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Impact of Agricultural Practices on Wheat Food Safety

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Abstract This study explores the impact of pre- and post-harvest agricultural practices on wheat food safety, focusing on pesticide residues, heavy metal contamination from fertilizers, irrigation water quality, and fungal mycotoxins. A detailed case study highlights pesticide residue levels in a high-production region, analyzing contributing factors, detection methods, and mitigation strategies. Additionally, the role of sustainable approaches such as precision agriculture, biofertilizers, biopesticides, and genetic improvements in enhancing food safety is discussed. Regulatory frameworks and global standards are examined to evaluate existing policies and their effectiveness. The findings underscore the need for balancing productivity with safety, addressing challenges such as climate change, and adopting emerging technologies for contaminant detection and management. This study emphasizes practical recommendations and future research priorities to ensure safer wheat production practices and safeguard public health.
Keywords Wheat food safety; Agricultural practices; Pesticide residues; Heavy metals; Sustainable solutions

1 Introduction

Wheat is a fundamental staple food worldwide, ranking as the third most-produced cereal after maize and rice. It serves as an inexpensive source of calories and protein, making it a crucial component of the global diet (Bibi and Ilyas, 2020). The importance of wheat is underscored by its role in food security, particularly in regions like India, where it is a major food crop (Gahlot et al., 2020). As the global population continues to rise, the demand for wheat is expected to increase, necessitating sustainable production practices to meet future needs (Ma and Cai, 2024).

Ensuring food safety in wheat production is vital due to the potential negative impacts of conventional agricultural practices. The excessive use of chemical fertilizers, pesticides, and herbicides can lead to soil degradation, water pollution, and the accumulation of harmful substances in wheat, compromising its nutritional value and safety (Bibi and Ilyas, 2020). Moreover, agricultural pollution poses significant threats to human health and the environment, highlighting the need for eco-friendly and sustainable farming practices. The adoption of improved wheat varieties and sustainable agricultural practices can enhance food security and safety, as demonstrated in studies focusing on Ethiopia and other regions (Shiferaw et al., 2014; Rebouh et al., 2023).

This study attempts to explore the impact of various agricultural practices on the safety of wheat as a food product, discuss how management strategies such as conservation tillage, eco-friendly practices, and the use of improved wheat varieties influence wheat performance, microbial communities, and overall food safety, and provide an overview of sustainable methods that can enhance wheat production while ensuring its safety for consumption.

2 Agricultural Practices Influencing Wheat Food Safety

2.1 Pesticide use and residue accumulation

Pesticide use in wheat farming is a common practice aimed at controlling pests and diseases to ensure high yields. However, the accumulation of pesticide residues in wheat grains poses significant food safety concerns. The adoption of eco-friendly agricultural practices, such as biological crop protection and the integration of resistant wheat varieties, can help mitigate these risks by reducing the reliance on chemical pesticides (Rebouh et al., 2023). These practices not only contribute to sustainable wheat production but also enhance food safety by minimizing pesticide residues.

2.2 Fertilizer application and heavy metal contamination

The application of chemical fertilizers is crucial for enhancing wheat yield, but it can lead to heavy metal contamination in the soil and wheat grains. Studies have shown that nitrogen fertilizers, while beneficial for wheat growth, can contribute to environmental pollution if not managed properly (Gahlot et al., 2020). Conservation agriculture practices, which include reduced fertilizer application and the use of organic amendments, can help mitigate heavy metal accumulation in wheat, thereby improving food safety (Romano et al., 2023).

2.3 Irrigation water quality

Irrigation is essential for wheat production, especially in regions with limited rainfall. However, the quality of irrigation water can significantly impact wheat food safety. Contaminated water sources can introduce harmful pathogens and pollutants into the wheat crop. Sustainable irrigation practices, such as the use of clean water sources and efficient water management systems, are vital for maintaining wheat food safety (Gahlot et al., 2020). These practices ensure that the water used does not compromise the quality and safety of the wheat produced.

2.4 Fungal contamination and mycotoxins

Fungal contamination in wheat can lead to the production of mycotoxins, which are toxic compounds that pose serious health risks to consumers. The adoption of eco-friendly agricultural practices, such as crop rotation and the use of resistant wheat varieties, can reduce the incidence of fungal infections in wheat crops (Romano et al., 2023). Additionally, conservation tillage practices have been shown to influence the microbial communities associated with wheat, potentially reducing the prevalence of harmful fungi (Gahlot et al., 2020). These strategies are crucial for minimizing mycotoxin contamination and ensuring the safety of wheat products.

In summary, the implementation of sustainable agricultural practices is essential for enhancing wheat food safety. By reducing pesticide residues, managing fertilizer application, ensuring irrigation water quality, and controlling fungal contamination, these practices contribute to the production of safe and healthy wheat.

3 Post-Harvest Practices and Their Role in Wheat Food Safety

3.1 Storage methods and fungal toxin proliferation

Storage methods play a critical role in the proliferation of fungal toxins in wheat. The presence of mycotoxigenic fungi such as *Fusarium*, *Aspergillus*, and *Penicillium* in stored grains can lead to the production of harmful mycotoxins like deoxynivalenol (DON) and ochratoxin (Magan et al., 2003; Leslie et al., 2021; Deligeorgakis et al., 2023). Environmental factors such as temperature and humidity significantly influence fungal growth and mycotoxin production. For instance, high humidity and temperatures can exacerbate the growth of *Fusarium* species and increase DON levels (Zhang et al., 2019). Storage conditions, such as hermetic versus conventional systems, also impact fungal incidence, with hermetic storage potentially reducing fungal growth compared to conventional methods (Scariot et al., 2018). Effective storage strategies, including maintaining low temperature and humidity, are essential to minimize mycotoxin contamination and ensure wheat food safety.

3.2 Impact of processing techniques on contaminant reduction

Processing techniques are vital in reducing contaminants in wheat. Cleaning, sorting, and drying are key post-harvest processes that help in reducing fungal contamination and mycotoxin levels (Leslie et al., 2021). These processes can remove a significant portion of the contaminated grains, thereby lowering the overall mycotoxin content. Additionally, certain end-product processing methods, such as milling and baking, can further reduce mycotoxin levels in wheat products. However, the effectiveness of these techniques can vary depending on the type of mycotoxin and the processing conditions. For example, while some mycotoxins may be reduced during baking, others might persist, necessitating comprehensive quality control measures throughout the processing chain (Deligeorgakis et al., 2023).

3.3 Quality control and safety testing along the supply chain

Quality control and safety testing are crucial components of ensuring wheat food safety along the supply chain. Regular monitoring of mycotoxin levels using advanced analytical techniques like HPLC-MS/MS is essential to ensure compliance with safety standards (Deligeorgakis et al., 2023). Implementing rigorous quality control measures at various stages, from storage to processing, helps in early detection and management of contamination risks. Safety testing not only involves checking for mycotoxins but also assessing the overall microbial community in stored grains, as shifts in microbial composition can indicate potential contamination issues. By maintaining stringent quality control protocols, the wheat supply chain can effectively manage and mitigate the risks associated with fungal toxins, ensuring the safety of wheat products for consumers (Scariot et al., 2018; Solanki et al., 2019).

In summary, post-harvest practices such as effective storage methods, processing techniques, and robust quality control measures are integral to managing fungal toxin proliferation and ensuring wheat food safety. These practices help in minimizing contamination risks and maintaining the quality of wheat products throughout the supply chain.

4 Case Study: Pesticide Residue Levels in Wheat in a High-Production Region

4.1 Background and rationale of the selected region

The selected region for this case study is the suburbs of Beijing, China, a high-production area for wheat. This region was chosen due to its intensive agricultural practices and the significant presence of pesticide residues in wheat fields, which pose potential risks to human health and the environment. The area is characterized by the frequent use of various pesticides, including carbendazim and tebuconazole, which have been detected at high levels in wheat samples (Tao et al., 2021). The rationale for selecting this region is to understand the impact of these agricultural practices on food safety and to develop strategies for mitigating pesticide residue levels in wheat.

4.2 Agricultural practices leading to pesticide residue buildup

In the Beijing suburbs, the co-occurrence of multiple pesticides in wheat fields is a common practice to protect crops from pests and diseases. However, this has led to the buildup of pesticide residues in both soil and wheat samples. The frequent detection of carbendazim, triazoles, and neonicotinoids in soil samples indicates a persistent use of these chemicals (Tao et al., 2021). Additionally, the application methods, such as foliar spray, significantly influence the uptake and translocation of pesticides in wheat, contributing to residue buildup (Fantke et al., 2011). The intensive use of pesticides without adequate management practices exacerbates the accumulation of residues in the environment and food products.

4.3 Detection methods and threshold exceedances in wheat samples

The detection of pesticide residues in wheat samples from the selected region is primarily conducted using advanced analytical techniques such as gas chromatography-mass spectrometry (GC/MS) and ultra-performance liquid chromatography-tandem mass spectrometry (UPLC-MS/MS) (Rezaei et al., 2017; Ding et al., 2023). These methods allow for the simultaneous determination of multiple pesticide residues and provide accurate quantification of their levels in wheat. In the Beijing region, certain pesticides, such as carbendazim and tebuconazole, have been found to exceed the maximum residue limits (MRLs), although they do not pose non-carcinogenic risks with one exception (Tao et al., 2021). The detection of residues above MRLs necessitates regular monitoring and stricter regulation to ensure food safety.

4.4 Mitigation strategies and recommendations for safer production

To mitigate pesticide residue levels in wheat and ensure safer production, several strategies can be implemented. First, optimizing pesticide application methods, such as using unmanned aerial vehicles (UAVs) and mister sprayers, can enhance control efficacy and reduce residue levels (Xiao et al., 2020). Second, adopting integrated pest management (IPM) practices can minimize the reliance on chemical pesticides and promote the use of alternative pest control methods (Figure 1) (Zhang et al., 2015). Third, implementing regular monitoring and risk assessment programs can help identify and manage potential risks associated with pesticide residues (Dalvie and London, 2009). Lastly, educating farmers on the safe and effective use of pesticides and promoting sustainable agricultural practices are crucial for reducing pesticide residues and protecting public health (Carvalho et al., 2017).

In summary, the case study of pesticide residue levels in wheat in the Beijing suburbs highlights the need for improved agricultural practices and monitoring to ensure food safety. By adopting advanced application methods, integrated pest management, and regular monitoring, the region can reduce pesticide residues and promote safer wheat production.

Figure 1 Average annual pesticide use intensity (kg ha^{-1} yr^{-1}), on arable and permanent cropland from 2005 to 2009 (Adopted from Zhang et al., 2015)

5 Technological and Sustainable Approaches for Improving Wheat Food Safety

5.1 Adoption of precision agriculture for pesticide and fertilizer management

Precision agriculture offers a sustainable approach to managing pesticides and fertilizers by tailoring applications to the specific needs of different field areas. This method reduces the environmental impact of excessive chemical use and enhances crop yield stability. For instance, precision nitrogen management in wheat has been shown to improve nitrogen use efficiency significantly, reducing the need for fertilizers by up to 80% without compromising yield or grain quality (Diacono et al., 2012). Additionally, precision agriculture systems have demonstrated the ability to reduce temporal yield variation, contributing to greater resilience against climate variability (Yost et al., 2017).

5.2 Use of biofertilizers and biopesticides as safe alternatives

Biofertilizers and biopesticides present eco-friendly alternatives to chemical fertilizers and pesticides, promoting sustainable agriculture. These biological inputs enhance soil fertility and plant health while minimizing environmental contamination. Studies have shown that biofertilizers can increase wheat growth and nitrogen accumulation, although the impact on grain yield may be modest (Cortivo et al., 2020). The use of microbial consortia as biofertilizers and biopesticides has been highlighted as a cost-effective and sustainable method to improve crop yields and maintain soil health (Seenivasagan and Babalola, 2021).

5.3 Role of genetic improvement in enhancing wheat resilience to pests and diseases

Genetic improvement through advanced technologies such as genome editing can significantly enhance wheat's resilience to pests and diseases. This approach addresses the challenges posed by climate change and the need for sustainable food production. Genome editing technologies, along with other molecular breeding strategies, facilitate the development of wheat cultivars with improved resistance to biotic and abiotic stresses (Figure 2) (Li et al., 2021). The integration of genetic improvements with management innovations can lead to more resilient wheat production systems, capable of thriving under diverse environmental conditions (Beres et al., 2020). Adopting precision agriculture, utilizing biofertilizers and biopesticides, and leveraging genetic improvements are key strategies for enhancing wheat food safety. These approaches not only improve yield and resilience but also contribute to environmental sustainability by reducing reliance on chemical inputs.

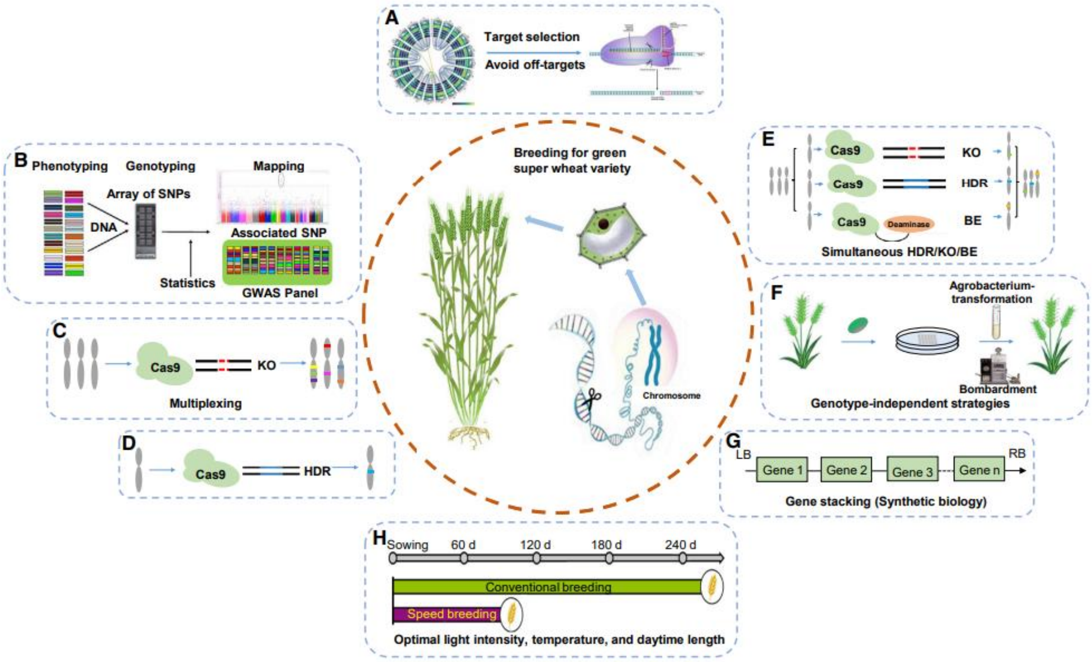

Figure 2 Breeding of a green super wheat variety through CRISPR/Cas-mediated gene editing and other breeding technologies (Adopted from Li et al., 2021)

Image caption: (A) Genome sequencing. Wheat genome and pan-genome sequencing provide basic information for designing an sgRNA target and the evaluation of offtarget effects in wheat genome editing. (B) GWAS analysis. GWAS enables the association of specific genes, SNPs, or markers on a chromosome with a specific trait. (C) A CRISPR/Cas-mediated multiplex system for multiple gene knockouts (KOs). (D) CRISPR/Cas-mediated HDR remains to be investigated as a means to improve HDR efficiency in wheat. (E) Development of a module for simultaneous HDR and/or base editing (BE) and knockout would greatly facilitate the translational breeding process for pyramiding favorable alleles in an elite wheat variety in a shorter time. (F) Development of diverse genotype-independent strategies. Genotype-independent strategies enable transformation of recalcitrant wheat varieties, thus facilitating the use of genome editing in diverse elite wheat germplasm. (G) Gene stacking by synthetic biology. Synthetic biology enables the accumulation of multiple transgenes of interest in the same plant genome to stack beneficial traits or generate a novel trait. (H) Speed breeding. Speed breeding enables a shortened generation time for seed harvesting in wheat. KO, knockout; BE, base editing; HDR, homologydirected repair (Adopted from Li et al., 2021)

6 Regulatory Framework and Global Standards for Wheat Food Safety

6.1 International standards and guidelines

The codex alimentarius commission, established by the food and agriculture organization (FAO) and the world health organization (WHO), plays a pivotal role in setting international food safety standards. Since its inception in 1963, the Commission has developed numerous standards, guidelines, and codes of practice to enhance food safety and nutrition globally. These standards cover a wide range of topics, including biotechnology, pesticides, pathogens, additives, and contaminants, and are designed to protect consumer health and ensure fair trade practices. The codex standards are recognized as international benchmarks, particularly following the world trade organization's (WTO) agreement on the application of sanitary and phytosanitary measures, which encourages member countries to harmonize their national regulations with codex standards (Tritscher et al., 2013; Wearne et al., 2024).

6.2 National policies on pesticide residue limits and heavy metals

National policies on pesticide residue limits are often aligned with the codex alimentarius standards, which are based on evaluations by the Joint FAO/WHO meeting on pesticide residues (JMPR). The codex committee on pesticide residues develops maximum residue limits (MRLs) to ensure consumer safety and facilitate international trade (Ambrus and Yang, 2016). These MRLs are crucial for maintaining food safety and are harmonized internationally to prevent trade barriers. However, the implementation and enforcement of these limits can vary by country, reflecting different national priorities and capacities.

6.3 Role of monitoring agencies in ensuring compliance

Monitoring agencies play a critical role in ensuring compliance with food safety standards. These agencies are responsible for the surveillance and enforcement of regulations related to pesticide residues and contaminants in food products. They work to ensure that food products meet both national and international safety standards, thereby protecting consumer health and facilitating fair trade practices (Halabi and Lin, 2017). The effectiveness of these agencies is crucial for the successful implementation of food safety standards, as they provide the necessary oversight and enforcement to maintain compliance.

In summary, the regulatory framework for wheat food safety is underpinned by international standards set by the codex alimentarius, which guide national policies on pesticide residues and heavy metals. Monitoring agencies are essential in ensuring compliance with these standards, thereby safeguarding consumer health and supporting global trade.

7 Challenges and Future Directions

7.1 Balancing productivity and food safety concerns

Balancing the need for high productivity with food safety concerns in wheat production is a significant challenge. The use of agrochemicals to boost yield can lead to contamination, affecting food safety. Emerging technologies, such as bioinoculants, offer a promising solution by enhancing nutrient uptake and soil fertility while reducing reliance on chemical inputs (Campos-Avelar et al., 2023). These technologies can help maintain productivity without compromising food safety, but require further research to optimize their application and effectiveness.

7.2 Climate change and its impact on food safety risks in wheat production

Climate change poses a substantial threat to wheat production, influencing both productivity and food safety. Rising temperatures and erratic weather patterns can exacerbate pest and disease pressures, leading to increased use of pesticides, which may compromise food safety (Bajwa et al., 2020; Miedaner and Juroszek, 2021). Additionally, climate change can alter the growth stages of wheat, potentially affecting the timing and effectiveness of pest management strategies (Valizadeh et al., 2014). Adaptation strategies, such as modifying sowing times and developing climate-resilient wheat varieties, are crucial to mitigate these risks (Singh et al., 2019; Habib-Ur-Rahman et al., 2022).

7.3 Emerging technologies for contaminant detection and mitigation

Emerging technologies play a critical role in detecting and mitigating contaminants in wheat production. The development of next-generation microbial inoculants can help combat phytopathogens, reducing the need for chemical pesticides and enhancing food safety (Campos-Avelar et al., 2023). Additionally, integrated pest management approaches that incorporate predictive modeling and early detection systems can improve pest control under changing climatic conditions, thereby reducing the risk of contamination (Bajwa et al., 2020). These technologies require ongoing research and development to ensure their efficacy and sustainability in diverse agricultural settings.

In summary, addressing the challenges of balancing productivity with food safety, adapting to climate change, and leveraging emerging technologies are essential for the future of safe and sustainable wheat production. These efforts will require coordinated research and innovation to develop effective strategies that ensure both high yields and food safety.

8 Concluding Remarks

The impact of agricultural practices on wheat food safety is multifaceted, involving pest control, soil health, and crop management. Intercropping systems have been shown to reduce pest abundance, offering a viable alternative to insecticides, although they do not significantly increase the presence of natural enemies. Conservation tillage practices, such as no-tillage, have been linked to improved microbial activity and wheat performance, highlighting the importance of sustainable practices in maintaining wheat production. The use of mineral fertilizers has been found to reduce phenolic compounds in wheat, increasing susceptibility to diseases, whereas organic inputs like composted FYM can mitigate these effects. Additionally, integrated nutrient management using Safe Rock®

Minerals has demonstrated improvements in wheat yield and quality, suggesting a sustainable approach to enhance soil fertility and plant health.

To enhance wheat food safety, it is recommended to adopt conservation agriculture practices, such as reduced or no-tillage, which have been shown to improve soil health and reduce pest pressures. Incorporating intercropping systems can further reduce reliance on chemical insecticides, promoting a more balanced ecosystem. The use of organic fertilizers and integrated nutrient management strategies, such as combining Safe Rock® Minerals with organic manures, can improve soil fertility and crop quality while reducing chemical inputs. Additionally, selecting disease-resistant cultivars and implementing crop rotations can mitigate the impact of pathogens and improve yield stability.

Future research should focus on optimizing intercropping systems to enhance the presence of natural pest enemies and further reduce chemical pesticide use. Investigating the long-term effects of conservation tillage on soil microbiomes and their role in crop health and productivity is crucial for sustainable agriculture. There is also a need to explore the interactions between different agronomic practices and their cumulative effects on wheat quality and safety, particularly in the context of climate change. Finally, developing and testing new disease-resistant wheat varieties that can thrive under diverse environmental conditions and management practices will be essential to ensure food security and safety. In summary, adopting sustainable agricultural practices, such as conservation tillage, intercropping, and integrated nutrient management, can significantly enhance wheat food safety by improving soil health, reducing pest pressures, and increasing crop resilience to diseases. Future research should continue to explore these areas to develop comprehensive strategies for sustainable wheat production.

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Conflict of Interest Disclosure
The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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