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Disrupt Non-Thermal-Based Revolutionary Ways for Postharvest Food Security: Mechanisms, Hurdles, and Future Prospects with Focus on Containment of Mycotoxins and Fungal Screenings

Muhammad Awais Fareed[1]*
Muti Ur Rahman[2]
Awais Mutti[1]
Summia Iqbal[1]
Muhammad Tayyab Mateen[1]
Iram Bilqees[1]
Rimsha Parveen[1]
Muhammad Sohail Imtiaz[1]
Muhammad Hamza Saeed[1]
Muhammad Usman Ghani[3]
Judith J. Kiptoo[4]
Memoona Imdad[1]
Lubna Shehzadi[1]

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Abstract

Global food security, public health, and agricultural sustainability face severe dangers from fungal contamination and mycotoxin accumulation which occur during postharvest processing of food. Traditional thermal processing methods fail to remove resistant fungal spores from food products, resulting in loss of nutritional and sensory quality. The development of new non-thermal technologies that provide sustainable solutions for fungal control and mycotoxin detoxification has become increasingly popular as an environmentally friendly approach. This analysis investigates the fundamental scientific principles and operational mechanisms and current technical progress of essential non-thermal technologies, which include high hydrostatic pressure, ozone treatment, ultraviolet radiation and pulsed electric fields and cold plasma and nanotechnology-based methods. The discussion explores how these technologies serve as antifungal solutions that protect against mycotoxins while remaining usable across different types of food products. The review presents primary study impediments, which include problems with industrial scalability, expensive operational expenses and existing regulatory restrictions. Integrated systems which combine artificial intelligence with smart monitoring

[1]Department of Plant Pathology, College of Agriculture, University of Sargodha, Sargodha-48100, Pakistan
Correspondence author: awaisfareed069@gmail.com
[2]Institute of Chemistry, The Islamia University of Bahawalpur, Bahawalpur-63100, Pakistan
[3]University of Agriculture, Faisalabad, Sub-Campus, Burewala Campus, Pakistan
[4]School of Biological and Physical Sciences, University of Nairobi, Nairobi, Kenya

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tools will create efficient safe operations according to future system development. Non-thermal technologies provide environmentally friendly solutions which improve food safety during postharvest processing while maintaining food quality in contemporary food distribution systems.

Keywords: Postharvest food safety; Fungal contamination; Mycotoxins; Non-thermal technologies; Food preservation; Sustainable processing.

1 Introduction

Fungal contamination of food and feed has resulted in a worldwide issue with both economic and health repercussions on large scale. Spores of fungi can be easily spread to infect, colonize and spoil agriculture products resulting in massive losses during pre- and postharvest. Their speedy adaptability and extensive dispersion can frequently compromise the efficiency of traditional disease control methods. Additionally, the morphological variations in fungi, stress resilience and dormancy also help them to survive under a wide range of environmental factors. Fungi are estimated to cause losses up to 10-23% of crop production and 10-20% at postharvest handling (Delgado-Ospina et al., 2025). Climate change also contributes to this problem as it provides good conditions to develop fungi and plant mitigation which increases the vulnerability to infections. Furthermore, it has been noted that fungal populations and international trends of mycotoxin distributions can change (Casu et al., 2024). Mycotoxins are harmful secondary metabolites that are mainly synthesized by fungi of the genera Aspergillus, Penicillium, Fusarium and Alternaria. Over 500 mycotoxins are known, but aflatoxins, ochratoxin A, fumonisins, trichothecenes, and zearalenone are the most important because they pose a great threat to food safety and human health (Gozzi et al., 2024). The toxicity of such compounds is quite diverse with carcinogenic, mutagenic, teratogenic, neurotoxic and immunosuppressive properties (Laika et al., 2024). Mycotoxin incidents of contamination are constantly being monitored and reported by regulatory agencies like the European Food Safety Authority (EFSA). The economic losses relating to the spoiled products are high with EU border rejections alone amounting to €7,000 to 11,000 per case (Ekwomadu et al., 2022). More so, mycotoxins have been already reported by the European Rapid Alert System for Food and Feed as among the most common notifications in 2023 and specifically in products based on nuts and cereals. Mycotoxins may spread out of the areas of the contaminated food into the inner body tissues particularly the high moisture fruits and vegetables (Lopes et al., 2023). One factor affecting this diffusion process is the concentration gradient, tissue integrity and the ripening stage (Lima da Silva et al., 2023). Additionally, the pollution is not selective to plant-based food and targets animal feedstocks and endangered various farming activities (El-Sayed et al., 2022). Although the adoption of good agricultural and storage methods a significant number of contamination levels are still the case in many developing areas which demonstrates the implementation of better control mechanisms (Gruber-Dorninger et al., 2025). Over the past few years, the issues of environmental variability and climate change have only increased the problems related to fungal contamination and mycotoxin production (Wang et al., 2025). Increased humidity and extreme weather conditions also favor the growth of fungi and production of toxins making it challenging to manage food safety systems (Molina-Hernandez et al., 2025). Such circumstances underscore the necessity of novel and practical solutions to reduce the threat of contamination. Non-thermal technologies to control fungal contamination and mycotoxins are increasingly popular over the past few years. A number of review studies discussed those methods but most of them were limited to the issue of mycotoxin detoxification and did not cover fungal kill or they did not mention recent methods (Atnafu et al., 2024). Non-thermal technologies are thus becoming a promising development over the traditional thermal processing. The allocation of these methods may be justified to the inactivation of microorganisms and a decrease of mycotoxin composition without compromising nutritional and sensory characteristics of food products. The high-pressure processing, ozone treatment and ultraviolet radiation, along with cold plasma technologies have shown a considerable potential in enhancing food safety without causing sports structural

alterations on food matrices (Yousefi et al., 2023). Moreover, the methods are eco-friendly and as a rule they do not consume as much energy as traditional methods do. Yet issues like high start-up requirements, scale and regulatory limitations will have to be overcome in order to make them common in the industrial world (Abou Dib et al., 2022). In this review the authors intend to give an overview of the emerging non-thermal technologies to be used to control fungal contamination and mycotoxins in postharvest food systems. Specifically, it discusses the mechanisms of action, effectiveness and limitations of key technologies such as high-pressure processing, ozone treatment, ultraviolet radiation, pulsed electric fields and cold plasma. Moreover, the review points out the latest developments, industrial usages and issues of implementing these technologies. Lastly future perspectives and research gaps are encompassed to aid in coming up with efficient, safe and sustainable food preservation strategies.

2 High Hydrostatic Pressure Technology for Food Preservation:

High-pressure processing or high hydrostatic pressure (HHP) requires the immersion of a product into water and exposure to high hydrostatic pressure (from 100 up to 800 MPa) in a vessel (Tomas et al., 2025). After bottling the product is usually packed in an appropriate-high pressure suitable container and pressurized few minutes before decompression. HPP techniques have two options basing on the nature of the food that is to be treated. HPP can be employed as batch type when handling solid food or large solid particle products and semi-continuous when handling liquid products and other items that can be pumped due to their ability to be fluid and flow through semi-continuous processes (Huang et al., 2026). Even though HPP is a non-thermal process, adiabatic heating, resulting in a temperature rise of 23° C/100 MPa of water-based and up to 9° C/100 MPa of oil-based foods is caused by pressure rise (Tiwari et al., 2025). HPP is mostly used in the processing of foods and in extending shelf life as both inactivate pathogenic and spoilage microorganisms. The factors which dictate this include the type of microbes and their lifecycle, processing time, pressure, food substance, temperature, pH and water activity. On the whole HPP influences only the non-covalent bonds since they are sensitive to pressure. HPP can be a useful post-harvest measure in order to minimize microbial pathogens in fresh produce in case little damage to the plant tissue occurs (Islam et al., 2022). Figure 1 shows the high-pressure processing system through its schematic design, which displays food products submerged in water within a high-pressure vessel and demonstrates the two processing methods that modern food preservation systems use.

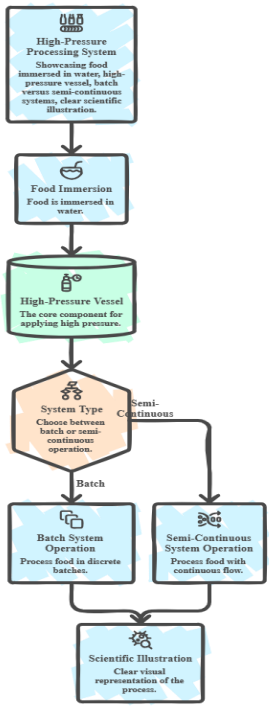

Figure 1: High-pressure processing system showing food immersed in water, high-pressure vessel, batch vs semi-continuous systems, clear scientific illustration

2.1 Underlying Mechanisms of Pressure-Induced Microbial Inactivation

Generally, cell membrane damage is a crucial reason behind cell death in HPP treatment and may result in cell leakage of intracellular elements and homeostasis loss (Molina-Hernandez et al., 2025). All these effects cause impairment of cell functions. Pressure-induced cell death in vegetative microorganisms occurs due to four factors (i) unfolding of proteins and enzymes such as partial or complete denaturation (ii) phase transition of cell membrane and change in fluidity (iii) disintegration of ribosomal subunit (iv) altering intracellular pH related to the enzyme inactivation and cell membrane In case of fungal spores HPP also causes cell wall and membrane ruptures in ascospores and the ornamentation of certain of the ascospores which resemble crowns. More recently, degradation of intracellular and extracellular proteins resulting in an inactive state of Aspergillus flavus spores and development of pores in cell membrane and wall (Delgado-Ospina et al., 2025). High-pressure processing or high hydrostatic pressure is a non-thermal type of preservation process that entails the use of pressure normally ranging between 100 and 800 Megabar to food products. The technology is capable of destroying microorganisms without using high temperatures which is why the technology does not damage the nutritional or sensory values of the food (Molina-Hernandez et al., 2025). The key microbial inactivation process due to HPP is related to structural and functional damage of cellular machinery. The integrity of the microbial cell membranes is impaired by the high pressure and results in a higher permeability and release of intracellular contents. Moreover, the denaturation of proteins under pressure and deactivation of enzymes essential to many cells disrupt the essential metabolic activities leading to the cell death eventually (Arumugam et al., 2025). However, compared to thermal treatments HPP also has very few ramifications on the covalent bonds that preserve the overall quality and freshness of the food products. The main pathways that lead to microbial death through high-pressure processing are shown in Figure 2, which demonstrates how HPP treatment causes cell membranes

to break, proteins to lose their natural structure, enzymes to stop functioning, cells to lose their internal materials, and fungal spores to sustain structural harm, which results in decreased microbial presence and better food safety.

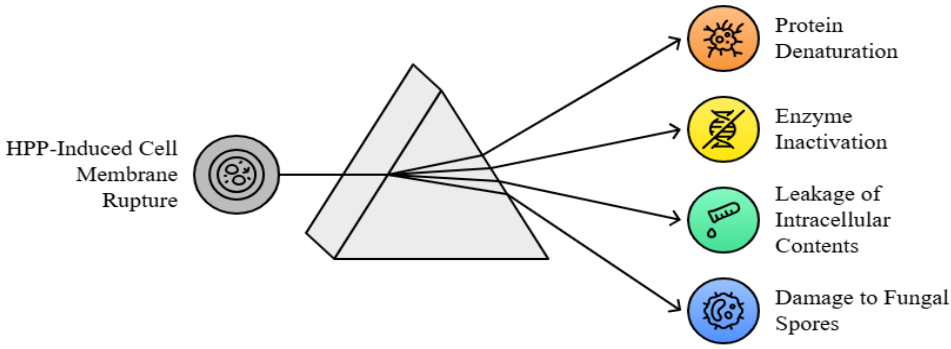

Figure 2: The diagram displays five processes that occur when HPP induces cell membrane rupture. The first process of the diagram shows cell membrane rupture. The second process shows protein denaturation. The third process displays enzyme inactivation. The fourth process shows the release of intracellular contents. The fifth process displays damage to fungal spores.

2.2 Efficacy Against Fungal Cells and Mycotoxin Reduction:

HPP has been shown to inactivate all active fungal cells at low temperatures and moderate pressures of 300 to 400 MPa. Certain fungal spores show greater resistance to destruction (Tiwari et al., 2025). The main factors which determine ascospore resistance to HPP include age, water, activity and diet content because older ascospores demonstrate greater resistance than younger ascospores (Monteiro et al. 2025). The body of study results demonstrated that HPP effectively prevented fungal growth throughout all grains. The HPP treatment at 380 MPa and 60°C for 30 minutes showed significant damage to the membranes of *Fusarium graminearum* spores which had been seeded in peptone water (Kalagatur et al., 2024). The complete spore inactivation for maize grains occurred at 550 MPa and 45°C when maintained at that temperature for 20 minutes which demonstrates that HPP effectiveness depends on both food matrix composition and water activity levels. The study showed that HHP 100–300 MPa treatments which lasted from 10 to 600 seconds and continued for six weeks prevented *Fusarium culmorum* from growing in winter wheat which had been submerged in distilled water (Stuhldreier et al., 2022). The HPP treatment which used 600 MPa pressure for 3 minutes at 4°C completely eliminated all molds from pitted sour cherries and the molds maintained their presence at extremely low levels throughout the complete five-month refrigeration period (Delgado-Ospina et al., 2025). This is to draw attention to the fact that fruit product makers may be concerned about the poor susceptibility of older fungal spores to HPP because very old spores can infect their products. Therefore, there are still scientific questions which need answers about how resistant spores are inactivated by industrial scale HPP machines which operate at maximum pressures of 650 MPa with or without temperatures up to 50°C (Molina-Hernandez et al., 2025). The multilayer ascospores wall undergoes continuous changes in its ultrastructural state which result in age related changes to the pressure resistance of ascospores. The protection of low water activity products shows different results according to the specific solute. The spore survival showed improvements in high pH conditions combined with nutrient rich media while low pH conditions led to spore survival decreases. The process of induced nutrient like physiological germination occurs in spores at low and moderate hydrostatic pressures between 150 and 200 MPa which leads to the inactivation of baroresistant microorganisms after germination (Adepoju et al., 2024). Fungal spores show relatively higher resilience because of their complex structure and protective coatings. However, HPP has shown

considerable promise in inactivating vegetative fungal cells. The success of HPP treatment depends on multiple factors which include temperature and the type of food matrix and treatment duration and pressure intensity. HPP has been shown to affect the stability of several mycotoxins by causing structural changes that may lessen their toxicity in addition to microbial inactivation (Delgado-Ospina et al., 2025). The total destruction of mycotoxins does not always happen because the efficiency of the process depends on the chemical structure of the toxin and the conditions used during processing. Optimal processing parameters are essential for HPP to achieve its maximum effectiveness in food safety applications.

2.3 Applications in Modern Food Processing Industries

The food industry has adopted high pressure processing (HPP) technology for various food sectors which include fruit juices, dairy products, seafood and ready to eat meals. The technology serves high end food products which maintain their natural taste and nutritional value through extended shelf-life capabilities (Emadi et al., 2022). HPP effectively kills spoilage bacteria and enzymes present in fruit juices and beverages without causing major loss of vitamins and color and flavor. The research study demonstrates that HPP preserves the texture and functional properties of dairy and meat products while enhancing their protection against harmful microorganisms (Molina-Hernandez et al. 2025). The global commercial use of HPP technology has increased because consumers now prefer products that have minimal processing and clean label ingredients and no artificial preservatives. Food processing companies use HPP as their main method of production because it delivers better results for their high value products (Doshi et al., 2023). The adoption of HPP technology in low moisture and solid food systems remains restricted because of two main challenges which involve non uniform pressure distribution and reduced efficiency during processing. The system remains difficult to access because operating costs and capital expenses for small and medium sized businesses remain at high levels (Yousefi et al., 2025).

2.4 Limitations, Scalability Issues and Optimization Needs:

The Industrial use of HPP technology remains restricted because the method offers advantages while displaying several fundamental flaws. The financial system experiences major challenges because specialized equipment requires both high initial costs and ongoing maintenance expenses. The method lacks effective treatment capabilities because fungal spores remain active and certain mycotoxins only undergo partial degradation. The procedure encounters challenges when implemented in large volume food production because of its existing technical problems. The combination of HPP with other non-thermal methods represents a better approach for improving food safety results (Focker et al., 2025).

3 Ozone Treatment in Food Safety

3.1 Mechanism of Action:

The method of treating food systems with ozone proves to be both safe and environmentally friendly while effectively decreasing microbial contamination. The strong oxidizing properties of ozone (O_3) enable it to function as an effective bacteria inactivation agent (Molina-Hernandez et al., 2025). Ozone can cause oxidative damage to vital biological components by permeating through the microbial cell wall and membrane. This process leads to protein oxidation, lipid oxidation and nucleic acid oxidation which ultimately results in cell destruction and death of microorganisms (Yousefi et al., 2025). The combination of ozone with biological systems produces reactive oxygen species (ROS) which increase oxidative stress on fungal cells. The ROS particles target essential macromolecules in fungi which results in genetic damage and decreases enzyme activity and ultimately prevents their growth and survival (Sitoe et al., 2025). The figure demonstrates how ozone treatment operates in food systems through its ability to enter fungal cells and produce reactive oxygen species which result in oxidative damage that destroys cell membranes, proteins, and DNA, thus killing microorganisms while breaking down mycotoxins.

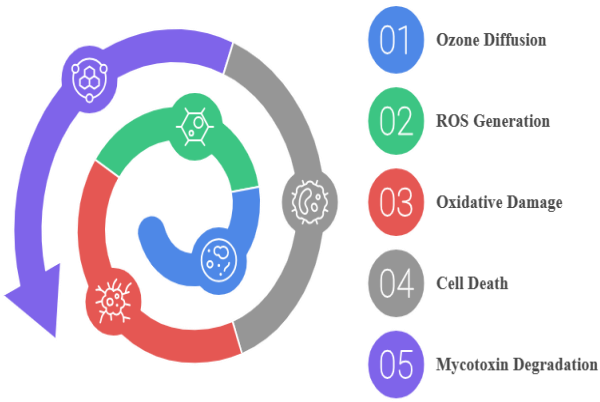

Figure 3: Ozone treatment mechanism showing ozone diffusion into fungal cells, generation of reactive oxygen species (ROS), oxidative damage to cell membrane, proteins, and DNA, leading to cell death and mycotoxin degradation

3.2 Effect on Fungi and Mycotoxin Degradation:

Researchers have conducted extensive studies to evaluate how effective ozone treatment is at eliminating different fungi species which include Aspergillus, Penicillium and Fusarium. The solution effectively removed fungal contamination from food surfaces and storage areas which included grains, nuts and fruits (Oliveira et al., 2025). Ozone plays an essential role in destroying mycotoxins while simultaneously killing fungi. The chemical reaction with mycotoxin molecules results in the formation of less dangerous substances through the process of double bond cleavage which alters the molecular structur. The effectiveness of mycotoxin degradation depends on three main factors because different ozone levels and exposure times and mycotoxin types determine the degradation process (Zapaśnik et al., 2025).

3.3 Applications in Food Systems:

Fruits, vegetables and cereals and nuts have all been preserved through ozone usage in different methods of postharvest food preservation. The substance gets used in both gaseous and aqueous forms to disinfect surfaces that contact food and areas where food gets stored. Ozone works best for organic and minimally processed foods because it reduces microbial contamination on fresh produce surfaces without leaving dangerous residues (Parray et al., 2025). Ozone treatment gets employed in grain storage facilities to control fungal growth while preventing mycotoxin contamination during long storage periods. The substance becomes more ecofriendly and safer through its rapid transformation into oxygen (Pawale et al., 2025).

3.4 Limitations and Optimization Requirements:

Ozone treatment has some drawbacks that need to be taken into account despite its effective results. The high instability of ozone leads to its rapid decomposition which results in decreased effectiveness when it is not applied in controlled conditions. High exposure durations together with high levels of exposure lead to oxidative damage of food components which results in changes to their nutritional value and appearance and taste (Sujayasree et al., 2025). The antimicrobial efficiency of ozone treatment requires optimization of three factors which include ozone concentration, exposure duration and treatment conditions. The creation of regulated delivery methods together with combination treatment procedures will enhance the practical use of ozone

for food preservation (Pandiselvam et al., 2025).

4 UltraViolet (UV) Radiation in Food Preservation

4.1 Mechanism of Action:

Ultraviolet (UV) radiation refers to a form of electromagnetic radiation with wavelengths ranging from 100 to 400 nm, among which UVC (200–280 nm) is the most effective for microbial inactivation. UV treatment is widely applied as a non-thermal preservation method due to its ability to damage microbial DNA and inhibit replication (Zavala et al., 2026). The primary mechanism involves the absorption of UV photons by nucleic acids, leading to the formation of thymine dimers in DNA strands. These structural alterations interfere with DNA replication and transcription processes, ultimately resulting in the inactivation of microorganisms. In fungal cells, UV radiation can also induce oxidative stress and disrupt cellular metabolism, further contributing to growth inhibition (Pravallika et al., 2025). Figure 4 shows how ultraviolet radiation kills microbes through its antimicrobial effect which damages their DNA by creating thymine dimers that stop both replication and transcription processes, resulting in full fungal cell death that decreases food contamination.

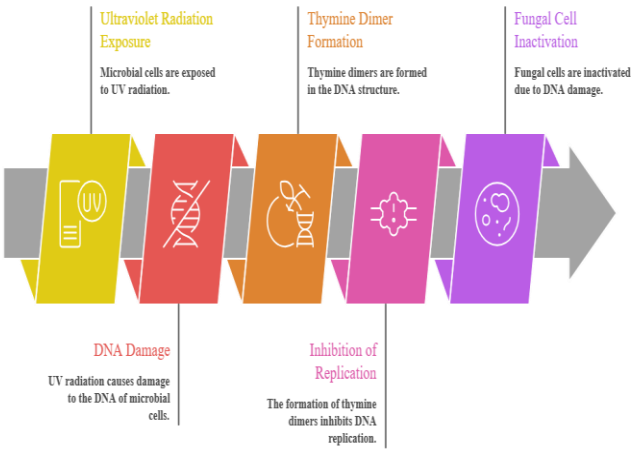

Figure 4: Ultraviolet radiation mechanism showing DNA damage in microbial cells, formation of thymine dimers, inhibition of replication and fungal cell inactivation

4.2 Effect on Fungi and Mycotoxins:

UV radiation has proven successful for decreasing fungal contamination rates which affect food surfaces that specially impact fresh fruits and vegetables and grains. The method works effectively for controlling surface fungi which include Aspergillus and Penicillium species. The treatment displays different effects on fungal spores because the results depend on the length and strength of exposure to the treatment (Drishya et al., 2022). The UV treatment process achieves two goals first it kills microorganisms and second it breaks down specific mycotoxins through photochemical reactions which change their molecular structure. Mycotoxin reduction results show limited effectiveness because various factors such as wavelength and exposure time and food composition determine the results (Yousefi et al., 2025).

4.3 Applications in Food Systems:

UV treatment serves as an effective method to disinfect the surfaces of food products and packaging materials and processing areas. The method shows its greatest effectiveness when applied to liquid foods, particularly fruit juices and beverages, which allow for uniform application of ultraviolet light. Postharvest handling uses ultraviolet irradiation to decrease microbial

contamination while extending product shelf life through chemical-free preservation methods (Tchonkouang et al., 2023). The combination of low operating expenses and simple implementation process and lack of chemical remnants makes UV technology an appealing choice for managing food safety in systems that require minimal food processing (Maioto et al., 2026).

4.4 Limitations and Challenges:

The surface decontamination of UV treatment is restricted by its ability to penetrate only the uppermost layer of materials. The solid and opaque nature of food products prevents UV light from reaching their inner parts which means that internal microorganisms remain unharmed. The presence of surface irregularities causes uneven exposure, which leads to incomplete microbial inactivation (Wang et al., 2024). Prolonged UV exposure results in unwanted food quality changes, which include discoloration, off-flavor development and nutrient degradation. The study results demonstrate that optimal treatment parameters require specific wavelength, intensity and exposure time settings to achieve effective microbial control while maintaining food quality (Molina-Hernandez et al., 2025).

5 Emerging Non-Thermal Technologies for Food Safety

5.1 Pulsed Electric Fields:

The emerging non-thermal pulsed electric field technology uses high-voltage electric pulses which operate in short intervals to destroy microorganisms during food processing. The primary mechanism of action involves electroporation which occurs when an electric field creates pores in microbial cell membranes, causing the cell membrane to lose its protective barrier, which results in cytoplasmic substances spilling out (Yousefi et al., 2025). The PEF system demonstrates its effectiveness when applied to liquid and semi-liquid food products which include fruit juices and milk and liquid eggs because these products allow for the establishment of a uniform electric field distribution. PEF controls fungal populations through its effectiveness against vegetative cells but like all non-thermal methods, it struggles to control fungal spores which show increased protection. PEF causes mycotoxin stability changes because it disrupts fungal metabolic functions which prevent toxin production. The field of PEF technology research remains constrained in its application to solid food materials because the technology cannot produce consistent electric fields and requires excessive power consumption. The industrial application of PEF technology requires both optimization work and the development of additional supporting systems (Yaya-González et al., 2025).

5.2 Cold Plasma Technology:

Cold plasma technology functions as an advanced non-thermal system which generates ionized gas to produce reactive species. The reactive elements in the system create interactions with microbial cells which results in oxidative damage to lipids and proteins and DNA, which leads to microbial death (Huang et al., 2026). Cold plasma technology shows strong effectiveness against multiple types of fungi and it specifically achieves success in mycotoxin degradation through chemical changes and oxidation processes. The system operates effectively in both its gaseous state and its plasma-activated water state, which enables its use across various food systems that include fresh produce and grains and packaging materials (Obileke et al., 2022). The food industry faces major obstacles from three main issues, which involve standardizing processes and making operations scalable and assessing their impact on food quality. The study requires additional research on how plasma-generated particles interact with complex food matrices in order to determine safe and consistent results (Nwabor et l., 2022).

5.3 Nanotechnology-Based Approaches:

Nanotechnology has emerged as a novel approach for improving food safety through the use of nanoparticles with antimicrobial and antimycotoxin properties. Metallic nanoparticles including silver (AgNPs) and zinc oxide (ZnO) and titanium dioxide (TiO_2) show potent antifungal effects because they disrupt cell membranes and create oxidative stress and they block normal cellular

functions (Teixeira et al., 2026). Nanotechnology enables the creation of nano-based coatings and packaging materials while also developing biosensors that detect fungal contamination and mycotoxins in real time. These innovations deliver substantial advantages which improve food preservation and monitoring systems. The widespread use of nanotechnology in food systems faces obstacles because of toxic substances and environmental effects and the need for regulatory approval. The safe implementation of the process requires organizations to complete full risk assessment and standardization procedures (Fikry et al., 2026).

5.4 Integrated and Hybrid Approaches:

Recent research has increasingly focused on the development of hybrid non-thermal technologies that combine multiple preservation methods to overcome individual limitations. For instance, the integration of HPP with mild heat, or the combination of cold plasma with ozone or UV treatment, has shown synergistic effects in enhancing microbial inactivation and mycotoxin degradation (Naseem et al., 2026). These combined approaches improve overall efficiency, reduce treatment intensity, and more effectively preserve food quality than single-method applications. Consequently, hybrid technologies represent a promising direction for future research and industrial-scale food processing (Wang et al., 2026). Table 1 presents a comparative analysis of major non-thermal technologies used in food preservation, showing their operational mechanisms, main benefits and limitations, and typical industrial uses for fungal contamination control and postharvest food safety enhancement (Molina-Hernandez et al., 2025; Yaya-González et al., 2025). The element shows a comparison between different non-thermal methods, including high-pressure processing (HPP), ozone and ultraviolet radiation (UV), pulsed electric fields (PEF), cold plasma, and nanotechnology, to demonstrate their operating principles, main benefits and drawbacks, and their use in contemporary food safety systems.

Table 1: Comparative Analysis of Non-Thermal Technologies:

Technology	Mechanism	Advantages	Limitations	Applications
HPP	High pressure disrupts cell membranes and proteins	High microbial inactivation, preserves quality	Expensive, limited for dry foods	Juices, dairy, RTE foods
Ozone	Oxidation via ROS	No residue, strong antimicrobial	Unstable, affects nutrients	Fruits, grains, storage
UV	DNA damage (thymine dimers)	Low cost, easy to use	Low penetration	Surface treatment
PEF	Electroporation of membranes	Effective in liquids	Limited in solids	Juices, milk
Cold Plasma	ROS & RNS damage cells	Highly effective, versatile	Scaling issues	Fresh produce, packaging
Nanotechnology	Nanoparticle interaction with cells	Advanced detection & control	Toxicity concerns	Packaging, sensors

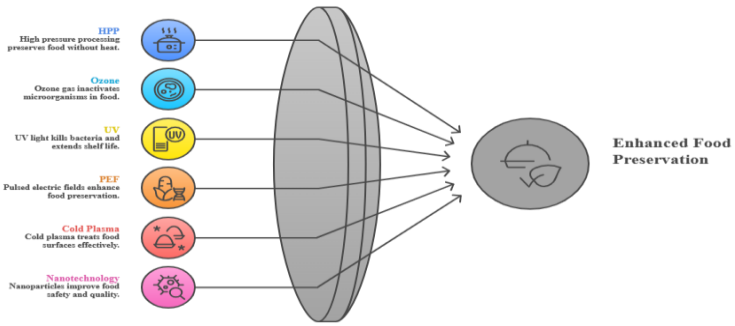

Figure 5: The infographic presents a comparison of non-thermal food preservation technologies which include HPP and ozone and UV and PEF and cold plasma and nanotechnology through their respective mechanisms and benefits and drawbacks while using modern scientific design elements.

6 Future Perspectives and Research Directions:

The application of non-thermal technologies for the control of fungal contamination and mycotoxins has shown significant potential however, several challenges remain to be addressed for their effective large-scale implementation. Future research should focus on improving the efficiency and consistency of these technologies under diverse food processing conditions. The optimization process requires operational parameters to be studied specifically for treatment intensity and exposure time and environmental conditions which need to be optimized to achieve dependable and consistent outcomes. The current state of non-thermal technologies presents a problem because their ability to scale up operations remains unproven. The laboratory testing of various techniques produced positive outcomes but industrial-scale implementation requires both technological progress and methods to reduce expenses and standardize operating procedures. The solutions to these problems need to be solved before commercial food processing systems can widely use these methods. Researchers have started to investigate new methods that use multiple non-thermal technologies through hybrid and integrated system development since the last few years. The combined treatments enable better microbial inactivation results with mycotoxin degradation through their synergistic effects which also decrease the operational challenges of the separate methods. The strategies provide an effective method to create better treatment results which lead to improved food safety outcomes. The advanced technologies which include artificial intelligence smart sensors and real-time monitoring systems will transform how postharvest food safety management operates. The AI-driven models enable organizations to forecast contamination threats while they fine-tune processing methods and maintain product quality throughout their entire food supply chain. Biosensors together with smart detection systems enable users to swiftly and precisely detect fungal contamination and mycotoxin presence which helps them take quick action to stop food waste. The existing research needs new studies to evaluate the extended safety of non-thermal technologies and their acceptance by regulatory bodies and their effects on the environment. The food industry needs comprehensive risk assessments and standardized guideline development to achieve safe and sustainable use of their technologies. The development of non-thermal preservation methods for future food systems needs ongoing innovation and interdisciplinary teamwork to succeed.

7 Conclusion:

Non-thermal technologies serve as effective substitutes for standard thermal processing techniques which enhance postharvest food safety. The methods mentioned which consist of high-pressure processing and ozone treatment and ultraviolet radiation and pulsed electric fields and cold plasma and nanotechnology-based strategies have shown their capacity to stop fungal contamination while they maintain the nutritional and sensory characteristics of food products. The various technologies use different methods which include membrane disruption and oxidative damage and DNA modification and electroporation to achieve their goal of killing microorganisms. The efficiency of the system depends on three elements which include the specific food matrix and the actual processing conditions and the level of fungal spores and mycotoxins that exist. The widespread industrial use of these systems remains blocked because they have high operational costs and face issues with system penetration and scalability and regulatory requirements. The recent development of hybrid treatment systems together with new tools which include artificial intelligence and intelligent monitoring systems creates fresh possibilities to boost the operational efficiency of these systems. The new developments enable organizations to conduct quality control in actual time while they find the best processing conditions to build better food safety control systems. Non-thermal technologies provide sustainable solutions which deliver efficient and innovative methods to combat increasing challenges of fungal contamination and mycotoxin control in food systems. The research and technological development process will require ongoing research and technology optimization and interdisciplinary collaboration to achieve successful implementation of their technology at scale which will guarantee safe production of high-quality food in the future.

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