

Impact of climate change on post-harvest fungal pathogens: Emerging risks and adaptive strategies

Abdelhak RHOUMA^{1*}

Abstract

Climate change is increasingly recognized as a critical factor influencing post-harvest fungal pathogens, with far-reaching consequences for food security, safety, and global trade. Rising global temperatures, altered precipitation patterns, and increased atmospheric CO₂ levels are reshaping the ecological dynamics of fungal species that infect stored crops. Key mycotoxin-producing fungi, such as *Aspergillus*, *Penicillium*, and *Fusarium*, are particularly sensitive to these changes, with studies indicating shifts in their geographic distribution, virulence, and toxin production. Warmer and more humid conditions accelerate fungal growth and mycotoxin biosynthesis, while extreme weather events disrupt traditional post-harvest drying and storage practices, exacerbating contamination risks. Additionally, climate-induced stress in crops may weaken their natural defenses, making them more susceptible to post-harvest infections. This review synthesizes current knowledge on how climate change influences post-harvest fungal pathogens, highlighting emerging risks such as the spread of thermotolerant strains, increased mycotoxin contamination, and the development of fungicide resistance. Furthermore, we explore adaptive strategies to mitigate these threats, including advancements in storage technologies (e.g., hermetic systems, controlled atmospheres), the application of biocontrol agents (e.g., antagonistic microbes, plant-derived antifungals), and the integration of predictive modeling for early disease detection. By addressing these challenges through multidisciplinary approaches—combining agronomy, microbiology, and climate science—we can develop resilient post-harvest management systems that safeguard food supplies in a warming world

Keywords: Climate change, post-harvest pathogens, fungal diseases, food security, predictive modeling, adaptive strategies

Impact du changement climatique sur les pathogènes fongiques post-récolte : Risques émergents et stratégies d'adaptation

Résumé

Le changement climatique est de plus en plus reconnu comme un facteur critique influençant les pathogènes fongiques post-récolte, avec des conséquences considérables pour la sécurité alimentaire, la salubrité et le commerce mondial. L'augmentation des températures mondiales, la modification des régimes de précipitations et l'élévation des niveaux de CO₂ atmosphérique redessinent la dynamique écologique des espèces fongiques qui infectent les cultures stockées. Les principaux champignons producteurs de mycotoxines, tels qu'*Aspergillus*, *Penicillium* et *Fusarium*, sont particulièrement sensibles à ces changements, des études indiquant des modifications dans leur distribution géographique, leur virulence et leur production de toxines. Des conditions plus chaudes et plus humides accélèrent la croissance fongique et la biosynthèse des mycotoxines, tandis que les événements météorologiques extrêmes perturbent les pratiques traditionnelles de séchage et de stockage post-récolte, exacerbant les risques de contamination.

*Corresponding author

¹ Regional Centre of Agricultural Research of Sidi Bouzid, Gafsa Road Km 6, B.P. 357, 9100 Sidi Bouzid, Tunisia;
e-mail : abdelhak.rhouma@gmail.com; ORCID ID: <https://orcid.org/0000-0001-6074-0076>

De plus, le stress induit par le climat chez les cultures peut affaiblir leurs défenses naturelles, les rendant plus sensibles aux infections post-récolte. Cette synthèse examine les connaissances actuelles sur la manière dont le changement climatique influence les pathogènes fongiques post-récolte, soulignant les risques émergents tels que la propagation de souches thermotolérantes, l'augmentation de la contamination par les mycotoxines et le développement de la résistance aux fongicides. En outre, nous explorons des stratégies d'adaptation pour atténuer ces menaces, y compris les avancées dans les technologies de stockage (par exemple, les systèmes hermétiques, les atmosphères contrôlées), l'application d'agents de biocontrôle (par exemple, les microbes antagonistes, les antifongiques d'origine végétale) et l'intégration de la modélisation prédictive pour la détection précoce des maladies. En relevant ces défis grâce à des approches multidisciplinaires – combinant l'agronomie, la microbiologie et la science du climat – nous pouvons développer des systèmes de gestion post-récolte résilients qui sauvegardent les approvisionnements alimentaires dans un monde qui se réchauffe.

Mots-clés : Changement climatique, pathogènes post-récolte, maladies fongiques, sécurité alimentaire, modélisation prédictive, stratégies d'adaptation

INTRODUCTION

Food security is increasingly threatened by post-harvest losses, with fungal pathogens playing a major role in the spoilage and contamination of stored agricultural commodities. It is estimated that 10–30% of global crop yields are lost post-harvest due to microbial activity, with fungi being the primary culprits (Kovač et al., 2022). Among these, mycotoxigenic genera such as *Aspergillus*, *Penicillium*, and *Fusarium* are of particular concern due to their ability to produce toxic secondary metabolites that pose serious health risks to humans and livestock. Climate change is now exacerbating these challenges by altering the environmental conditions that influence fungal growth, reproduction, and virulence. Rising global temperatures, increased atmospheric CO₂ levels, erratic rainfall patterns, and more frequent extreme weather events are reshaping the ecological niches of post-harvest pathogens, leading to shifts in their geographic distribution, seasonal prevalence, and infection dynamics (Ferrigo et al., 2021; Lončarić et al., 2021; Zhang et al., 2021; Miranda-Apodaca et al., 2023).

Historically, post-harvest fungal control has relied on chemical fungicides, proper drying, and optimized storage conditions. However, climate variability is undermining these traditional methods (Islam et al., 2025). For instance, warmer temperatures accelerate fungal metabolism, increasing spoilage rates, while unseasonal rains disrupt the drying process, leaving crops more susceptible to mold infestations. Additionally, elevated CO₂ levels may alter plant physiology, reducing natural resistance to fungal infections (Zhao et al., 2025). These changes are not only increasing the prevalence of known pathogens but may also facilitate the emergence of new, more aggressive fungal strains adapted to extreme conditions. Furthermore, climate-induced stress on crops can weaken their structural and biochemical defenses, making them more vulnerable to post-harvest infections even if they appear healthy at harvest (Zhao et al., 2025).

The implications of these shifts extend beyond food spoilage, as many post-harvest fungi produce mycotoxins—such as aflatoxins, ochratoxins, and fumonisins—that are carcinogenic, immunosuppressive, and harmful

even at low concentrations (**Wang et al., 2025**). Climate change is expected to increase mycotoxin contamination in key staple crops, posing significant risks to food safety and trade. Developing countries, where post-harvest infrastructure is often inadequate, will likely bear the greatest burden (**Bano et al., 2023**). Addressing these challenges requires a

multidisciplinary approach, integrating advances in microbiology, climate science, and food preservation technologies (**Madhushan et al., 2025**). This review explores the complex interactions between climate change and post-harvest fungal pathogens, evaluates emerging risks, and discusses adaptive strategies to mitigate their impact on global food systems.

CLIMATE CHANGE AND ITS INFLUENCE ON FUNGAL PATHOGENS

1. Temperature effects

Temperature is a critical determinant of fungal growth, reproduction, and metabolic activity, with each species exhibiting distinct thermal optima. Climate change-driven increases in global temperatures are fundamentally altering the dynamics of post-harvest fungal pathogens. Many mycotoxigenic fungi, including *Aspergillus flavus* and *Fusarium verticillioides*, thrive in warmer conditions, with their optimal growth ranges shifting upward as average temperatures rise (**Garcia-Benitez et al., 2020**). Studies indicate that a 2-4°C increase in ambient temperature can significantly accelerate fungal colonization rates in stored grains, reducing safe storage periods by up to 30%. Moreover, elevated temperatures not only enhance fungal proliferation but also stimulate mycotoxin biosynthesis. For instance, aflatoxin production by *A. flavus* peaks at 30-35°C, while *Penicillium verrucosum* (producer of ochratoxin A) shows increased toxicity at sustained temperatures above 25°C (**Peter Mshelia et al., 2020**). These thermal shifts are also facilitating the geographic expansion of traditionally tropical fungi into temperate regions, exposing new agricultural systems to unfamiliar post-harvest threats (**Bano et al., 2023**). Perhaps most concerning is the potential for temperature extremes to select for thermotolerant fungal strains capable of surviving in conditions that would normally inhibit

microbial growth, thereby complicating existing management strategies that rely on ambient drying or temperature-controlled storage (Figure 1) (**Thole et al., 2021**).

2. Humidity and rainfall variability

The interplay between fungal pathogens and moisture is perhaps the most direct consequence of climate change on post-harvest systems. Increased atmospheric humidity and erratic rainfall patterns are creating ideal conditions for fungal spore germination and hyphal growth during critical post-harvest stages (**Tchouandem Nzali et al., 2024**). Many destructive species, such as *Aspergillus ochraceus* and *Fusarium graminearum*, require water activity (a_w) levels above 0.85 to initiate growth, thresholds that are increasingly met as climate models predict higher baseline humidity in key agricultural regions (**Islam et al., 2025**). The problem is compounded by more frequent extreme rainfall events, which can prevent proper field drying of crops like maize and wheat, leaving them vulnerable to fungal colonization before entering storage (**Sánchez Espinosa et al., 2023**). In developing countries where mechanical drying is scarce, this has led to a 40% increase in post-harvest mold incidence in recent decades (**Fareed Mohamed Wahdan et al., 2020**). Additionally, the alternation between drought and deluge creates unique challenges—drought-stressed crops often develop microcracks that

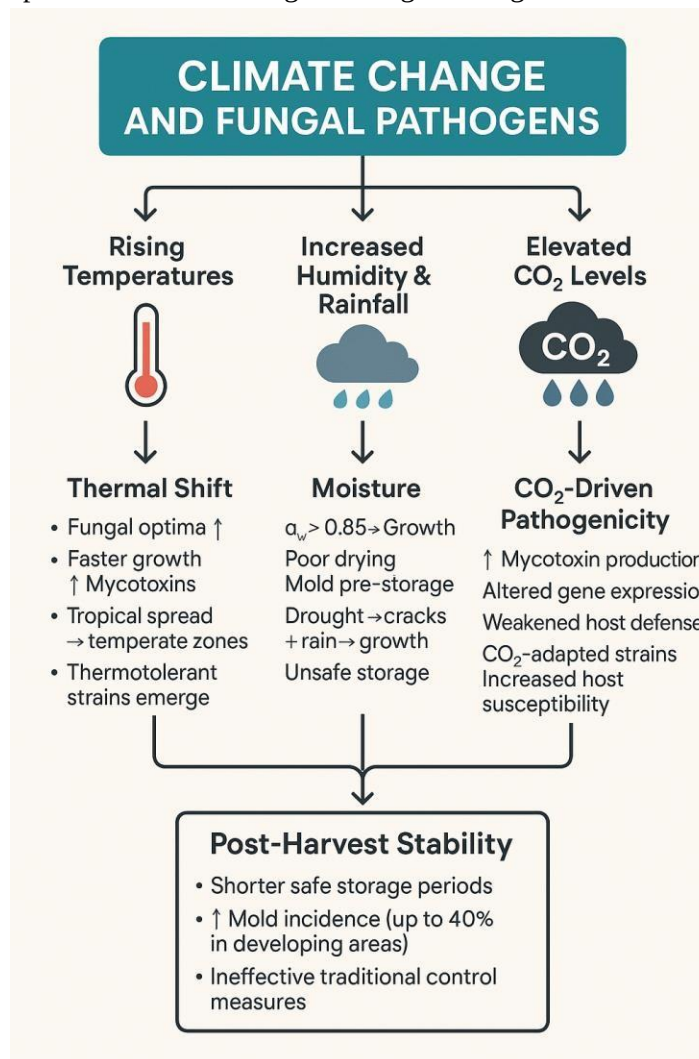
facilitate fungal entry, while subsequent rains provide the moisture needed for explosive mold growth (**Janić Hajnal et al., 2023**). This moisture variability also affects storage environments, with traditional granaries in humid regions now maintaining internal humidity levels that persistently exceed the safe thresholds for fungal control, rendering conventional storage practices inadequate (Figure 1) (**Zhao et al., 2022**).

3. CO₂ and fungal pathogenicity

While less immediately obvious than temperature or moisture effects, rising atmospheric CO₂ levels are inducing complex changes in both fungal behavior and host-pathogen interactions (**Cotter et al., 2024**). Elevated CO₂ has been shown to alter the secondary metabolism of numerous fungal species, with some strains increasing mycotoxin production by as much as 200% under high-CO₂ conditions (**Schoss et al., 2022**). This may be due to CO₂-induced changes in fungal gene expression or to modified substrate availability in host plants. Importantly, the physiological

changes in crops grown under elevated CO₂—including altered carbohydrate composition and reduced protein content—can make stored produce more susceptible to fungal attack. For example, wheat grown under high CO₂ tends to have softer kernels and thinner pericarps, providing less physical barrier to *Fusarium* invasion (**Chen et al., 2019**). Simultaneously, the chemical defense compounds in many crops (e.g., phenolics in nuts or capsaicin in peppers) may decrease in concentration under future CO₂ scenarios, further reducing natural resistance to post-harvest pathogens (**Zhao et al., 2025**). Perhaps most intriguing are emerging findings that certain fungi can directly utilize atmospheric CO₂ through novel metabolic pathways, potentially leading to more aggressive CO₂-adapted strains. These multifaceted CO₂ effects create a perfect storm where both the pathogen's virulence and the host's susceptibility may increase in tandem under future climate scenarios (Figure 1) (**Dogan et al., 2023**).

Figure 1: Impacts of Climate Change on Fungal Pathogens in Post-Harvest Systems



EMERGING RISKS FROM KEY FUNGAL PATHOGENS

1. Mycotoxin-producing fungi under climate stress

The intersection of climate change and mycotoxin biosynthesis represents one of the most pressing food safety challenges of our time (Zingales et al., 2022). Mycotoxigenic fungi, particularly *Aspergillus*, *Alternaria*, *Fusarium*, and *Penicillium* species, are demonstrating alarming adaptive responses to changing environmental conditions (Ferrigo et al., 2021;

Lončarić et al., 2021; Zhang et al., 2021; Miranda-Apodaca et al., 2023). Warmer temperatures have been shown to upregulate aflatoxin production in *A. flavus* by as much as 400% when temperatures exceed 35°C, while simultaneously reducing the fungal growth threshold from 14 days to just 7 days for significant contamination (Kos et al., 2023). For *Fusarium* species, the combination of elevated CO₂ and temperature fluctuations is creating ideal

conditions for enhanced production of both fumonisins and trichothecenes, with maize crops showing 2-3 times higher contamination levels in climate-stressed regions (**Ferrigo et al., 2021**). Particularly concerning is the emerging evidence that climate-induced drought stress in crops may trigger compensatory mechanisms in fungi, leading to "stress metabolite" production where mycotoxins are generated as survival compounds rather than secondary metabolites (**Wang et al., 2025**). This paradigm shift suggests that even suboptimal conditions for fungal growth may still result in dangerous toxin levels (**Abel Palacios et al., 2022**). The European Food Safety Authority has projected that by 2050, previously "safe" regions for mycotoxin contamination will expand northward by approximately 150-200 km per decade, putting an additional 250 million people at risk of exposure to unsafe mycotoxin levels in staple foods (Figure 2) (**Kovač et al., 2022**).

2. Evolution of resistant and novel fungal strains

The rapid climate transformation is serving as a powerful evolutionary pressure on fungal populations, driving the emergence of both resistant and novel pathogenic strains. Recent genomic studies have identified climate-adapted *Aspergillus* isolates with mutations in the aflR gene (the primary regulator of aflatoxin biosynthesis) that allow toxin production across a wider temperature range (35-42°C compared to the traditional 28-35°C range) (**Mekapogu et al., 2021; Degani et al., 2025**). Simultaneously, fungicide resistance is accelerating under climate stress conditions; with *Penicillium digitatum* (citrus green mold) demonstrating 80% reduced sensitivity to imazalil in Mediterranean regions where temperature extremes and fungicide use coincide. Perhaps most alarming is the emergence of hybrid fungal species through climate-driven range overlaps, such as the recently identified

Aspergillus fusarioide, a thermotolerant hybrid between *A. flavus* and *Fusarium verticillioides* capable of producing both aflatoxins and fumonisins (**Kovač et al., 2022; Madhushan et al., 2025**). These novel strains often exhibit unpredictable virulence patterns and toxin profiles, confounding existing detection methods and control strategies. The phenomenon of "climate-mediated hybridization" may create entirely new classes of post-harvest pathogens before our diagnostic and regulatory systems can adapt (Figure 2) (**Islam et al., 2024**).

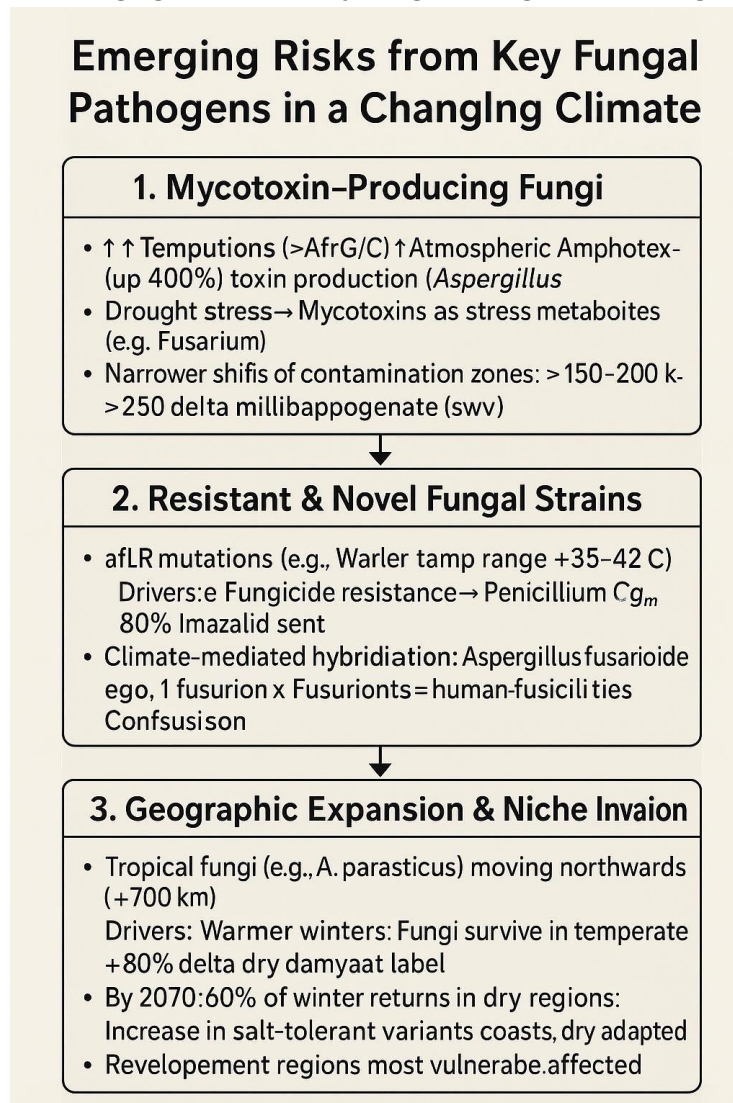
3. Geographic expansion and niche invasion

The traditional geographic boundaries of fungal distribution are undergoing dramatic shifts, with previously contained tropical species establishing footholds in temperate regions. *Aspergillus parasiticus*, historically limited to latitudes below 35°, has been recently documented in Central European grain stores, representing a 700 km northward expansion since 1990 (**Patejuk et al., 2024**). This geographic creep is being facilitated by multiple climate factors: warmer winters allow fungal survival in previously lethal cold storage conditions, while increased atmospheric moisture enables establishment in regions that were traditionally too arid for mold proliferation (**Carmona-Hernandez et al., 2019**). The invasion dynamics follow distinct patterns - coastal regions are experiencing salt-tolerant fungal variants due to rising sea levels and storm surges, while continental interiors face novel dry-adapted strains. Predictive modeling suggests that by 2070, over 60% of global wheat storage facilities will face exposure to at least one new fungal pathogen outside their historical experience (**Zhou et al., 2024**). This geographic reorganization is particularly problematic because many storage systems and food safety regulations

were designed around local (rather than global) fungal threats, leaving systems vulnerable to invasive species against which they have no natural defenses or management experience (Agan et al., 2020). The economic implications are staggering, with estimates suggesting that

geographic range expansions alone could increase global post-harvest losses by \$30 billion annually by 2030, with developing countries in tropical transition zones being disproportionately affected (Figure 2) (Simões et al., 2023; Khaskheli et al., 2025).

Figure 2: Emerging Risks from Key Fungal Pathogens in a Changing Climate



ADAPTIVE STRATEGIES TO MITIGATE CLIMATE-DRIVEN POST-HARVEST FUNGAL RISKS

1. Next-generation storage technologies

The limitations of traditional storage methods in a changing climate have spurred innovation in post-harvest preservation technologies. Hermetic storage systems, which create oxygen-depleted environments through completely sealed containers, have demonstrated remarkable efficacy against diverse fungal threats. Recent advancements in ultra-hermetic bags incorporating oxygen-absorbing nanomaterials can reduce fungal proliferation by 99% even under high humidity conditions (Palumbo et al., 2022; Valenzuela et al., 2023). Controlled atmosphere storage is undergoing a revolution through AI-driven dynamic gas modulation, where machine-learning algorithms continuously adjust CO₂/O₂ ratios in response to real-time fungal spore detection sensors (Strano et al., 2022). Perhaps most promising are the new phase-change material (Cheng et al., 2022) cooling systems that maintain optimal storage temperatures without electricity - particularly crucial for developing regions where energy access remains inconsistent. Solar-powered dehydrators with humidity feedback loops are proving 40% more effective than traditional sun-drying methods in climate-variable regions, while blockchain-enabled grain monitoring allows for real-time tracking of storage conditions throughout supply chains. These technological solutions are increasingly being designed as modular, scalable systems to accommodate diverse crops and economic contexts (Figure 3) (Ziv et al., 2021).

2. Biological control and ecological interventions

Biological control strategies are evolving beyond simple antagonist applications to sophisticated ecological management approaches.

The latest generation of biocontrol utilizes fungal consortia rather than single species, combining *Trichoderma asperellum* (for *Aspergillus* spp. suppression), *Bacillus subtilis* (against *Fusarium* spp.), and *Clonostachys rosea* (for *Penicillium* spp. control) in climate-optimized formulations (Carmona-Hernandez et al., 2019; Ramudingana et al., 2025). Plant-derived antifungal compounds are seeing renewed interest, with nano-encapsulated essential oils demonstrating prolonged release and 80% greater efficacy than conventional applications (Magri et al., 2023; Yu, 2025). A groundbreaking development is the use of "mycobiome engineering" - deliberately cultivating beneficial fungal communities on crops pre-harvest that continue to provide protection during storage (Ramudingana et al., 2025). Farmer-managed natural regeneration (FMNR) of antifungal tree species around storage facilities is emerging as a low-cost ecological buffer, with species like neem and moringa reducing ambient humidity and providing volatile antifungal compounds. These biological approaches are being integrated into climate-smart agricultural packages that consider the entire pre- and post-harvest continuum (Figure 3) (Nxumalo et al., 2021; Nthuku et al., 2023).

3. Predictive systems and decision support tools

The unpredictability introduced by climate change has made advanced forecasting systems essential for proactive fungal management (Thar et al., 2021). Next-generation predictive models now incorporate real-time satellite weather data, crop stress indicators, and fungal genomic information to generate location-specific risk forecasts 14-28 days in advance (Ananias et al., 2021). The FAO's recently launched "MycoAlert"

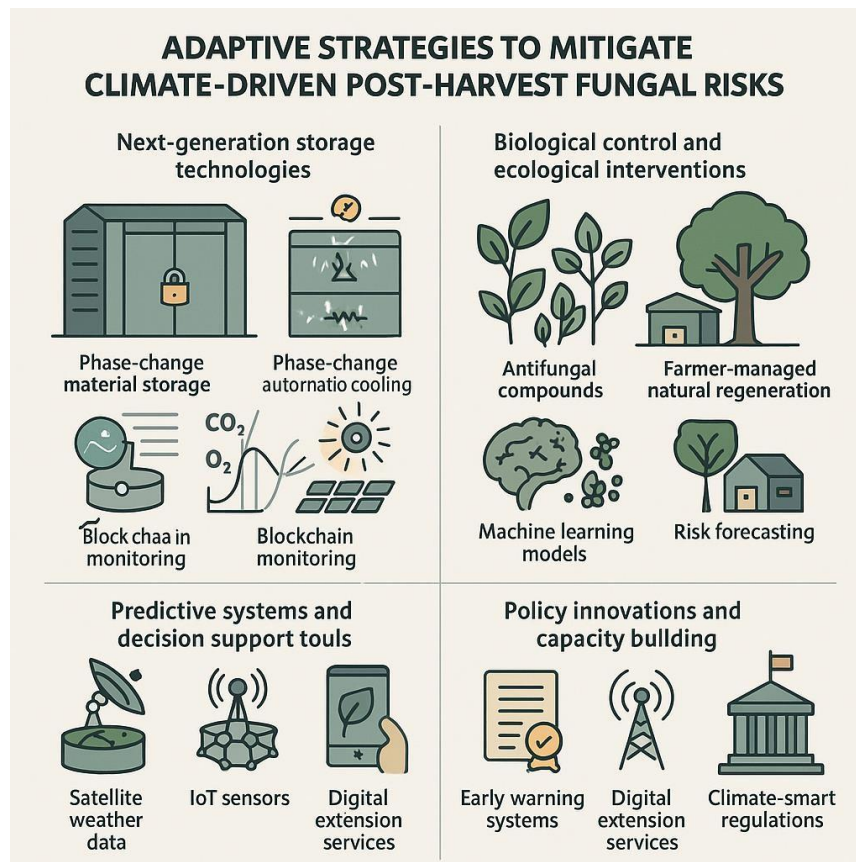
system uses ensemble modeling to predict mycotoxin outbreaks with 85% accuracy across 60 countries (**Costa et al., 2017; Schmidt et al., 2023**). At the farm level, affordable IoT sensor networks monitor microclimates in storage units, triggering automated ventilation or alerting farmers via mobile apps when conditions approach fungal growth thresholds (**Sottocornola et al., 2023**). Machine learning algorithms trained on decades of fungal outbreak data can now identify emerging risk patterns invisible to human analysts, such as the correlation between specific rainfall patterns 3 months pre-harvest and subsequent *Aspergillus* contamination risks (**Al Shoffe et al., 2024**). These systems are increasingly being linked to blockchain-based traceability platforms that enable targeted recalls and dynamic pricing based on verified storage conditions. Perhaps most impactful is the integration of these tools with climate adaptation planning at national levels, allowing for strategic reserve placement and storage infrastructure development in anticipation of shifting fungal threat patterns (Figure 3) (**Pina et al., 2021**).

4. Policy innovations and capacity building

Effective adaptation requires transforming institutional frameworks and knowledge systems.

Progressive grain storage certification programs now mandate climate-resilient features, while "fungal adaptation credits" are being piloted as financial incentives for adopting advanced storage technologies (**Maier and Chikez, 2021**). National early warning systems are being strengthened through participatory surveillance networks that combine indigenous knowledge with scientific monitoring (**Paiva et al., 2022**). A critical innovation is the development of "climate-smart post-harvest extension services" that deliver location-specific advice through digital platforms, reaching 5 million smallholders globally. International collaborations like the Climate-Resilient Storage Initiative are establishing regional centers of excellence for fungal adaptation research and technology transfer (**Schmidt et al., 2023**). Perhaps most significantly, food safety regulations are being updated to account for climate-induced changes in mycotoxin patterns, with dynamic tolerance levels that adjust based on regional climate stress indicators (**Kitinoja and Barrett, 2015**). These policy innovations are creating enabling environments for comprehensive fungal risk management in an era of climate uncertainty (Figure 3) (**McNamara and Tata, 2015; Garney et al., 2022**).

Figure 3: Adaptive Strategies to Mitigate Climate-Driven Post-Harvest Fungal Risks



CONCLUSIONS

The escalating impact of climate change on post-harvest fungal pathogens presents a complex and evolving threat to global food security, necessitating urgent and coordinated action. As this review has demonstrated, rising temperatures, shifting precipitation patterns, and elevated atmospheric CO₂ are fundamentally altering the biology and ecology of key mycotoxigenic fungi, including *Aspergillus*, *Fusarium*, and *Penicillium* species. These changes are not merely quantitative—increased fungal growth rates or mycotoxin production—but qualitative, driving the emergence of novel fungal hybrids, expanding geographic ranges, and fostering resistance to

conventional management strategies. The consequences extend beyond agricultural losses, posing significant public health risks through mycotoxin exposure and undermining economic stability in regions reliant on crop exports. Traditional post-harvest practices, developed under more stable climatic conditions, are increasingly inadequate, highlighting the need for transformative approaches that integrate cutting-edge technology, ecological insights, and proactive policy frameworks.

Looking ahead, the future of post-harvest management must embrace innovation at multiple levels. First, research must prioritize the

development of climate-resilient crop varieties with enhanced innate resistance to fungal colonization, leveraging advances in genomics and gene editing. Second, storage technologies must evolve beyond static solutions to dynamic, adaptive systems capable of responding to real-time environmental fluctuations, such as smart silos with self-regulating microclimates. Third, global surveillance networks must be strengthened to monitor emerging fungal threats, utilizing AI-driven predictive models and decentralized data collection from farmers and storage facilities. Importantly, these efforts must be underpinned by inclusive knowledge-sharing platforms that bridge the gap between scientific research, policymaking, and on-the-ground implementation, particularly in vulnerable regions where infrastructure gaps are most acute.

The path forward also demands a paradigm shift in how we conceptualize post-harvest systems—from isolated endpoints in agricultural production to integrated components of climate

adaptation strategies. This includes reimagining food supply chains as circular economies, where waste from fungal-infected crops is repurposed into biofuels or biodegradable materials, thereby reducing overall loss. International cooperation will be critical, as fungal pathogens do not respect borders, and climate impacts are inherently transnational. Initiatives such as the Global Fungal Risk Mapping Consortium could play a pivotal role in harmonizing standards, sharing technologies, and mobilizing resources to combat this silent crisis. Ultimately, the battle against post-harvest fungal pathogens in a changing climate is not just a technical challenge but also a test of our collective capacity to innovate, collaborate, and prioritize long-term resilience over short-term gains. By addressing these issues today, we can safeguard food systems for future generations while mitigating the cascading impacts of fungal diseases on health, economies, and ecosystems worldwide.

REFERENCES

- ABEL PALACIOS, H.; STEFANELLO, A.; GARCÍA GAVILÁNEZ, M.S.; CASTRO DEMERA, D.A.; GARCIA, M.V.; VÁSQUEZ CASTILLO, W.A.; ALMEIDA MARCANO, M.A.; SAMANIEGO MAIGUA, I.R.; COPETTI, M.V. Relationship between the Fungal Incidence, Water Activity, Humidity, and Aflatoxin Content in Maize Samples from the Highlands and Coast of Ecuador. *Toxins* 2022, 14, 196. <https://doi.org/10.3390/toxins14030196>
- AGAN, A.; DRENKHAN, R.; ADAMSON, K.; TEDERSOO, L.; SOLHEIM, H.; BØRJA, I.; MATSIKAKH, I.; TIMMERMAN, V.; NAGY, N.E.; HIETALA, A.M. The Relationship between Fungal Diversity and Invasibility of a Foliar Niche—The Case of Ash Dieback. *J. Fungi* 2020, 6, 150. <https://doi.org/10.3390/jof6030150>
- AL SHOFFE, Y.; JOHNSON, L.K. Opportunities for Prediction Models to Reduce Food Loss and Waste in the Postharvest Chain of Horticultural Crops. *Sustainability* 2024, 16, 7803. <https://doi.org/10.3390/su16177803>
- ANANIAS, E.; GASPAR, P.D.; SOARES, V.N.G.J.; CALDEIRA, J.M.L.P. Artificial Intelligence Decision Support System Based on Artificial Neural Networks to Predict the Commercialization Time by the Evolution of Peach Quality. *Electronics* 2021, 10, 2394. <https://doi.org/10.3390/electronics10192394>
- BANO, A.; GUPTA, A.; PRUSTY, M.R.; KUMAR, M. Elicitation of Fruit Fungi Infection

- and Its Protective Response to Improve the Postharvest Quality of Fruits. *Stresses* 2023, 3, 231-255.
<https://doi.org/10.3390/stresses3010018>
- CARMONA-HERNANDEZ, S.; REYES-PÉREZ, J.J.; CHIQUITO-CONTRERAS, R.G.; RINCON-ENRIQUEZ, G.; CERDAN-CABRERA, C.R.; HERNANDEZ-MONTIEL, L.G. Biocontrol of Postharvest Fruit Fungal Diseases by Bacterial Antagonists: A Review. *Agronomy* 2019, 9, 121.
<https://doi.org/10.3390/agronomy9030121>
 - CHEN, J.; SHEN, Y.; CHEN, C.; WAN, C. Inhibition of Key Citrus Postharvest Fungal Strains by Plant Extracts In Vitro and In Vivo: A Review. *Plants* 2019, 8, 26.
<https://doi.org/10.3390/plants8020026>
 - CHENG, Y.-J.; WU, Y.-J.; LEE, F.-W.; OU, L.-Y.; CHEN, C.-N.; CHU, Y.-Y.; KUANG, Y.-C. Impact of Storage Condition on Chemical Composition and Antifungal Activity of Pomelo Extract against *Colletotrichum gloeosporioides* and Anthracnose in Post-harvest Mango. *Plants* 2022, 11, 2064.
<https://doi.org/10.3390/plants11152064>
 - COSTA, G.; ROCCHI, L.; FARNETI, B.; BUSATTO, N.; SPINELLI, F.; VIDONI, S. Use of Nondestructive Devices to Support Pre- and Postharvest Fruit Management. *Horticulturae* 2017, 3, 12.
<https://doi.org/10.3390/horticulturae3010012>
 - COTTER, A.; DRACATOS, P.; BEDDOE, T.; JOHNSON, K. Isothermal Detection Methods for Fungal Pathogens in Closed Environment Agriculture. *J. Fungi* 2024, 10, 851.
<https://doi.org/10.3390/jof10120851>
 - DEGANI, O. PLANT FUNGAL DISEASES AND CROP PROTECTION. *J. Fungi* 2025, 11, 274. <https://doi.org/10.3390/jof11040274>
 - DOGAN, A.; ERKAN, M. Responses of High Carbon Dioxide Concentration on Postharvest Quality of Fresh Fig Fruit during Storage. *Horticulturae* 2023, 9, 293.
<https://doi.org/10.3390/horticulturae9030293>
 - FAREED MOHAMED WAHDAN, S.; HOSSEN, S.; TANUNCHAI, B.; SCHÄDLER, M.; BUSCOT, F.; PURAHONG, W. Future Climate Significantly Alters Fungal Plant Pathogen Dynamics during the Early Phase of Wheat Litter Decomposition. *Microorganisms* 2020, 8, 908.
<https://doi.org/10.3390/microorganisms8060908>
 - FERRIGO, D.; SCARPINO, V.; VANARA, F.; CAUSIN, R.; RAIOLA, A.; BLANDINO, M. Influence of H₂O₂-Induced Oxidative Stress on In Vitro Growth and Moniliformin and Fumonisin Accumulation by *Fusarium proliferatum* and *Fusarium subglutinans*. *Toxins* 2021, 13, 653.
<https://doi.org/10.3390/toxins13090653>
 - GARCIA-BENITEZ, C.; CASALS, C.; USALL, J.; SÁNCHEZ-RAMOS, I.; MELGAREJO, P.; DE CAL, A. Impact of Postharvest Handling on Preharvest Latent Infections Caused by *Monilinia* spp. in Nectarines. *J. Fungi* 2020, 6, 266.
<https://doi.org/10.3390/jof6040266>
 - GARNEY, W.R.; WILSON, K.L.; GARCIA, K.M.; MURALEETHARAN, D.; ESQUIVEL, C.H.; SPADINE, M.N.; PANJWANI, S.; AJAYI, K.V. Supporting and Enabling the Process of Innovation in Public Health: The Framework for Public Health Innovation. *Int. J. Environ. Res. Public Health* 2022, 19, 10099.
<https://doi.org/10.3390/ijerph191610099>
 - ISLAM, M.N.; REZA, M.N.; IQBAL, M.Z.; LEE, K.-H.; JANG, M.-K.; CHUNG, S.-O. Spatial and Temporal Variability of Environmental Variables in Chinese Solar Greenhouses in the Summer Season. *Horticulturae* 2025, 11, 421.
<https://doi.org/10.3390/horticulturae11040421>

- ISLAM, T.; DANISHUDDIN; TAMANNA, N.T.; MATIN, M.N.; BARAI, H.R.; HAQUE, M.A. Resistance Mechanisms of Plant Pathogenic Fungi to Fungicide, Environmental Impacts of Fungicides, and Sustainable Solutions. *Plants* 2024, 13, 2737. <https://doi.org/10.3390/plants13192737>
- JANIĆ HAJNAL, E.; KOS, J.; RADIĆ, B.; ANIĆ, M.; RADOVIĆ, R.; KUDUMIJA, N.; VULIĆ, A.; ĐEKIĆ, S.; PLEADIN, J. Impact of Climate Changes on the Natural Prevalence of Fusarium Mycotoxins in Maize Harvested in Serbia and Croatia. *Foods* 2023, 12, 1002. <https://doi.org/10.3390/foods12051002>
- KHASKHELI, M.A.; NIZAMANI, M.M.; TARAFDER, E.; DAS, D.; NOSHEEN, S.; MUHAE-UD-DIN, G.; KHASKHELI, R.A.; REN, M.-J.; WANG, Y.; YANG, S.-W. Sustainable Management of Major Fungal Phytopathogens in Sorghum (*Sorghum bicolor* L.) for Food Security: A Comprehensive Review. *J. Fungi* 2025, 11, 207. <https://doi.org/10.3390/jof11030207>
- KITINOJA, L.; BARRETT, D.M. Extension of Small-Scale Postharvest Horticulture Technologies—A Model Training and Services Center. *Agriculture* 2015, 5, 441-455. <https://doi.org/10.3390/agriculture5030441>
- KOS, J.; ANIĆ, M.; RADIĆ, B.; ZADRAVEC, M.; JANIĆ HAJNAL, E.; PLEADIN, J. Climate Change—A Global Threat Resulting in Increasing Mycotoxin Occurrence. *Foods* 2023, 12, 2704. <https://doi.org/10.3390/foods12142704>
- Kovač, M.; Bulaić, M.; Nevistić, A.; Rot, T.; Babić, J.; Panjičko, M.; Kovač, T.; Šarkanj, B. Regulated Mycotoxin Occurrence and Co-Occurrence in Croatian Cereals. *Toxins* 2022, 14, 112. <https://doi.org/10.3390/toxins14020112>
- LONČARIĆ, A.; ŠARKANJ, B.; GOTAL, A.-M.; KOVAČ, M.; NEVISTIĆ, A.; FRUK, G.; SKENDROVIĆ BABOJELIĆ, M.; BABIĆ, J.; MILIČEVIĆ, B.; KOVAČ, T. Penicillium expansum Impact and Patulin Accumulation on Conventional and Traditional Apple Cultivars. *Toxins* 2021, 13, 703. <https://doi.org/10.3390/toxins13100703>
- MADHUSHAN, A.; WEERASINGHA, D.B.; ILYUKHIN, E.; TAYLOR, P.W.J.; RATNAYAKE, A.S.; LIU, J.-K.; Maharachchikumbura, S.S.N. From Natural Hosts to Agricultural Threats: The Evolutionary Journey of Phytopathogenic Fungi. *J. Fungi* 2025, 11, 25. <https://doi.org/10.3390/jof11010025>
- MAGRI, A.; CURCI, M.; BATTAGLIA, V.; FIORENTINO, A.; PETRICCIONE, M. Essential Oils in Postharvest Treatment against Microbial Spoilage of the Rosaceae Family Fruits. *AppliedChem* 2023, 3, 196-216. <https://doi.org/10.3390/appliedchem3020013>
- MAIER, D.E.; CHIKEZ, H. Recent Innovations in Post-Harvest Preservation and Protection of Agricultural Products. *Agriculture* 2021, 11, 1275. <https://doi.org/10.3390/agriculture11121275>
- MCNAMARA, P.E.; TATA, J.S. Principles of Designing and Implementing Agricultural Extension Programs for Reducing Post-harvest Loss. *Agriculture* 2015, 5, 1035-1046. <https://doi.org/10.3390/agriculture5041035>
- MEKAPOGU, M.; JUNG, J.-A.; KWON, O.-K.; AHN, M.-S.; SONG, H.-Y.; JANG, S. Recent Progress in Enhancing Fungal Disease Resistance in Ornamental Plants. *Int. J. Mol. Sci.* 2021, 22, 7956. <https://doi.org/10.3390/ijms22157956>
- MIRANDA-APODACA, J.; ARTETXE, U.; AGUADO, I.; MARTIN-SOUTO, L.; RAMIREZ-GARCIA, A.; LACUESTA, M.; BECERRIL, J.M.; ESTONBA, A.; ORTIZ-BARREDO, A.; HERNÁNDEZ, A.; ET AL. Stress Response to Climate Change and Postharvest Handling in Two Differently Pigmented Lettuce Genotypes: Impact on

- Alternaria alternata* Invasion and Mycotoxin Production. *Plants* 2023, 12, 1304. <https://doi.org/10.3390/plants12061304>
- NTHUKU, B.M.; KAHARIRI, E.W.; KINYUA, J.K.; NYABOGA, E.N. Fungal Endophytes of Moringa (*Moringa oleifera* L.), Neem (*Azadirachta indica*) and Lavender (*Lavandula angustifolia*) and Their Biological Control of Fusarium Wilt of Banana. *Microbiol. Res.* 2023, 14, 2113-2132. <https://doi.org/10.3390/microbiolres14040143>
 - NXUMALO, K.A.; AREMU, A.O.; FAWOLE, O.A. Potentials of Medicinal Plant Extracts as an Alternative to Synthetic Chemicals in Postharvest Protection and Preservation of Horticultural Crops: A Review. *Sustainability* 2021, 13, 5897. <https://doi.org/10.3390/su13115897>
 - PAIVA, T.; RIBEIRO, M.P.; COUTINHO, P. Capacity-Building Model to Promote Innovation and Sustainability in the Portuguese Agro-Industrial Sector. *Sustainability* 2022, 14, 15873. <https://doi.org/10.3390/su142315873>
 - PALUMBO, M.; ATTOLICO, G.; CAPOZZI, V.; COZZOLINO, R.; CORVINO, A.; DE CHIARA, M.L.V.; PACE, B.; PELOSI, S.; RICCI, I.; ROMANIELLO, R.; ET AL. Emerging Postharvest Technologies to Enhance the Shelf-Life of Fruit and Vegetables: An Overview. *Foods* 2022, 11, 3925. <https://doi.org/10.3390/foods11233925>
 - PATEJUK, K.; NAJBEREK, K.; PACEK, P.; BOCIANOWSKI, J.; PUSZ, W. Fungal Phytopathogens: Their Role in the Spread and Management of Invasive Alien Plants. *Forests* 2024, 15, 2214. <https://doi.org/10.3390/f15122214>
 - PETER MSHELIA, L.; SELAMAT, J.; ISKANDAR PUTRA SAMSUDIN, N.; RAFII, M.Y.; ABDUL MUTALIB, N.-A.; NORDIN, N.; BERTHILLER, F. Effect of Temperature, Water Activity and Carbon Dioxide on Fungal Growth and Mycotoxin Production of Acclimatised Isolates of *Fusarium verticillioides* and *F. graminearum*. *Toxins* 2020, 12, 478. <https://doi.org/10.3390/toxins12080478>
 - PINA, M.; GASPAR, P.D.; LIMA, T.M. Decision Support System in Dynamic Pricing of Horticultural Products Based on the Quality Decline Due to Bacterial Growth. *Appl. Syst. Innov.* 2021, 4, 80. <https://doi.org/10.3390/asi4040080>
 - RAMUDINGANA, P.; MAKHADO, N.; KAMUTANDO, C.N.; THANTSHA, M.S.; MAMPHOGORO, T.P. Fungal Biocontrol Agents in the Management of Postharvest Losses of Fresh Produce—A Comprehensive Review. *J. Fungi* 2025, 11, 82. <https://doi.org/10.3390/jof11010082>
 - SÁNCHEZ ESPINOSA, K.C.; FERNÁNDEZ-GONZÁLEZ, M.; ALMAGUER, M.; GUADA, G.; RODRÍGUEZ-RAJO, F.J. Puccinia Spore Concentrations in Relation to Weather Factors and Phenological Development of a Wheat Crop in Northwestern Spain. *Agriculture* 2023, 13, 1637. <https://doi.org/10.3390/agriculture13081637>
 - SCHMIDT, D.; BUTTURI, M.A.; SELLITTO, M.A. Opportunities of Digital Transformation in Post-Harvest Activities: A Single Case Study of an Engineering Solutions Provider. *AgriEngineering* 2023, 5, 1226-1242. <https://doi.org/10.3390/agriengineering5030078>
 - SCHOSS, K.; KOČEVAR GLAVAČ, N.; DOLENC KOCE, J.; ANŽLOVAR, S. Supercritical CO₂ Plant Extracts Show Antifungal Activities against Crop-Borne Fungi. *Molecules* 2022, 27, 1132. <https://doi.org/10.3390/molecules27031132>
 - SIMÕES, D.; DE ANDRADE, E.; SABINO, R. Fungi in a One Health Perspective. *Encyclopedia* 2023, 3, 900-918. <https://doi.org/10.3390/encyclopedia3030064>

- SOTTOCORNOLA, G.; BARIC, S.; STELLA, F.; ZANKER, M. Development of a Knowledge-Based Expert System for Diagnosing Post-Harvest Diseases of Apple. *Agriculture* 2023, 13, 177. <https://doi.org/10.3390/agriculture13010177>
- STRANO, M.C.; ALTIERI, G.; ALLEGRA, M.; DIRENZO, G.C.; PATERNA, G.; MATERA, A.; GENOVESE, F. Postharvest Technologies of Fresh Citrus Fruit: Advances and Recent Developments for the Loss Reduction during Handling and Storage. *Horticulturae* 2022, 8, 612. <https://doi.org/10.3390/horticulturae8070612>
- TCHOUANDEM NZALI, C.; ABDELBAKI, C.; KUMAR, N. Assessing the Effects of Climate Variability on Maize Yield in the Municipality of Dschang—Cameroon. *Land* 2024, 13, 1360. <https://doi.org/10.3390/land13091360>
- THAR, S.P.; RAMILAN, T.; FARQUHARSON, R.J.; CHEN, D. Identifying Potential for Decision Support Tools through Farm Systems Typology Analysis Coupled with Participatory Research: A Case for Smallholder Farmers in Myanmar. *Agriculture* 2021, 11, 516. <https://doi.org/10.3390/agriculture11060516>
- THOLE, V.; VAIN, P.; MARTIN, C. Effect of Elevated Temperature on Tomato Post-Harvest Properties. *Plants* 2021, 10, 2359. <https://doi.org/10.3390/plants10112359>
- VALENZUELA, J.L. Advances in Postharvest Preservation and Quality of Fruits and Vegetables. *Foods* 2023, 12, 1830. <https://doi.org/10.3390/foods12091830>
- WANG, J.; TOLOSA, J.; WANG, W.; YANG, X. Mycotoxins and Fungal Toxins: Current Status and Future Perspectives. *Toxins* 2025, 17, 176. <https://doi.org/10.3390/toxins17040176>
- YU, J. Chemical Composition of Essential Oils and Their Potential Applications in Postharvest Storage of Cereal Grains. *Molecules* 2025, 30, 683. <https://doi.org/10.3390/molecules30030683>
- ZHANG, H.; WANG, G.; YANG, Q.; YANG, X.; ZHENG, Y.; LIU, Y.; XING, F. Effects of Light on the Ochratoxigenic Fungi *Aspergillus ochraceus* and *A. carbonarius*. *Toxins* 2021, 13, 251. <https://doi.org/10.3390/toxins13040251>
- ZHAO, S.; SUN, Y.; SU, L.; YAN, L.; LIN, X.; LONG, Y.; ZHANG, A.; ZHAO, Q. Significant Enrichment of Potential Pathogenic Fungi in Soil Mediated by Flavonoids, Phenolic Acids, and Organic Acids. *J. Fungi* 2025, 11, 154. <https://doi.org/10.3390/jof11020154>
- ZHOU, J.; ZHANG, X.; QU, Z.; ZHANG, C.; WANG, F.; GAO, T.; YAO, Y.; LIANG, J. Progress in Research on Prevention and Control of Crop Fungal Diseases in the Context of Climate Change. *Agriculture* 2024, 14, 1108. <https://doi.org/10.3390/agriculture14071108>
- ZINGALES, V.; TARONCHER, M.; MARTINO, P.A.; RUIZ, M.-J.; CALONI, F. Climate Change and Effects on Molds and Mycotoxins. *Toxins* 2022, 14, 445. <https://doi.org/10.3390/toxins14070445>
- ZIV, C.; FALLIK, E. Postharvest Storage Techniques and Quality Evaluation of Fruits and Vegetables for Reducing Food Loss. *Agronomy* 2021, 11, 1133. <https://doi.org/10.3390/agronomy11061133>