment was conducted twice for each selected hazard type, once within the context of conventional fodder production systems (pasture, hay, silage) and the other considering hydroponic systems (sprouted grains, soilless cultivation). This comparative approach allowed the evaluation of how the method of production influences the likelihood of hazard occurrence, the conditions for their amplification, and the severity of their consequences for animal and public health. “Hazard × system” pairs were then placed into risk heatmaps as the one shown in Figure 1, which were meant as a visual aid to facilitate comparison between risk scores.

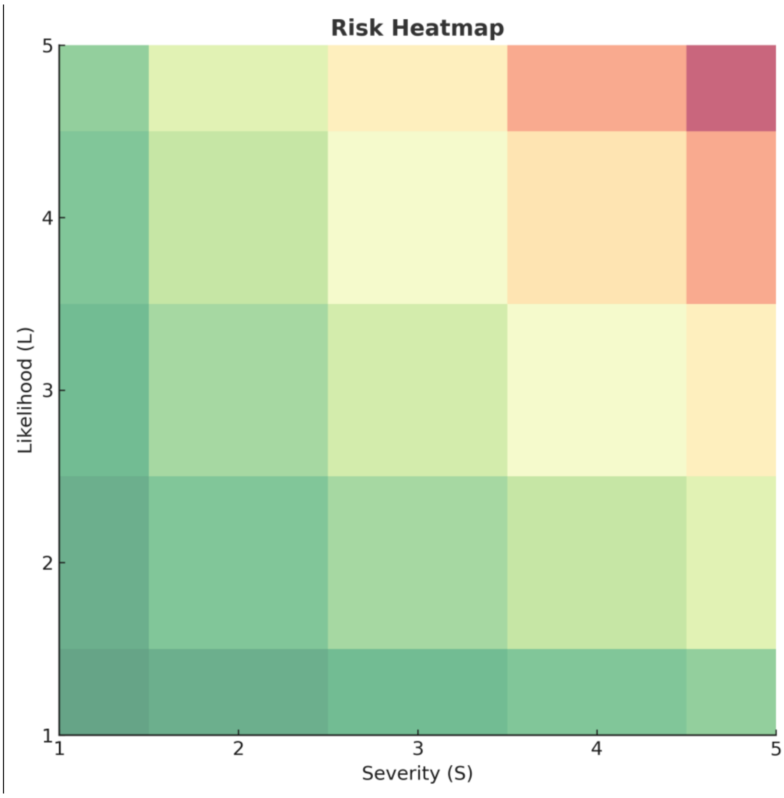

Figure 1 – Template of the risk heatmap used in the risk assessment. The horizontal axis (Severity, S) represents the magnitude of adverse effects, while the vertical axis (Likelihood, L) indicates the probability of occurrence. Each component is ranked from 1 to 5.

4. RESULTS

4.1. Relevant Hazards Associated to Fodder Consumption

The literature review allowed to identify several hazards associated to fodder consumption. Scientific literature emphasized that fodder is not only the foundation of livestock productivity but also a critical vehicle for the transmission of biological hazards. Conventional feeding systems, such as pasture, hay, and silage, expose animals to diverse microbial and fungal contaminants originating from soil, water, and inadequate post-harvest practices. In recent years, hydroponic fodder production has emerged as a controlled alternative that eliminates many soil-borne risks. However, it introduces unique challenges associated with microbial ecology in moist sprouting environments and the potential accumulation of fungal metabolites. Numerous investigations demonstrated that the humid, nutrient-rich conditions of hydroponic sprouting chambers promote the proliferation of opportunistic bacteria and molds, which in turn can compromise animal health and productivity [51, 52].

Among bacterial hazards, *L. monocytogenes* and *Salmonella* spp. are considered particularly significant. *L. monocytogenes* has long been associated with poorly fermented silage and remains a leading cause of neurological disorders and abortions in ruminants. The pathogen not only reduces animal productivity but also poses a zoonotic threat, especially through contaminated milk [53]. Similarly, *Salmonella* spp. contamination in fodder systems can originate from irrigation water, dust, and contaminated seed stock. Studies in feed mills and controlled feeding facilities confirmed that this pathogen can persist in production environments, leading to diarrhea, septicemia, and growth retardation in calves [54, 55]. Hydroponic fodder, while less exposed to soil contamination, is not immune to bacterial hazards. Recirculating water systems can act as reservoirs for *E. coli* O157 and other Shiga toxin-producing strains, with potential to enter the food chain if monitoring and sanitation are insufficient [56, 57].

Among the most critical hazards, were fungi and their metabolites. Mycotoxins such as aflatoxins, fumonisins, deoxynivalenol (DON), and zearalenone (ZEN) are increasingly detected in both conventional and hydroponic fodders. *Aspergillus flavus* and *Fusarium verticillioides* are recognized as major producers of aflatoxins and fumonisins, respectively, while *Fusarium graminearum* is a common source of DON [58]. These toxins have serious biological effects: aflatoxin B1 is metabolized in dairy cows to aflatoxin M1, which passes into milk; DON suppresses immunity and reduces feed intake; ZEN acts as an estrogenic compound disrupting reproduction; fumonisins impair liver and kidney function. Surveys showed that hydroponic sprouts, if stored for more than 48 hours under warm and humid conditions, become vulnerable to colonization by these fungi, leading to measurable levels of mycotoxins [59]. Multi-mycotoxin contamination, where two or more metabolites occur simultaneously, is now recognized as the norm rather than the exception, creating synergistic effects that aggravate animal health risks [60]. Several studies reveal that the constant humidity and high organic matter of sprouted grains can accelerate fungal growth if management lapses occur.

Studies on hydroponic production systems demonstrated that molds such as *Aspergillus flavus*, *Fusarium graminearum*, and *Penicillium roqueforti* readily colonize sprouted barley and maize fodder when storage exceeds 48–72 hours, leading to detectable concentrations of aflatoxins, deoxynivalenol, and zearalenone [61, 62]. These toxins, even at subclinical levels, are known to impair rumen function, reduce feed intake, suppress immune responses, and alter reproductive efficiency in cattle and swine. Aflatoxin B1, in particular, undergoes biotransformation in lactating cows to aflatoxin M1, which can be secreted into milk and exceed regulatory thresholds, thus linking hydroponic fodder directly to food safety concerns in the dairy chain [63].

Longitudinal feed surveys reinforce the ubiquity of mycotoxin co-contamination. Multi-center analyses covering Europe, North America, and Asia consistently confirm that more than 70% of feed samples contain two or more mycotoxins simultaneously, and that masked or modified metabolites such as deoxynivalenol-3-glucoside frequently evade conventional screening but retain biological activity [64, 65]. This has direct relevance for hydroponics, where sprouts are rarely tested systematically, and the rapid microbial succession in moist environments may promote both classical and emerging fungal metabolites. Controlled trials demonstrate that the aerobic stability of hydroponic sprouts rapidly declines after harvest, with concomitant increases in *Fusarium* and *Aspergillus* colony counts and corresponding toxin levels [66].

The biological consequences for animals are substantial. Exposure to fumonisins has been linked to hepatic lesions, pulmonary edema in swine, and leukoencephalomalacia in horses. Zearalenone acts as an estrogenic mycotoxin, reducing fertility in dairy cows and sows, and deoxynivalenol diminishes feed palatability while suppressing immunity, increasing susceptibility to bacterial and viral infections [67, 68]. Hydroponic fodder, by providing a continuous supply of moist feed, may exacerbate the chronic exposure risk if feeding management is not synchronized with sprout growth and utilization. Preventive measures such seed disinfection, sanitation of trays, continuous monitoring of water quality, and strict enforcement of harvest-to-feeding intervals are thus essential [69, 70].

Parasites represent another important hazard side associated to fodder, particularly in conventional pasture-based systems. Infective larvae of nematodes such as *Haemonchus contortus*, *Ostertagia ostertagi*, and *Cooperia* spp. are commonly acquired by grazing animals, causing reduced feed conversion efficiency, anemia, diarrhea, and chronic production losses [71]. Protozoa, including *Eimeria* spp. and *Cryptosporidium parvum*, are also strongly associated with feed and water contamination, leading to coccidiosis and neonatal diarrhea. Their relevance extends beyond animal productivity: *Cryptosporidium parvum* is a recognized zoonotic agent, with oocysts capable of surviving in moist environments and hydroponic water systems if disinfection is inadequate [72]. Although hydroponic fodder eliminates soil exposure, inadequate water sanitation or contaminated seeds can reintroduce parasitic hazards, underscoring the need for seed treatment and validated disinfection protocols [73].

Viral risks, while less common, are of catastrophic potential. Recent experimental evidence has demonstrated that pathogens such as African swine fever virus (ASFV) and foot-and-mouth disease virus (FMDV) can remain viable in feed matrices, including plant-based ingredients, for weeks during simulated shipping conditions [74]. This raises concern that hydroponic fodder systems, particularly when using imported seeds or untreated nutrient solutions, could inadvertently serve as vehicles of transboundary viral pathogens. Studies emphasize that feed hygiene, ingredient sourcing, and holding times are critical control points to mitigate viral spread via fodder [75, 76]. Although the probability of viral contamination is low compared to bacterial and fungal hazards, the magnitude of impact in the event of an outbreak makes viral risk an essential consideration in both conventional and hydroponic systems [77].

Among biological hazards, mycotoxins remain the most insidious due to their chronic, cumulative effects. Subclinical exposure to aflatoxins, fumonisins, zearalenone, and deoxynivalenol has been linked to immunosuppression, endocrine disruption, reduced fertility, and increased susceptibility to secondary infections [78]. Co-contamination is particularly concerning in hydroponic fodder, where molds can proliferate rapidly under conditions of poor ventilation and high relative humidity. Surveys of hydroponic barley fodder show that improperly stored sprouts can accumulate multiple *Fusarium* toxins, with biological impacts including reduced rumen microbial efficiency and compromised growth rates [79]. These findings highlight that hydroponic systems, while mitigating soil-borne parasites and heavy metals, require rigorous control of moisture, temperature, and feeding intervals to prevent chronic mycotoxin exposure in livestock [80].

The identified hazards encompassed biological, chemical, and physical categories, each of which can directly compromise animal health, reduce productivity, and, in some cases, threaten public health through zoonotic transmission or the presence of harmful residues in animal-derived products. The relevance of fodder-related hazards is underscored by the fact that feed accounts for the majority of exposure routes in food-producing animals, meaning that the quality and safety of feed directly influence the overall safety of the food chain.

4.2. Qualitative Risk Assessment

Based on the literature review, 7 different hazard types were considered:

- *Listeria monocytogenes*;
- *Salmonella* spp.;
- Mycotoxins;
- Parasitic hazards;
- Viral hazards;
- Chemical hazards;
- Physical hazards.

Using the previously presented methodological framework, each identified hazard was evaluated separately for conventional fodder production systems (including pasture, hay, silage) and for hydroponic systems (sprouted grains). The assessment considered both the severity of the hazard and its likelihood of occurrence, resulting in a final risk rating expressed as the product $R = S \times L$. The findings, which are discussed point-by-point below, are visually presented in Figures 2 and 3 and summarized in Table 5.

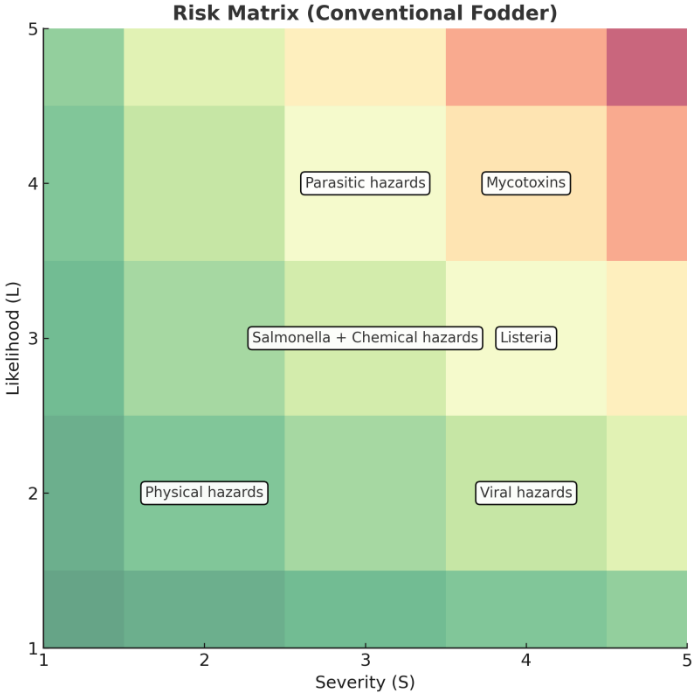

Figure 2 - Risk heatmap showing the risk scores for different hazard types in conventional fodder production systems.

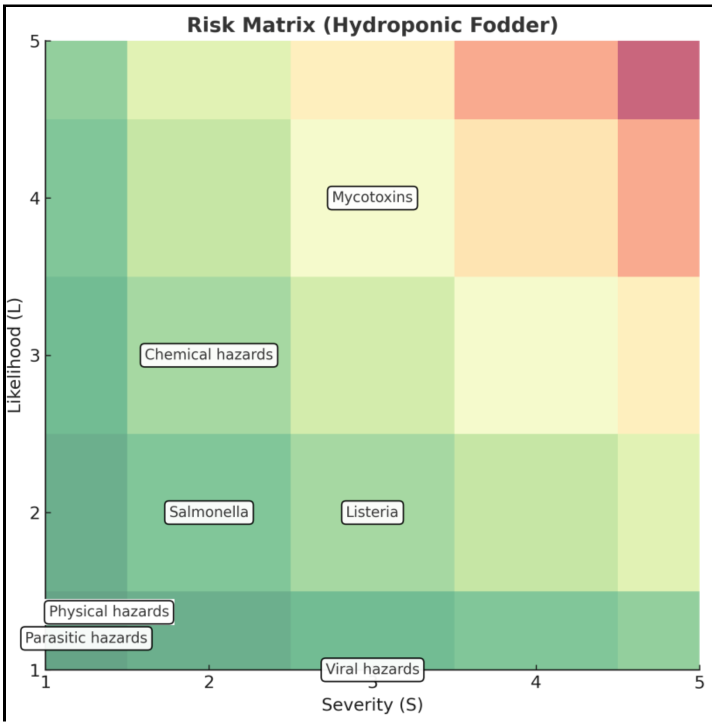

Figure 3 - Risk heatmap showing the risk scores for different hazards in hydroponic fodder production systems.

4.2.1. *Listeria monocytogenes*

Listeria monocytogenes remains one of the most significant feedborne pathogens due to its strong link with silage and its zoonotic potential. In conventional fodder systems, the bacterium proliferates in poorly fermented silage, especially when oxygen ingress or insufficient lactic acid production prevents adequate acidification. This creates an environment highly conducive to Listeria survival, leading to outbreaks of listeriosis in cattle and sheep. Clinical manifestations include encephalitis, septicemia, and abortions, all of which result in high productivity losses. Additionally, the pathogen may enter the milk supply, posing a direct risk to human consumers. For this reason, the risk rating for conventional production is Moderate (S4 × L3 = 12). In hydroponic systems, by contrast, the absence of silage and soil reduces the risk considerably. The main pathway for contamination would be through seeds or irrigation water, making the risk Low (S3 × L2 = 6). Nevertheless, the potential for waterborne contamination requires continuous monitoring.

4.2.2. *Salmonella* spp.

Salmonella spp. are widely distributed in the environment and remain a persistent feedborne hazard. In conventional fodder, the primary risks arise during harvesting and storage, when feed may come into contact with manure, rodents, or contaminated soil. Salmonellosis in livestock results in diarrhea, dehydration, and mortality, particularly in calves and poultry. From a public health perspective, *Salmonella* is one of the most important zoonotic foodborne pathogens. The conventional rating is Moderate (S3 × L3 = 9), reflecting both the severity of clinical disease and the frequency of contamination events. In hydroponic systems, the absence of soil and manure contact reduces the risk dramatically. However, contamination may still occur if irrigation water is untreated or seeds are not properly disinfected. As such, the hydroponic rating is Low (S2 × L2 = 4).

4.2.3. Mycotoxins (Aflatoxin B1, DON, ZEN, fumonisins)

Mycotoxins represent one of the most critical hazards due to their chronic toxicity, ability to suppress immunity, impair reproduction, and reduce growth. In conventional systems, silage and stored grains create highly favorable conditions for fungal proliferation, particularly when storage practices are inadequate. Aspergillus species produce aflatoxins, Fusarium produces deoxynivalenol (DON), fumonisins, and zearalenone (ZEN). These compounds cause a wide range of disorders including reduced feed intake, hepatotoxicity, immunosuppression, infertility, and in severe cases, death. Moreover, aflatoxin B1 is metabolized to aflatoxin M1 and secreted into milk, representing a direct food safety risk. Consequently, the conventional risk is High (S4 × L4 = 16). In hydroponic systems, field fungi are less common, yet the warm and moist environment of growth chambers can encourage mold development if sprouts are stored for extended periods. Under these conditions, opportunistic molds may produce toxins, leading to a Moderate rating (S3 × L4 = 12).

4.2.4. Parasitic hazards

Parasitic hazards are closely linked with pasture-based feeding and are among the most important risks in conventional systems. Infective stages of nematodes and protozoa persist on pasture and are easily ingested with forage. In livestock, parasitism results in anemia, diarrhea, poor weight gain, and high morbidity, especially in young animals. Chronic infestations lead to reduced productivity and substantial economic losses. In wet pastures, *Fasciola hepatica* (liver fluke) may also infect animals, causing chronic liver damage and reproductive failure. This justifies a Moderate risk rating (S3 × L4 = 12) for conventional systems. In contrast, hydroponic production is soil-free and conducted in a controlled environment, which prevents the transmission of pasture-borne parasites. Therefore, the hydroponic rating is Very Low (S1 × L1 = 1).

4.2.5. Viral hazards (FMDV, ASFV)

Although fodder is not a primary vector for viral diseases, its role as an indirect vehicle cannot be overlooked. Viruses such as FMDV and ASFV may enter livestock herds through contaminated feed ingredients, transport, or handling equipment. Outbreaks of these diseases are catastrophic, causing widespread mortality and trade restrictions. In conventional systems, where feed may be exposed to fomites or by-products, the risk is Moderate (S4 × L2 = 8). In hydroponic systems, the likelihood of viral contamination is substantially lower due to controlled environments, but contamination remains possible if water sources are compromised. Therefore, the risk rating is Very Low (S3 × L1 = 3).

4.2.6. Chemical hazards

Chemical contaminants represent a broad category of hazards that often exert chronic effects rather than acute disease. In conventional fodder, pesticide residues may remain in forage crops, while heavy metals such as lead, cadmium, and mercury can accumulate from contaminated soils or irrigation water. Chronic exposure leads to organ toxicity, reduced productivity, and the appearance of residues in milk and meat, creating public health risks. Accordingly, the conventional rating is Moderate (S3 × L3 = 9). In hydroponic fodder, soil-related contaminants are minimized, but residues from seed treatment and disinfectants used in irrigation systems may remain. Improper management could lead to accumulation, warranting a Low risk rating (S2 × L3 = 6).

4.2.7. Physical hazards

Physical hazards, while not frequent, still pose significant risks in conventional systems. Stones, soil, metallic fragments, and plastics may contaminate hay or silage during harvesting and storage. Ingestion of such materials can lead to traumatic reticuloperitonitis ("hardware disease") in cattle, resulting in costly veterinary interventions and production losses. This justifies a Low risk rating (S2 × L2 = 4). Hydroponic systems, by contrast, are conducted in tightly controlled indoor conditions, eliminating nearly all potential for physical contamination. As such, the hydroponic rating is Very Low (S1 × L1 = 1).

Table 5 – Qualitative risk assessment results for conventional and hydroponic fodder systems.

Hazard	Conventional production risk rating	Hydroponic production risk rating	Notes
Listeria monocytogenes	Moderate (S4×L3 = 12)	Low (S3×L2 = 6)	High prevalence in silage; reduced but not eliminated risk in hydroponics.
Salmonella spp.	Moderate (S3×L3 = 9)	Low (S2×L2 = 4)	Strongly linked to manure and soil; rare in hydroponics.
Mycotoxins (Aflatoxin B1, DON, ZEN, fumonisins)	High (S4×L4 = 16)	Moderate (S3×L4 = 12)	Silage highly vulnerable; hydroponics affected by moisture storage issues.
Parasitic hazards	Moderate (S3×L4 = 12)	Very Low (S1×L1 = 1)	Soil-borne parasites eliminated in hydroponics.
Viral hazards (FMDV, ASFV)	Moderate (S4×L2 = 8)	Very Low (S3×L1 = 3)	Rare but severe events; lower risk in hydroponics.
Chemical hazards	Moderate	Low (S2×L3 =	Soil pesticides and heavy

	(S3×L3 = 9)	6)	metals vs disinfectants in hydroponics.
Physical hazards	Low (S2×L2 = 4)	Very low (S1×L1 = 1)	Mechanical contamination absent in hydroponics.

5. DISCUSSION

The present study systematically compared the risk profiles of conventional and hydroponic fodder production systems using a qualitative risk assessment framework. By integrating literature-based evidence and risk matrices, the study highlighted both the persistent hazards of traditional systems and the emerging vulnerabilities of hydroponic systems.

In conventional systems, the obtained risk scores showed that mycotoxins, *Listeria monocytogenes*, and parasitic infections represent the highest hazards. This is consistent with numerous reports that emphasize the ubiquity of mycotoxin contamination in silage and stored grains, particularly aflatoxin B1, deoxynivalenol, fumonisins, and zearalenone [58–65]. The assignment of a Moderate risk level to *Listeria* and *Salmonella* also aligns with global surveys showing silage as a primary reservoir of *L. monocytogenes* and soil/manure as major contamination sources for *Salmonella spp.* [53–55]. These findings reinforce the notion that conventional fodder safety is primarily limited by environmental variability, poor fermentation, and storage practices.

Hydroponic fodder production significantly altered this hazard profile. The most evident advantage of hydroponics is the elimination of soil-borne parasites and physical contaminants, whose risks were rated as Very Low or Low. This reflects the closed, controlled conditions of sprouting chambers that minimize exposure to external contamination sources. At the same time, hydroponics introduced specific risks, particularly related to the persistence of molds and the accumulation of mycotoxins during prolonged storage beyond 48 hours. Several studies on sprouted barley and maize confirm that *Aspergillus flavus*, *Fusarium graminearum*, and *Penicillium roqueforti* can colonize hydroponic sprouts, producing measurable toxin levels [61–63]. These results explain the Moderate risk rating assigned to mycotoxins in hydroponics, even in the absence of field fungi.

Another distinct vulnerability of hydroponic systems is linked to water quality and microbial ecology. Recirculating irrigation solutions can support biofilm formation, providing niches for opportunistic bacteria [56, 57]. Although the overall risk rating for bacterial hazards in hydroponics was low compared to conventional systems, this aspect highlights the need for rigorous water sanitation protocols and validated disinfection strategies. The identification of disinfectant residues and seed-treatment chemicals as hazards posing a Low risk further indicates that chemical risk in hydroponics shifts from environmental contaminants (pesticides, heavy metals) to management-related inputs.

These findings collectively illustrate that hydroponic systems do not eliminate hazards but redistribute them into new domains, requiring tailored critical control points. This observation is consistent with recent reviews on hydroponic food and feed safety, which emphasize that moisture, sanitation, and rapid utilization of sprouts are decisive factors for minimizing risks [66, 70, 80].

From a One Health perspective, the implications of these results are significant. Unsafe feed compromises animal health, reduces productivity, and creates direct zoonotic risks through milk, meat, and other animal-derived products. The comparative analysis underscores that both production systems require proactive risk management: silage inoculation, storage hygiene, and pasture parasite control in conventional systems, and strict sanitation, seed disinfection, and harvest-to-feeding discipline in hydroponics.

Limitations of this study must also be acknowledged. The qualitative risk assessment framework, while useful for structuring comparisons, inevitably involves subjectivity in assigning severity and likelihood scores. Moreover, hydroponic systems remain relatively underrepresented in peer-reviewed literature, limiting the availability of quantitative data and hampering more structured approaches. Future studies should focus on field-based experiments, quantitative microbial risk assessments, and long-term monitoring of mycotoxin dynamics in hydroponic sprouts. Integrating economic analysis with biological risk modeling would also strengthen the decision-making basis for producers.

In summary, the discussion confirms that conventional systems are dominated by high-to-moderate-risk hazards such as mycotoxins, bacterial pathogens, and parasites, whereas hydroponics substantially mitigates these but introduces new vulnerabilities associated with microbial ecology and water management. Neither system is risk-free, but both can be managed effectively through targeted interventions. These findings contribute to the global discourse on sustainable livestock production and emphasize the importance of system-specific feed safety strategies.

6. CONCLUSIONS

The present study investigated the safety of conventional and hydroponic fodder production systems, with a particular focus on the different hazards that affect animal health, productivity, and in some cases even public health through the food chain. Building upon a review of the scientific literature, hazards were systematically classified and evaluated using a qualitative risk assessment approach, which enabled a structured comparison based on their respective severity and likelihood of occurrence across production systems.

The analysis demonstrated that conventional fodder systems, including pasture, hay, and silage, continue to carry substantial risks associated with environmental variability, soil contact, and storage conditions. Among the most relevant hazards, *Listeria monocytogenes* and *Salmonella* spp. remain frequent contaminants of silage and manure-exposed forages, while toxigenic fungi (*Aspergillus*, *Fusarium*, *Penicillium*) may contribute to high levels of mycotoxin contamination, including aflatoxins, fumonisins, deoxynivalenol, and zearalenone. Parasites, viral pathogens, chemical and physical hazard were identified as other relevant hazards, confirming that conventional systems require strict measures to mitigate different hazard types.

Hydroponic fodder production, in contrast, was shown to significantly reduce the risk associated with many soil-borne and physical hazards. However, the study also revealed that hydroponics introduces distinct risks linked to its dependence on water circulation, controlled humidity, and seed treatment practices. Mold proliferation in sprouting chambers, particularly under extended storage beyond 48 hours, was identified as a major contributor to mycotoxin contamination in hydroponic feeds. Furthermore, biofilm-associated opportunistic bacteria and residues from disinfectants or seed treatments emerged as hazards typical of hydroponic environments. These findings highlight that hydroponics redistributes rather than eliminating hazards, requiring different management approaches.

From a scientific standpoint, the study advances the understanding of fodder safety by integrating a qualitative risk assessment framework with a comparative analysis of production methods. The practical implications are considerable: for conventional systems, the focus should remain on silage management, mycotoxin mitigation, and pasture parasite control. For hydroponic systems, risk management must prioritize water sanitation, tray hygiene, strict feeding intervals, and chemical residue assessment. Policymakers and producers can utilize the insights from this research to design system-specific critical control points, thereby improving the overall safety and sustainability of livestock feeding practices.

Nonetheless, the study also acknowledges limitations inherent to qualitative risk assessment, such as the inherent residual subjectivity in assigning severity and likelihood scores. Future works should aim to complement qualitative findings with quantitative risk modeling, field trials in different productive and environmental situations, and integration of economic analyses to assess the cost-effectiveness of hazard control measures.

In conclusion, this research demonstrates that hydroponic fodder production holds great promise as a sustainable and resilient alternative to conventional feeding systems, particularly under conditions of land scarcity and climatic variability. At the same time, the findings make clear that careful attention must be paid to the system-specific risks associated with microbial ecology, moisture, and water quality. By clarifying the distinct hazard profiles of conventional and hydroponic systems, the thesis contributes to both scientific knowledge and practical strategies for safer and more sustainable livestock production.

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