A Feasibility Study on the Commercial Application of a Paper-based Microfluidic Device for the Detection of Deoxynivalenol for the Inner Mongolian Grassland Livestock Industry

Xige Hao*

The Experimental High School Attached to Beijing Normal University, Beijing, China

*Corresponding author

Keywords: detection of deoxynivalenol (DON), mycotoxin, livestock health, Inner Mongolia grassland, animal food chain, paper-based microfluidic device (DON-Chip), rapid and cost-effective detection, ASSURED criteria (Affordable, Sensitive, Specific, User-friendly, Rapid, Robust, Equipment-free, and Deliverable), commercial product, cost-benefit model

Abstract: The objective of this study was to assess the engineering and productization of a technological innovation, namely a "paper-based microfluidic device," which has been previously utilized abroad for the rapid and cost-effective detection of deoxynivalenol (DON) [1]. The findings of this study were utilized to develop a commercial product that is tailored to the specific development needs of the livestock industry in Inner Mongolia. We investigated the current situation of the Inner Mongolian livestock industry affected by toxins, identified potential scenarios of toxin contamination of pasture and processed feeds, and explored the device's capacity to provide low-cost and rapid DON detection, as well as the pathway to realization of ASSURED criteria from solution to product [2]. Furthermore, an economic benefits model for the implementation of the product is proposed, based on an analysis of a typical pasture in Inner Mongolia. The benefits and impacts of the product on the livestock industry in Inner Mongolia are discussed, as well as the opportunities, challenges, and future development directions it faces.

1. Introduction

1.1. Background Information

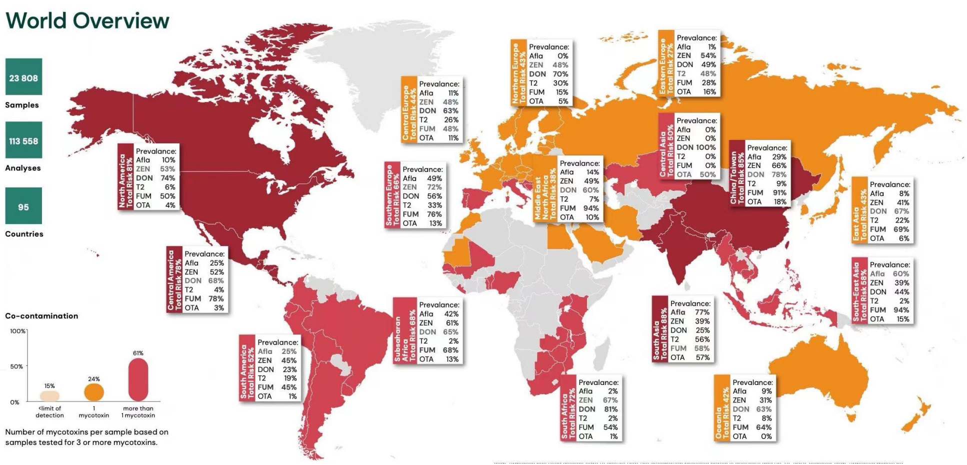

Figure 1 Global map of mycotoxin prevalence and risk in different regions [3]

From ‘The DSM Mycotoxin Survey of 2023’, we can see the variations in contamination levels of the mycotoxins over the years. In the last 10 years contamination with the six main mycotoxins in all commodities (raw materials as well as finished feed) seems to be stable on a global perspective [3]. Figure 1 shows the current global prevalence status of the six mycotoxins in 2023.

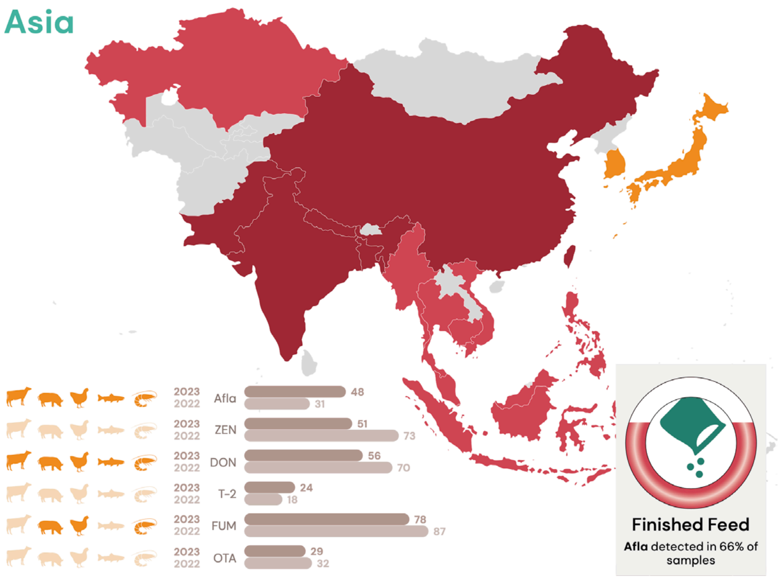

Figure 2 Risks posed to 5 animal species by the prevalence and concentration of each mycotoxin in all samples from Asia [3]

Prevalence of FUM in Asian corn kernels and DON in Asian DDGS seems to be quite stable, whereas average of positives shows an increase over the past 5 years. Deoxynivalenol (DON), a mycotoxin produced by the Fusarium fungi, contaminates staple crops such as wheat, corn, and barley, which are essential components of both human food and animal [3]. As can be seen in Figure 2, DON is highly prevalent in all five species analyzed in Asia.

Inner Mongolia's grasslands represent a fundamental component of China's livestock sectors, exhibiting vast expanses that are conducive to farming and animal husbandry practices. However, these regions are confronted with considerable challenges posed by mycotoxins, particularly DON, which is commonly referred to as the "vomitoxin." We found some of the real status of DON contamination in feed:

- DON is highly prevalent in animal feed, with studies showing that in China, including regions like Inner Mongolia, contamination rates can exceed 96% in feed samples. The toxin is particularly prevalent in wheat bran, wheat, and corn products, with contamination levels ranging between 200.9 ng/g to 6480.6 ng/g [4].
- In many cases, DON levels exceed China's regulatory safety standards, posing risks not only to livestock but also to food safety for humans consuming animal-derived products [5].

1.2. Problems in feed safety and quality

DON contamination in feed presents significant risks to both animal health and the quality of livestock products. The toxin is commonly found in cereals like wheat and corn, which are critical components of animal feed. The hazards of DON contamination in Inner Mongolia grasslands are mainly:

1.2.1. Impact on Livestock Health

The livestock in Inner Mongolia, including cattle, sheep, swine, and poultry, are highly susceptible to the toxic effects of DON. When animals consume feed contaminated with DON, it disrupts protein synthesis, leading to a range of health issues:

- Reduced Feed Intake: Animals exhibit decreased appetite, which leads to weight loss and poor growth performance. For example, broiler chickens and pigs fed DON-contaminated diets often experience reduced growth rates and poor feed conversion efficiency [6].
- Digestive Problems: Symptoms such as vomiting and diarrhea are common, affecting nutrient absorption and overall health. The toxin also affects the microflora of the digestive system, especially in pigs, causing shifts in bacterial populations that further hinder digestion and nutrient absorption [7].

- Immune Suppression: Prolonged exposure weakens the immune system, making animals more susceptible to diseases.

1.2.2. Economic Consequences

The agricultural economy of Inner Mongolia is heavily reliant on the productivity of its livestock and crop yields. DON contamination leads to:

- Reduced Crop Quality: Contaminated grains may be rejected for commercial use, leading to financial losses.
- Increased Veterinary Costs: Treating affected livestock adds to the expenses of farmers already facing reduced income.
- Trade Restrictions: High levels of mycotoxins can lead to export limitations, affecting the broader economic landscape.

1.2.3. Food Safety Risks

While DON is a concern for animal health, it also poses risks to human health when contaminated crops enter the food supply:

- Acute Toxicity: Consumption can cause nausea, vomiting, abdominal pain, and diarrhea in humans. In dairy cows, DON-contaminated feed does not necessarily reduce milk production, but the excretion of DON and its metabolites in milk raises concerns about the safety of dairy products.
- Chronic Exposure: Long-term ingestion, even at low levels, may lead to immune deficiencies and other health complications.
- Regulatory Challenges: Ensuring that food products meet safety standards requires rigorous testing and monitoring, adding to the logistical burden on food producers.

1.2.4. Environmental Factors Promoting DON Prevalence

Inner Mongolia's climatic conditions—cool temperatures and moderate rainfall—are conducive to the growth of Fusarium fungi. This environment leads to:

- Increased Crop Infection: Higher incidence of Fusarium head blight in cereals.
- Co-Contamination with Other Mycotoxins: DON often appears alongside Fumonisins (FUM) and Zearalenone (ZEN), complicating detection and increasing the toxicity of contaminated feed and food products.

1.2.5. Challenges in Detection and Management

- Lack of Rapid Testing Methods: Traditional laboratory tests are time-consuming and not practical for on-site analysis.
- Limited Awareness: Ranchers may not be fully aware of the risks or lack the resources to test and mitigate contamination.
- Ineffective Control Measures: Without proper strategies, such as crop rotation and resistant varieties, controlling Fusarium infections remains difficult.

The prevalence of DON toxin poses a significant threat to both the livestock industry and public health. Addressing these challenges requires effective monitoring, rapid detection methods, and comprehensive management strategies to reduce contamination levels. By implementing these solutions, Inner Mongolia can safeguard the integrity of its livestock, protect the health of its consumers, and ensure economic stability.

1.3. Risks and Requirements

In Inner Mongolia's grassland regions, the application of a paper-based microfluidic device, such as the DON-Chip, for mycotoxin detection can significantly enhance food safety and livestock management by integrating key elements from the whole feed lifecycle [5].

1.3.1. Risks in the pasture and feed lifecycle

In the pastoral areas of Inner Mongolia, the risk points for exposure to Deoxynivalenol (DON) contamination in forage and feed during the stages of growing, harvesting, processing, transportation, storage, and feeding include the following aspects:

1) Growing Stage

- Climate Conditions: The climatic characteristics of Inner Mongolia, such as high humidity and warm growing seasons, make it prone to infections by Fusarium fungi, which are the primary source of DON. This is particularly true for crops like corn, wheat, and barley, where fungal infections lead to increased DON levels [4].
- Crop Varieties: Different crop varieties exhibit varying levels of resistance to Fusarium fungi. Varieties with lower resistance are more susceptible to fungal infections, thereby increasing the production of DON [5].

2) Harvesting Stage

- Timing of Harvest: If crops encounter continuous rainfall or high humidity conditions before harvesting, particularly during the ripening stage, the risk of fungal infection increases significantly. In such cases, delayed harvesting can result in extensive fungal growth, raising the risk of DON contamination [7].
- Mechanical Damage: Improper mechanical operations during harvesting, such as cuts and breakages, can provide entry points for fungal infection, thereby increasing the risk of DON contamination [6].

3) Processing Stage

- Cleanliness of Processing Environment: If the processing equipment and environment are not kept sanitary, fungal spores can spread on equipment surfaces or in the air, contaminating the feed during processing [8].
- Processing Methods: Moist processing methods (e.g., silage) can lead to fungal growth if humidity is not properly controlled, increasing the risk of DON contamination [9].

4) Transportation Stage

- Transportation Conditions: Forage and feed exposed to high humidity or rain during transportation can create favorable conditions for fungal growth. If transportation vehicles are not dry or lack proper covering, fungi can easily proliferate, leading to DON contamination [10].
- Duration of Transportation: Long or delayed transportation can result in fungal infections and DON contamination in the feed under optimal temperature and humidity conditions [11].

5) Storage Stage

- Humidity and Temperature Control: If feed is stored in high humidity or warm environments, fungi can continue to grow in the stored feed, increasing the risk of DON contamination. Storage facilities lacking proper ventilation systems or humidity control will significantly raise the risk of contamination [12].
- Insufficient Quality Inspection: If infected feed is mixed into storage without strict quality inspection before storage, it can lead to large-scale feed contamination [13].

6) Feeding Stage

- Extended Feed Storage: In pastoral areas, feed is often stored for extended periods to prepare for winter. If the storage conditions are improper, especially with higher humidity, the risk of DON contamination will further increase [14].
- Lack of Timely Inspection: If the feed is not inspected or tested in time before feeding, contaminated feed may be given to livestock, leading to health problems such as reduced appetite and weight loss [15].

The risk of DON contamination extends to all stages of fodder and feed production in Inner Mongolia's pastoral areas, including growing, harvesting, processing, transportation, storage, and feeding. To effectively reduce DON contamination, appropriate preventive measures must be taken at each stage, such as selecting resistant crop varieties, maintaining good environmental hygiene, strictly controlling humidity and temperature, and regularly testing feed quality. These measures can significantly reduce the impact of DON contamination on livestock production in grazing areas and ensure the health and safety of both feed and livestock.

1.3.2. Requirements

Early-stage Detection. Using the DON-Chip at these stages ensures early detection of DON that may arise due to unfavorable conditions, such as temperature, humidity, and biological hazards (e.g., mold, pests, or contamination) [1]. This can help assess the suitability of grains and feed for storage or immediate use [8].

Mobile and Realtime. Deploying mobile testing units equipped with DON-Chip technology can significantly improve the reach of testing in remote pastoral regions. These units can provide farmers and agricultural cooperatives with immediate, actionable data on mycotoxin levels, enabling real-time decision-making regarding the treatment, storage, or disposal of contaminated feed [9]. This capacity for rapid, field-based detection ensures that decisions are timely, helping to avoid long-term storage or processing of contaminated stocks.

Fast and Easy of Use. During the harvest, rapid on-site testing can detect mycotoxin contamination, which helps make decisions regarding grain handling, such as whether immediate corrective actions (like drying or special storage) are necessary. Regular monitoring during storage is crucial since environmental factors like moisture can promote mold growth and increase toxin levels over time [14]. This proactive testing reduces the risk of toxins accumulating in stored feed.

Compliance. DON-Chip can also be used as a certification tool for ranches adhering to domestic or international quality assurance programs. Regular testing will ensure compliance with safety standards, preventing contaminated products from entering both local and export markets [15].

The strategic deployment of paper-based microfluidic devices for DON detection across Inner Mongolia's agricultural sector will have a profound impact on the management of food and feed safety. By focusing on testing at multiple stages—harvest, storage, and livestock feed—the technology will significantly reduce the risks associated with DON contamination [5]. This, in turn, will safeguard the health of animals, ensure the safety and quality of food products, and maintain economic stability in Inner Mongolia’s pastoral farming communities.

1.4. Objective

The goal of adapting the “Paper-Based Microfluidic Device (DON-Chip)” for use in Inner Mongolia’s pastoral regions is to address the critical issues of DON contamination in animal feed and food safety. This region experiences frequent contamination of grains, such as wheat, corn, and barley, by mycotoxins like DON, which severely affects both livestock health and productivity. The objectives are to develop the DON-Chip from a solution into a commercially viable product that can be used in various practical scenarios of DON contamination risks.

Rapid On-Site DON Detection. The main objective is to provide farmers and agricultural workers with a portable, easy-to-use, and rapid testing device that can detect DON contamination in real-time, particularly during critical points in the feed supply chain such as post-harvest, during storage, and before feed utilization. This on-site testing capability allows for immediate decision-making to prevent contaminated feed from entering the food chain.

Enhanced Food and Feed Safety. By enabling regular and accurate monitoring of mycotoxins, the DON-Chip will ensure that animal feed meets safety standards, thus reducing the risk of contamination in livestock and improving food safety for humans. It is essential to prevent mycotoxin-induced health issues in animals, such as digestive problems, immune suppression, and reduced productivity, which directly impact the economic viability of farming in Inner Mongolia.

Cost-Effective and Accessible Technology. The DON-Chip technology must be adapted for affordability and accessibility to the rural farming communities of Inner Mongolia. The goal is to develop a product that reduces the cost of testing, provides easy handling without the need for specialized equipment, and requires minimal training for use. This will significantly reduce the economic burden on farmers, allowing them to conduct frequent tests without reliance on costly laboratory services.

Integration with Existing Agricultural Practices. The device needs to seamlessly integrate with existing agricultural workflows in Inner Mongolia. This involves ensuring that the DON-Chip is durable, able to withstand harsh environmental conditions, and simple enough to be used by farmers directly in the field. The goal is to make the device a routine part of the feed production and storage process, improving the overall quality of feed and reducing contamination risks at every stage.

Support for Quality Assurance Programs. Another key objective is to align the DON-Chip technology with domestic and international safety standards for mycotoxin contamination. The device should help farms in Inner Mongolia adhere to certification requirements, whether for local markets or export, ensuring that their products are safe, compliant, and competitive. The product must meet the stringent limits set for DON levels in feed, ensuring that feed used for different livestock categories (e.g., swine, ruminants) is within safe limits.

By achieving these objectives, the DON detection product will not only safeguard the health of animals and the quality of food products in Inner Mongolia but also contribute to the economic sustainability of the region's livestock sector. The product's deployment will help mitigate mycotoxin risks, streamline the feed testing process, and support the region's long-term feed security.

1.5. Scope and Relevance

The scope of this research centers on deploying the "Paper-Based Microfluidic Device (DON-Chip)" to combat the pervasive issue of Deoxynivalenol (DON) contamination in Inner Mongolia's grassland agriculture [1]. The research specifically addresses the challenges of detecting and managing mycotoxin in the lifecycle of animal feed—from growing, harvest, storage, processing, and eventual feeding [8].

This research aims to provide a viable product for monitoring DON levels directly in the field, facilitating immediate decision-making that could prevent the introduction of contaminated feed into the animal food chain [14]. The goal is to integrate this technology seamlessly into existing livestock practices, ensuring that it is not only effective in detecting mycotoxins but also accessible and easy to use for local herders [9].

By improving DON management, the DON detection product will enhance feed safety and livestock health, thus supporting the economic stability and sustainability of livestock operations in the region [15]. This technological advancement is particularly crucial in Inner Mongolia, where the economy is heavily reliant on livestock and where environmental conditions can favor DON proliferation [5]. The research underlines the importance of this technology in enabling herders to meet both domestic and international safety standards, safeguarding animal health, and securing the quality of livestock products from the region [12].

2. Methodology

The DON-Chip is a paper-based microfluidic device that enables the rapid and cost-effective quantification of DON in food, feed, and feed ingredients. It incorporates a competitive immunoassay and employs gold nanoparticles for signal detection, thereby enabling the measurement of DON concentrations in food and feed products [8]. It aims to provide a portable, rapid, and cost-effective method for on-site detection, offering a viable alternative to traditional laboratory methods [14].

While the current DON chip solution offers a greater degree of advantage than some commercial products, but they must be designed and manufactured in accordance with the requisite specifications to be considered a viable commercial proposition [9].

From the perspective of a viable product, it is essential to further develop the DON detection product and ensure it meets the ASSURED criteria (Affordable, Sensitive, Specific, User-friendly, Rapid, Robust, Equipment-free, and Deliverable) [2], several steps can be undertaken.

2.1. Affordability

Cost Reduction in Materials: The current paper-based microfluidic device (DON-Chip) already emphasizes low-cost materials, costing less than $2 per test [1]. Further reductions in production costs can be achieved through mass production and optimization of materials used for fabrication [15].

Scale Production: Manufacturing at scale will help to reduce the cost of consumables and equipment further, making the device more accessible to broader markets, especially in resource-limited regions like rural areas in Inner Mongolia [5].

2.2. Sensitivity

Optimization of Detection Range: The DON-Chip has demonstrated a detection range of 0.01−20 ppm, which is suitable for most field applications [1]. However, continuous improvement in antibody affinity and signal detection (e.g., by refining gold nanoparticle conjugation methods) could further enhance the sensitivity of the device to detect even lower levels of DON, which is critical for regulatory compliance in sensitive environments like animal feed [6].

Improvement of Calibration Curves: The calibration curves used for detection could be refined to improve accuracy, especially in the low concentration ranges [1]. The paper already uses ratio metric analysis to improve detection precision, which can be further optimized [12].

2.3. Specificity

Minimize Cross-Reactivity: While the DON-Chip demonstrates high specificity for DON and its acetylated derivatives, further work could reduce cross-reactivity with other mycotoxins (e.g., ZEN or aflatoxins), ensuring that the device can distinguish DON with minimal false positives from other contaminants [1].

Advanced Antibodies: Developing monoclonal antibodies that exclusively bind DON could enhance the specificity of the detection method, minimizing interference from other toxins [7].

2.4. User-friendly

Simplification of Test Procedures: The current procedure already focuses on ease of use, with pre-loaded reagents and minimal sample preparation. Further developments could focus on making the detection system even more intuitive, such as providing more straightforward visual indicators of contamination levels or integrating step-by-step guidance through smartphone applications [5].

Training Materials: Develop easy-to-follow training guides for non-technical users (e.g., herders), ensuring they can use the device accurately without needing extensive training [12].

2.5. Rapidity

Reduced Time for Results: The DON-Chip currently provides results within 12 minutes, which is suitable for field use [1]. Further reductions in the time to results could enhance its appeal, potentially allowing for near real-time decision-making on feed safety [6].

Optimizing Flow Rate: The paper highlights the importance of capillary flow speed in microfluidic channels. Further optimization of channel design or fluidics could help speed up the detection process while maintaining accuracy [1].

2.6. Robustness

Field-Ready Design: The DON-Chip needs to withstand a wide range of environmental conditions, such as temperature and humidity fluctuations that might occur in Inner Mongolia [1]. Research should focus on ensuring the device remains functional under varying conditions, perhaps by enhancing the stability of the reagents used, especially for long-term storage [7].

Stability Testing: Ongoing tests under different environmental stressors (temperature, pH, humidity) could ensure the chip's robustness across diverse operating environments, as well as its shelf life for long-term usability [11].

2.7. Equipment-Free

Further Simplification of Imaging: The paper discusses a portable imaging system for reading the results, but this could be further streamlined by using smartphones as the detection platform. Most users have access to smartphones, and using them for reading the results can make the device truly equipment-free [12].

Power-Free Operation: Any external power requirements (e.g., for imaging systems) could be eliminated by integrating the entire process into a paper-based detection system with a colorimetric readout that requires no additional equipment [9].

2.8. Deliverability

Easy Distribution and Scalability: The DON-Chip should be developed to be lightweight and compact, making it easy to distribute in bulk to remote areas such as rural China or Inner Mongolia. Partnerships with local livestock cooperatives or governments could ensure wide distribution [5].

Supply Chain Management: Establish a reliable supply chain for critical reagents, ensuring that herders and feed producers can regularly replenish their supplies without long delays, even in grassland regions [15].

In summary, while the DON-Chip solution described in the paper already aligns well with some of the ASSURED criteria, further improvements in the product's robustness for field use, reduction of detection time, simplification of the user interface, and making the device completely equipment-free (e.g., integrating smartphone-based analysis) will ensure that the product is fully compliant with ASSURED criteria and can be used effectively in various settings, especially grassland regions like Inner Mongolia [12].

3. Implementation Process

The successful development of the DON detection product from its technology solution to a fully functional product involves several key steps in the implementation process. These steps ensure that the product is not only technically capable but also ready for widespread adoption in livestock industry in Inner Mongolia.

3.1. Prototype Development

Material Selection: During the initial stages of development, the choice of materials is critical. The device is made using cost-effective, environmentally durable paper substrates. Hydrophobic barriers are created using techniques like wax printing or screen printing, ensuring that the microfluidic channels are robust and functional in various environmental conditions typical of rural Inner Mongolia [8].

Reagent Optimization: Collaborations with biochemical experts and companies are necessary to optimize the reagents used in the DON detection product. High-affinity reagents such as antibodies or aptamers are selected to ensure precise detection of DON. Additionally, the reagents are designed to remain stable across a range of temperatures and humidity levels, crucial for field conditions [14].

3.2. Testing and Validation

Lab Testing: Initial testing occurs in controlled laboratory conditions, where known concentrations of DON are introduced to calibrate the product’s sensitivity and specificity. This iterative process allows the development team to make necessary adjustments to reagent concentration, ensuring the product performs as expected [9].

Field Testing: Once lab testing confirms the device’s reliability, it is deployed in real-world livestock settings. Field testing in Inner Mongolia ensures that the product performs consistently under local environmental conditions, such as variable temperatures, dust, and humidity. User feedback is gathered from herders and ranch workers to fine-tune the product’s usability [15].

3.3. Manufacturing Scale-up

Production Process: After successful validation, the focus shifts to scaling up production. The manufacturing process is designed to ensure consistency in the production of large volumes of DON detection product units while maintaining the product’s low cost. Automated production techniques, such as mass printing of paper substrates and reagent application, are employed to meet market demand efficiently [5].

Quality Control: During the manufacturing process, strict quality control measures are implemented to ensure that every DON detection product meets the required sensitivity, specificity, and durability standards. Each batch is rigorously tested before distribution [12].

3.4. Distribution and Herder Training

Supply Chain Development: Distribution networks are established to ensure that the DON detection product reaches even the most remote grassland areas of Inner Mongolia. Partnerships with local ranch cooperatives and suppliers help facilitate smooth delivery [6].

Training Programs: Comprehensive training programs are developed to educate herders and ranch workers on how to use the DON detection product effectively. Training materials include pictorial guides, instructional videos, and in-person workshops where possible. These programs ensure that users understand how to interpret test results and take appropriate actions based on the data.

3.5. Market Introduction and Support

Market Rollout: The initial introduction of the DON detection product into the market is accompanied by marketing campaigns aimed at raising awareness of the product’s benefits, particularly its ability to reduce DON contamination and improve livestock health [7].

Customer Support: A support infrastructure is established to handle inquiries, provide technical assistance, and manage feedback from users. This ensures that any issues encountered by herders during the device’s early adoption are resolved quickly and efficiently [11].

Through this comprehensive implementation process, the DON detection product is poised to become an essential tool for managing DON contamination in Inner Mongolia’s livestock sector. Its combination of affordability, sensitivity, and ease of use ensures that it will have a lasting impact on feed safety and productivity in the region [14].

4. Benefit Analysis

4.1. Qualitative Benefit Analysis

The development and deployment of the DON detection product in Inner Mongolia's livestock industry offer numerous benefits to herders, livestock industry, economics, environments and society. Key benefits include:

4.1.1. Improved Livestock Health and Productivity

Early detection of DON contamination in feed prevents livestock from ingesting harmful DON. This leads to healthier animals with better growth rates, reduced mortality, and fewer veterinary interventions, contributing to overall farm productivity [8].

4.1.2. Economic Stability

Herders can avoid financial losses due to reduced livestock productivity, wasteful feed utilization, and costly veterinary treatments. Early detection and intervention save herders significant expenses, enhancing the region's economic resilience [9].

4.1.3. Increased Quality and Safety of Livestock Product

By ensuring that DON-contaminated feed does not enter the feed chain, Herders can produce safer animal products like milk, meat, and eggs, which increases consumer trust and ensures compliance with food safety regulations [14].

4.1.4. Empowerment of Local Herders

The DON detection product is portable, affordable, and easy to use, allowing small and medium-sized Herders to independently monitor feed quality and make informed decisions without relying on costly laboratory testing [5].

4.1.5. Environmental Benefits

Early detection of contaminated feed reduces waste and helps herders practice environmentally friendly livestock. The paper-based nature of the DON detection product also aligns with sustainable stockbreeding goals by reducing reliance on non-biodegradable materials [6].

4.1.6. Strengthened Livestock Industry

By improving livestock health and productivity, the DON detection product contributes to a stronger and more competitive livestock industry in Inner Mongolia, enhancing the region's market position both domestically and internationally [12].

4.2. Cost-Benefit Model

The DON detection product is an innovative, paper-based microfluidic device designed for rapid and affordable detection of DON, a mycotoxin commonly found in cereal crops like wheat and corn. In Inner Mongolia's grasslands, DON contamination poses significant risks to livestock health and productivity. This economic model evaluates the cost-benefit of implementing the DON detection product in a typical Inner Mongolian rangeland [8].

4.2.1. Key Variables and Parameters

1) Ranch Profile

- Number of Animals: 1,000 (e.g., cattle:500 sheep:500)
- Annual Revenue per Animal: $450（Cattle:$750, Sheep:$150）
- Total Annual Revenue: $450,000

2) Impact of DON Contamination

- Contamination Rate: 88.7% (based on Li et al., 2018) [14]
- Productivity Loss Without Intervention: 10% of total revenue ($45,000)
- Health Effects on Livestock: Reduced feed intake, lower weight gain, immune suppression, increased veterinary costs

3) Testing Costs and Effectiveness

- Traditional Laboratory Testing
    - Cost per Test: $30
    - Number of Tests per Year: 50
    - Total Annual Testing Cost: $1,500
    - Prevention Effectiveness: 20% reduction in DON-related losses [5]
- DON-Chip Testing
    - Cost per Test: $2
    - Number of Tests per Year: 50
    - Total Annual Testing Cost: $100
    - Prevention Effectiveness: 80% reduction in DON-related losses

4.2.2. Economic Calculations

1) Losses Due to DON Contamination Without Testing

- Annual Loss: 10% of $450,000 = $45,000

2) Savings from Implementing DON-Chip Testing

- Prevented Losses: 80% of $45,000 = $36,000
- Net Savings: $36,000 (prevented losses) - $100 (testing cost) = $35,900

3) Savings from Traditional Testing

- Prevented Losses: 20% of $45,000 = $9,000
- Net Savings: $9,000 (prevented losses) - $1,500 (testing cost) = $7,500

4) Additional Benefits of DON-Chip Testing

- Reduced Veterinary Costs: Estimated annual savings of $3,000 due to healthier livestock
- Improved Livestock Market Value: 2% increase in revenue from better animal health = $9,000
- Total Additional Benefits: $3,000 + $9,000 = $12,000
- Total Net Benefit with DON-Chip: $35,900 (net savings) + $12,000 (additional benefits) = $47,900

4.2.3. Summary

Implementing the DON detection product for regular DON detection offers significant economic advantages for livestock farms in Inner Mongolia:

- Substantial Net Savings: Approximately $47,900 annually compared to $7,500 with traditional testing methods.
- High Prevention Effectiveness: 80% reduction in DON-related productivity losses due to frequent and timely testing.
- Low Testing Costs: Only $100 annually for DON-Chip testing versus $1,500 for traditional methods.
- Additional Economic Benefits: Reduced veterinary expenses and increased market value of livestock contribute an extra $12,000 in savings.

The affordability and immediacy of the DON detection product enable herders to conduct frequent on-site testing, facilitating early detection and intervention. This proactive approach minimizes the adverse effects of DON contamination on animal health and livestock profitability.

4.2.4. Recommendations

1) Adoption of DON detection product Testing.

Herders should integrate regular DON detection product testing into their management practices to maximize economic benefits and enhance livestock health.

2) Education and Training.

Provide training programs for herders and ranch workers on using the DON detection product effectively and interpreting results accurately.

3) Government Support.

Policymakers should consider offering subsidies or incentives to encourage widespread adoption of the DON detection product, promoting food safety and economic stability.

4) Integration with Other Management Strategies.

Combine DON detection product testing with additional mycotoxin management practices, such as crop rotation and proper feed storage, for comprehensive risk mitigation.

4.2.5. Limitations

1) Assumptions: The model is based on average values and may vary with different ranch sizes, animal species, and market conditions.

2) Other Mycotoxins: The presence of additional mycotoxins may require broader testing strategies.

3) Market Fluctuations: Changes in livestock market prices can impact the overall economic outcomes.

In conclusion, the economic model demonstrates that the DON detection product is a cost-effective tool for improving the profitability and sustainability of livestock ranches in Inner Mongolia. By significantly reducing losses due to DON contamination and enhancing animal health, the DON detection product contributes to the economic well-being of herders and supports the broader livestock industry in the region. Its low cost and high effectiveness make it a valuable investment, offering substantial returns in terms of both financial savings and improved livestock productivity.

4.3. Extended Cost-Benefit Model Analysis

4.3.1. Extended cost-benefit model for the whole feed lifecycle

Extending upon the initial model, the cost-benefit model of the DON detection product is applied to all stages of the feed supply chain: growing, harvesting, processing, storage, transportation, and feeding. Implementing the DON detection product at each stage allows for early detection of DON contamination, significantly enhancing prevention measures [8].

- Comprehensive Testing: Conducting tests at all six stages increases the total annual tests to 75 (apportion to each ranch 5 tests/per stage of 1-5).

- Affordable Testing Costs: At $2 per test, the total annual cost for DON dection testing is $150.
- High Prevention Effectiveness: Early and frequent testing leads to a 95% reduction in DON-related losses.
- Significant Net Savings: Preventing 95% of the potential $45,000 annual loss results in $42,750 saved. Subtracting the $150 testing cost yields a net annual saving of $42,600.
- Additional Benefits: Improved feed quality enhances livestock health and productivity, potentially increasing revenue by an additional $12,000 through reduced veterinary costs and better market prices.

Implementing the DON detection product throughout the entire feed supply chain maximizes economic benefits by substantially reducing DON contamination losses. The minimal testing costs and high effectiveness in prevention lead to significant net savings and improved overall profitability for livestock ranches in Inner Mongolia.

4.3.2. Extended cost-benefit model for the whole Inner Mongolia regions

This model evaluates the economic impact of deploying the DON detection product throughout Inner Mongolia region. By integrating the DON detection product across all stages of the feed supply chain, the region can effectively mitigate the economic losses of DON contamination.

- Regional Livestock Profile: Inner Mongolia hosts approximately 80 million livestock animals, mainly sheep and cattle, with an average annual revenue of $450 per animal, totaling $36 billion.
- Potential Losses Due to DON Contamination: Without intervention, a 10% productivity loss could result in annual losses of $3.6 billion.
- DON Detection Product Implementation:
  - Comprehensive Testing: Conducting three tests per animal annually across cultivation, harvesting, processing, storage, transportation, and feeding stages.
  - Affordable Testing Costs: At $2 per test, total annual testing costs amount to $120 million.
- Economic Benefits:
  - High Prevention Effectiveness: Achieving a 95% reduction in DON-related losses saves $1.8 billion annually.
  - Net Savings: Subtracting testing costs from prevented losses yields a net annual saving of $1.68 billion.
  - Additional Gains: Improved livestock health and productivity contribute an extra $1.2 billion through reduced veterinary costs and enhanced market opportunities.
  - Total Net Benefit: The region stands to gain approximately $2.88 billion annually.

Implementing the DON detection product across the Inner Mongolia region offers substantial economic advantages, significantly reducing losses due to DON contamination and boosting the overall profitability of the livestock industry. The minimal testing costs combined with high prevention effectiveness underscore the value of widespread adoption, promoting sustainability and economic growth in the region.

5. Discussion

5.1. Opportunities

The success of paper-based microfluidic technology applied to DON detection from solution to a viable product, will bring lots of opportunities in the related area:

5.1.1. Opportunity for Expansion

By expanding the DON detection product to detect multiple mycotoxins, the platform could provide even greater value to herders and the broader livestock sector, addressing a wider range of contamination risks and ensuring broader feed safety.

5.1.2. Integration with Digital Solutions

There is an opportunity to connect the DON detection product with mobile devices or other digital platforms for real-time data logging and trend analysis, enhancing decision-making and providing long-term monitoring benefits.

5.1.3. Connection with AI and Big Data

DON detection product is put into operation, so that the livestock feed safety data of each grassland pasture can be collected and analyzed, and the artificial intelligence big data connecting the environment, ecology, animal husbandry, and government regulation will release more social value of the product.

5.2. Challenges

Despite the promising benefits of the DON detection product, there are challenges to its widespread adoption:

5.2.1. Technical Challenges

Adapting the DON detection product to handle diverse and complex feed samples remains a hurdle. The device must be robust enough to deliver accurate results in varying environmental conditions, including temperature and humidity fluctuations typical of Inner Mongolia.

5.2.2. Herder Education and Training

Ensuring that herders and ranch workers are trained to use the product effectively is essential for its success. There may be barriers in terms of technology acceptance and the need for user-friendly training materials.

5.2.3. Market Adoption

The initial cost of deployment and convincing herders of the economic benefits may require government support and incentive programs to accelerate adoption rates.

5.3. Future directions

To ensure the long-term sustainability and impact of the DON detection product, future developments must focus on several key directions:

5.3.1. Multi-Mycotoxin Detection

Expanding the DON detection product to detect a broader range of mycotoxins will enhance its utility in Inner Mongolia and beyond, providing comprehensive feed safety solutions.

5.3.2. Digital Integration

Incorporating digital features such as smartphone connectivity for real-time data analysis can improve ease of use, making the product more accessible and scalable across various livestock operations.

5.3.3. Sustainability

The paper-based nature of the DON detection product supports environmentally friendly practices. The sustainable sensing technology with paper microfluidic could be also applied to applications in health, environment and food safety. Further reducing plastic use in production and ensuring the product is recyclable will align with global sustainability goals.

5.3.4. Global Applications

Beyond Inner Mongolia, the DON detection product can be adapted for use in other regions facing similar mycotoxin contamination challenges, promoting sustainable livestock practices worldwide.

6. Conclusion

The commercialization of the DON detection product represents a groundbreaking advancement in the detection and management of Deoxynivalenol (DON) contamination in Inner Mongolia's grasslands livestock industries. As a paper-based microfluidic technology product, the DON detection product addresses critical concerns related to feed safety, livestock health, and agricultural economic stability. Its affordability, ease of use, and rapid testing capabilities enable herders to detect and prevent mycotoxin contamination effectively, minimizing losses in livestock productivity and safeguarding feed safety.

The implementation of the DON detection product across the entire feed supply chain—from cultivation, to storage, to feeding—promises substantial economic benefits. The technology could prevent significant financial losses by enhancing early detection of contamination, reducing veterinary costs, and improving the overall productivity of livestock in the region. Furthermore, the adoption of the DON detection product aligns with sustainability goals, promoting environmentally friendly practices by reducing waste and providing a cost-effective testing solution.

In summary, the DON detection product has the potential to revolutionize feed safety management in Inner Mongolia, thereby contributing to a more resilient agricultural economy and enhanced livestock health. However, continued product R&D, education, propagation and strategic support will be crucial in realizing its full potential across the region and beyond.

References

[1] Jiang, Q., Wu, J., Yao, K., Yin, Y., Gong, M. M., Yang, C., & Lin, F. (2019). based microfluidic device (DON-Chip) for rapid and low-cost deoxynivalenol quantification in food, feed, and feed ingredients. ACS sensors, 4(11), 3072-3079. https://doi.org/10.1021/acssensors.9b01895

[2] Kumar, S., Kaushal, J. B., & Lee, H. P. (2024). Sustainable Sensing with Paper Microfluidics: Applications in Health, Environment, and Food Safety. Biosensors, 14(6), 300. https://doi.org/10.3390/ bios14060300

[3] Dsm-firmenich, World Mycotoxin Survey, The Global Threat, January - December 2023

[4] Ma, R., Zhang, L., Liu, M., Su, Y.T., Xie, W.M., Zhang, N.Y. "Individual and Combined Occurrence of Mycotoxins in Feed Ingredients and Complete Feeds in China." Toxins 10, no. 3 (2018). https://www.mdpi.com/2072-6651/10/3/113.

[5] Guan, Y., Lv, H., Wu, G., Chen, J., Wang, M., Zhang, M. "Effects of Lactic Acid Bacteria Reducing the Content of Harmful Fungi and Mycotoxins on the Quality of Mixed Fermented Feed." Toxins 15, no. 3 (2023). https://www.mdpi.com/2072-6651/15/3/226.

[6] Awad, W. A., Ghareeb, K., Böhm, J., and Zentek, J. "The Impact of Deoxynivalenol on Health and Performance of Broiler Chickens and Pigs." Animal Feed Science and Technology 132, no. 1-2 (2006): 1-25.

[7] Waché, Y., Valat, C., Postollec, G., Bougeard, S., and Soumet, C. "Effect of Mycotoxin Contamination on Digestive Health and Microflora in Pigs." Journal of Animal Science 90, (2008): 99-108.

[8] Zhao, L., Zhang, L., Xu, Z., Liu, X., Chen, L., Dai, J. "Occurrence of Aflatoxin B1, Deoxynivalenol, and Zearalenone in Feeds in China during 2018–2020." Journal of Animal Science (2021). https://link.springer.com/article/10.1186/s40104-021-00603-0.

[9] Ma, Y., Wang, H., and Li, C. "Response of Sheep Rumen Fermentation and Microbial Communities to Feed Infected with the Endophyte Epichloë Gansuensis." Journal of Microbiology (2021). https://link.springer.com/article/10.1007/s12275-021-1113-9.

[10] Jalilzadeh-Amin, G., Dalir-Naghadeh, B., et al. "Prevalence and Concentration of Mycotoxins in Animal Feed in the Middle East and North Africa (MENA): A Systematic Review and Meta-

Analysis." Toxins 15, no. 3 (2023). https://www.mdpi.com/2072-6651/15/3/214.

[11] Zhao, X., Degen, A., Hao, L., and Liu, S. "Ruminant Lick Blocks, Particularly in China: A Review." Sustainability 14, no. 13 (2022). https://www.mdpi.com/2071-1050/14/13/7620.

[12] Shi, H., Li, S., Bai, Y., Prates, L.L., Lei, Y., and Yu, P. "Mycotoxin Contamination of Food and Feed in China: Occurrence, Detection Techniques, Toxicological Effects and Advances in Mitigation Technologies." Food Control (2018). https://www.sciencedirect.com/science/article/pii/S0956713518301439.

[13] Hao, W., Guan, S., Li, A., Wang, J., An, G., and Hofstetter, U. "Mycotoxin Occurrence in Feeds and Raw Materials in China: A Five-Year Investigation." Toxins (2023). https://www.mdpi.com/2072-6651/15/1/63.

[14] Ning, X., Du, R., Ye, Y., Ji, J., Jin, S., Li, J., and Liu, T. "Eco-Friendly One-Step Egg White Gel Preparation for Sensitive Detection of 13 Trichothecenes in Oats Using UHPLC-MS/MS." Analytical and Bioanalytical Chemistry (2024). https://link.springer.com/article/10.1007/s00216-024-05438-y.

[15] Wu, L., Li, J., Li, Y., Tang, Y., and Liu, H. "Aflatoxin B1, Zearalenone and Deoxynivalenol in Feed Ingredients and Complete Feed from Different Provinces in China." Journal of Animal Science (2016). https://link.springer.com/article/10.1186/s40104-016-0122-8.