# A Review of Garlic and Onion Powder Food Safety Risks, Microbial Detection, and Inactivation Methods

Prepared for the American Spice Trade Association

by *Manita Adhikari, Karina Desiree, Peter Rubinelli, and Jennifer C. Acuff*

of the Food **S**afety, **M**icrobiology, **A**nd **R**esearch **T**echnology Lab at University of Arkansas System Division of Agriculture

Table of Contents

## Introduction

**Purpose:** This paper provides a summary of available food safety information related to dried onion and garlic in terms of relative pathogen prevalence, contamination routes, potential preventive controls, and knowledge gaps.

**Scope:** Included in this document are descriptions of observed and potential routes of contamination, examples of recalls of these spices, a summary of prevalence testing, and research findings about detection and mitigation of foodborne pathogens in dried onion and garlic products. Knowledge gaps are highlighted to indicate how industry stakeholders and researchers could proceed with focused research questions to better answer the overall issue of "what kind and how much contamination is expected in these spices?"

**Background:** There have not been any recorded outbreaks of foodborne illness specifically attributed to dried onion and garlic products. However, it is well accepted that spices may have very high microbial loads due to the nature of the processing steps. The potential for this contamination, coupled with the increased use of spices and new trends that incorporate these ingredients without a kill-step require inquiry into questions related to risk, prevention of contamination, and mitigation steps if or when contamination of these products occur. Like other spices, some intrinsic factors of these products can pose challenges when attempting to quantify microbial populations, such as pH and antimicrobial components. However, progress in the last decade to address these issues promises substantial progress for building on the few prevalence studies that have been conducted thus far.

## Dried Onion and Garlic Spices as Vehicles for Pathogens

Spices are used for food preparation globally at increasing rates to add flavor, aroma, and color, as well as in new product development and food preservation. A constant and steady increase of 2.9% (values based on FAO economic data: FAO, 2023) in the production of spices has been observed from 1990 to 2018, reaching 49.6 tons (Mathot et al., 2021). Like many other agricultural crops, spices are susceptible to microbial contamination before, during, and after harvest, but primarily during drying steps. The lack of suitable decontamination treatments, inadequate sanitary conditions, and environmental factors contribute to high levels of microbial contamination of all spice varieties (Mathot et al., 2021).

Spices present food safety risks that may not be immediately obvious to consumers since the drying process is not technically considered a sufficient "kill step." Although storage in a low-water activity environment prevents growth of bacteria and fungi, they may survive in the desiccated state for extended periods of time. Spices generally have high aerobic plate counts, and *Salmonella* and *Bacillus* have been isolated from many samples, including isolates harboring antibiotic resistance genes (Gyorgy et al., 2021). Furthermore, it is not uncommon for spices to be stored in refrigerated conditions to preserve quality aspects, which would also promote extended pathogen persistence.

Dried herbs and spices have been recalled more frequently in recent years, potentially due to better detection capabilities (Mathot et al., 2021). *Salmonella enterica*, *Bacillus* spp. (including *Bacillus cereus*), *Clostridium perfringens*, *Cronobacter* spp., *Shigella*, and *Staphylococcus aureus* are a few of the foodborne pathogens that have been identified in spices. Recently, 21 tons of onion powder manufactured in California and distributed throughout the U.S. and Canada was recalled due to *Salmonella* contamination (Food Safety News, 2023). The complexity of supply chains associated with spices and herbs and how they are used in other food products makes it more challenging to investigate outbreaks associated with spices. From 1973 to 2010, 14 outbreaks were linked to spices (FDA, 2017). Ten of these outbreaks were attributed to *Salmonella enterica* serotypes, while the remaining 4 outbreaks were attributed to *Bacillus* spp. The spices implicated with these outbreaks were black pepper, red pepper, white pepper, unspecified pepper, curry powder, anise seed, fennel seed, turmeric, a spice blend, and seasoning blend known to contain broccoli powder. One of the largest of these outbreaks occurred in 2010 involving *S.* Montevideo, affecting 272 people who consumed salami that included contaminated red and black pepper that were traced to two separate companies in New York and New Jersey (CDC, 2010). More recently, *S.* Weltevreden was found in onion and *S.* Mbandaka in garlic (FDA, 2017). Other recent outbreaks were a *Clostridium perfringens* outbreak affecting 30 people in Spain linked to cinnamon (Food Safety News, 2023), an outbreak of *S.* Oranienburg in raw onion in the U.S (CDC, 2023; FDA, 2010; FDA, 2021), and *Salmonella* in ground cumin (FDA, 2023). Though dried onion and garlic have not yet been specifically implicated in outbreaks thus far, the popularity of these products, growing reports of recalls and outbreaks of spices, and growing popularity of garlic and onion powders as among the most popular spices worldwide surely emphasize the need investigate the microbial safety of these products.

## Processing and Potential Routes of Contamination

Several points exist in the production chain where spices can become contaminated. The ingredients are frequently grown on small farms in spice-producing countries and then sold and combined with harvests from other farms, making tracking or holding product with necessary controls immensely challenging if not impossible. The spices are usually dried outside in the open environment before being sent to companies to be processed and packaged. Storage prior to dehydration may take place outside or within controlled refrigerated storage, which could allow for further contamination or long-term persistence of pathogens in cooler conditions that limit microbial metabolism. Most safety gaps are basic, like failing to restrict animal and insect access to products throughout harvest, processing, or storage, or failing to respect the rules of hygiene and cleaning.

According to the FDA Risk Profile on Pathogens and Filth in Spices (2017), there are several points throughout the production process where spices—such as garlic and onion powders—can be contaminated, starting at the farm level. In contrast with many spices and herbs that are grown above ground, garlic and onion are grown below ground with direct soil contact. Animals in the production environment may introduce pathogens or filth, which may remain in soil, irrigation water, or manure-amended soil for an extended time. Additionally, the practice of sun-drying spices may expose food products to animal droppings and mold growth. Contamination from workers, such as when spices are hand-picked or handled throughout the production process, should also be considered. During processing, inadequate cleaning and sanitation equipment and food contact surfaces may introduce pathogens to the food product. This may also lead to cross contamination, especially when raw and post-pathogen treated spices are passed through the same pipe or contact the same equipment. Once pathogens have been introduced to the food product, pathogens such as *Salmonella enterica* can survive in desiccated, low water activity storage conditions for an extended time.

Following the initial harvest, fresh garlic and onion are processed to powders by undergoing several steps (Figure 1). In the U.S., most of these steps are done in an automated production line. Following inspection for bruises and visual defects, garlic bulbs are cracked into cloves. Garlic cloves and onion heads are peeled and washed to remove debris. Peels are separated to the bottom of the conveyor with water circulation and gravity, after which the garlic cloves and onion heads are sliced into 1.5-3 mm slices to ensure uniform drying. Sliced products are dehydrated using a fully automatic continuous dehydrator to initially lower moisture content of the product. Then, products are further dried at 65-80°C (10-40% RH, 1-4 m/s air velocity) for at least 5 hours to remove >90% moisture. Garlic and onion slices must be initially dehydrated before drying to ensure optimal drying time thus minimizing exposure to high temperature that might degrade final product quality (i.e., odor, flavor, quality). Following drying, dried garlic and onion are stored as semi-dried products. During the milling process, garlic and onion semi-dried products are rehydrated to 6% moisture and then milled to differently sized granules: chopped (5-8 mesh), minced, (8-16 mesh), and powder (>80 mesh). Final products are sifted using corresponding mesh sizes, packaged, and shipped.

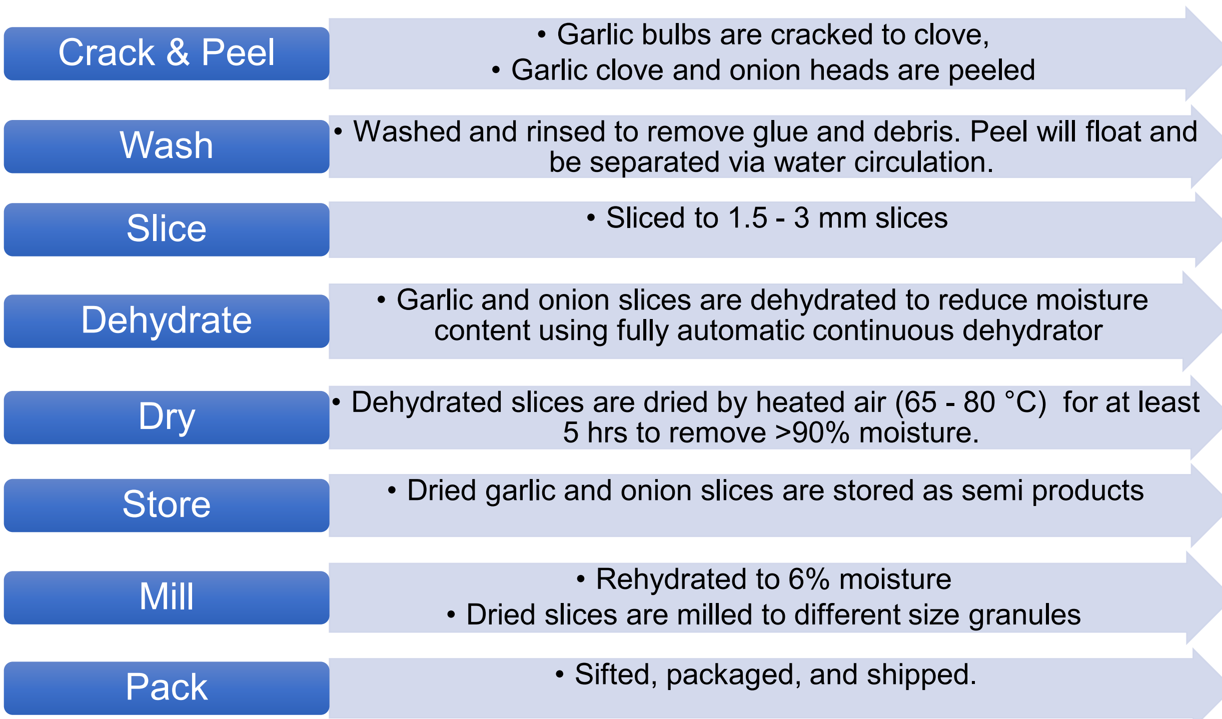


*Figure 1. Dried garlic and onion products processing (Gelgook, n.d.; Baixin Machinery, 2022; Medina and Garcia, 2007).*

## Microbial Diversity and Pathogen Prevalence in Dried Onion and Garlic

Though there are no known outbreaks associated with dried onion and garlic products, there have been recalls due to contamination of these products with pathogens. Given the difficulties in detection of pathogens from spices and previous assumption that these products would not be considered risky, it is possible that dried onion and garlic products may have been responsible for outbreaks without positive identification. Recurring examples of contamination of these products are described further to highlight the potential risks that require attention to dried onion and garlic.

Many studies specifically test spices for presence/absence of *Salmonella* and other pathogens. Van Doren et al. (2013) measured the prevalence of *Salmonella* in all shipments of imported FDA-regulated spices (including dried onion and garlic) from 2007-2009. Prevalence was defined as the number of items positive for *Salmonella* divided by the total number of items tested. *Salmonella* serotypes were also determined for these spice samples. *Salmonella* Mbandaka was found in garlic and other spices at a frequency of 5.4% of total *Salmonella*-contaminated shipments. *Salmonella*

Weltevreden was found in onion, along with other spices, at a frequency of 6.3% of total *Salmonella*-contaminated shipments (Van Doren et al., 2013). Banerjee and Sarkar (2003) assessed the microbiological quality of 27 spices purchased from retail outlets throughout India, presumably not regulated by FDA. *Bacillus cereus* and *Clostridium perfringens* were undetectable, but *Salmonella* and Enterobacteriaceae were detected in 17% of the garlic samples in the range of 2.0-3.0 log CFU/g and 1.0-3.0 log CFU/g, respectively. Six samples of garlic from six different Indian states were analyzed. All contained 3.0-3.9 log CFU/g aerobic mesophilic bacteria, bacterial spores in the range of 2.0-5.0 log CFU/g, and molds ranging from 1.0-4.0 log CFU/g (Banerjee & Sarkar, 2003).

Zhang et al., (2017) tested 11 spices collected from 1,406 imported shipments offered for entry to the United States from 2012 to 2015 for *Salmonella* prevalence. Of these 11 spices, ground garlic had the lowest prevalence (1.7%, 1 out of 59 samples) for *Salmonella*. Still, dried ground garlic tested at retail had a prevalence of 0.49% (3 out of 615 samples tested) of *Salmonella*. The prevalence at retail was not consistently and significantly different from the prevalence at entry, highlighting that although post-import treatments may reduce *Salmonella* populations for some spices, there is still a need for improvement (Zhang et al., 2017).

The presence or absence of specific pathogens in dried onion and garlic products should not be the only consideration when determining presumed prevalence of contaminating populations. Indicator organisms or overall microbial load may also be useful in understanding expected contaminants and prevalence. Hara-Kudo et al. (2006) analyzed 40 imported spices purchased in retail shops in Japan. Six different garlic products were tested (2 from China, 1 from USA, and 3 of unknown origin). Aerobic bacteria were present in the garlic products at a mean log CFU/g of 3.2 and ranged from 1.2 to 4.5 log CFU/g. Spore-forming bacteria were detected in some of the garlic products at a mean log CFU/g of 1.1 and ranged from <1.0 to 1.9 log CFU/g. No *Salmonella* were detected in the garlic products in this survey (Hara-Kudo et al., 2006).

Implementing food safety plans to limit or address potential contaminants could assist with both safety and quality issues for spice producers. Karam et al. (2021) collected 13 different spices, including garlic powder, from producers representing four different manufacturing categories: 1) following a food safety management system (FSMS) such as HACCP (i.e., certified); 2) non-FSMS (non-certified); 3) imported from France; and 4) bulk (unpackaged). Composite 100-g samples were analyzed using selective media for total aerobic plate counts, *E. coli,* coliforms, sulfite reducers, *C. perfringens*, yeasts/molds, and *Salmonella*. The results indicated unacceptably high aerobic plate counts for garlic powders of packaging categories 1, 2, and 4, according to standards of the International Commission on Microbial Specifications for Foods (ICMSF). Although garlic powders had no detectable coliforms, *E. coli*, or *Salmonella* in any of the packaging categories, *C. perfringens* was detectable (1 log CFU/g) in bulk garlic powder (category 4). Yeasts/molds in garlic powders of bulk and non-certified categories (2 and 4) were detectable and met or exceeded the acceptable ICMSF level (Karam et al., 2021). Though this survey had limitations in scope, it demonstrates the need for food safety management plans coupled with import/export regulations and accountability.

Klebukowska et al. (2015) investigated microbial quality of three different forms of garlic powder from three different producers and processed into powder by two different companies. These forms and samples consisted of four ground lyophilized samples, three granulated dried samples, and 19 ground dried samples. These were enumerated for total viable counts, lactic acid bacteria (LAB), Enterobacteriaceae, yeasts and molds, and *Bacillus*. The samples were also tested for presence/absence of *Salmonella*, and *Listeria monocytogenes*. Lyophilized garlic samples exhibited 3-5 log CFU/g LAB, 2-5 log CFU/g *Bacillus*, but no detectable Enterobacteriaceae, yeasts/molds, *Salmonella,* or *Listeria monocytogenes*. Granulated dried garlic samples exhibited 4 log CFU/g LAB, 1-3 log CFU/g molds, 2-3 log CFU/g *Bacillus*, and no detectable Enterobacteriaceae, *Salmonella,* or *Listeria monocytogenes*. Ground dried garlic samples exhibited 2-5.5 log CFU/g LAB, 1 of 19 were positive for Enterobacteriaceae (2 log CFU/g), 1-3 log CFU/g mold, 2-5 log CFU/g *Bacillus*, and no detectable *Salmonella* or *Listeria monocytogenes* (Klebukowska et al., 2015). *Bacillus* species present were identified as predominantly *Bacillus subtilis* and no *Bacillus cereus* was found (Klebukowska et al., 2015).

Although fungi are often viewed as a primarily quality issue for food manufacturers, some molds can grow and produce toxins under certain environmental conditions that can pose a safety risk to consumers. Tancinova et al. (2014) tested 67 spice samples. Of these 33 were positive for molds (49.3%). Eleven genera of molds were isolated from these spices with *Aspergillus* and *Penicillium* being the most common. *Aspergillus* section *Nigri,* known to produce ochratoxin A, was the most common isolate. Garlic powder contained *A. Nigri*, *Penicillium allii*, and *P. chrysogenum*. Onion powder contained *A. flavus*, *A. Nigri*, *P. glabrum*, and *P. chrysogenum*. Granulated onion contained *A. Nigri*, *Penicillium* spp., and *Rhizopus stolonifer*. Granulated onion exhibited detectable aflatoxin B and cyclopiazonic acid from *A. flavus*. Particularly if storage conditions are not heavily controlled to reduce moisture, toxin-producing molds could present food safety concerns in these products.

An additional layer of concerns about contamination of spices with pathogens are the potential for these contaminants to exhibit antibacterial resistance. Evaluating more than 50 different spices, Gyorgy et al. (2021) found detectable aerobic mesophilic and aerobic spore-forming bacteria (including *Bacillus cereus*) present in granulated and ground garlic originating from Austria and China, respectively, and in a pepper and garlic mix from Poland. The ground garlic from China also contained detectable (30 CFU/g) *Salmonella*. The *Bacillus cereus* detected in ground garlic from the sample from China was not characterized further, but a *Bacillus cereus* strain from ground pepper in the same study was found to be multi-drug resistant against beta-lactams, macrolides, aminoglycosides, and quinolones. A limitation of this study was that antibiotic resistance testing was limited to *Bacillus* isolates and not performed on *Salmonella* and

*Pseudomonas* isolates found. Brown and Jiang (2008) also investigated the prevalence of antibiotic resistant bacteria in 29 spice products, comparing 18 conventional versus 11 organic spices. The mean total bacterial counts in conventional garlic and onion powders tested were similar (4 log CFU/g), while organic garlic powder was about 1 log CFU/g lower. Nine antibiotics were tested on 52 bacterial isolates (26 from conventional and 26 from organic spice samples). Eleven isolates were identified as multi-drug resistant (3 or more antibiotics) and were comprised of seven *Bacillus* and four *Staphylococcus* species. Of these 11, 4 isolates were from organic garlic powder (*B. lentimorbus* and *B. cereus*) and 1 was from onion powder (*B. megaterium*) (Brown & Jiang, 2008).

The desiccation of onion and garlic products may stress and reduce some pathogen populations that have contaminated the raw ingredient by a small amount, but drying is not considered a sufficient kill step. Therefore, contamination of these raw ingredients and the ability to persist through the rest of the processing steps should be considered. Moreira et al. (2009) analyzed 15 samples of dehydrated green onion, along with other spices, sold in Sao Paulo, Brazil from Jan. 2004 to April 2006. The onion was positive for *Bacillus cereus* in 8.3% of samples, but no *Salmonella* or *S. aureus* was detected in onion. Two samples (16.6%) had unacceptably high levels of coliforms, but no additional details were given (Moreira et al., 2009). Bennett et al. (2003) conducted a 1-year prospective case-control study of a *Salmonella* outbreak in Australia which occurred in 1998-1999. Seventy-eight cases of *Salmonella* Virchow, an invasive form of *Salmonella*, were reported in early 1998 in the New South Wales region, compared to 24 cases in the same period a year earlier. One person died and 12 were hospitalized. Of the 54 cases followed up, 32 had *Salmonella* Virchow infections of the same phage type (PT8). All cases that had reported consuming semi-dried tomatoes had also consumed fresh garlic. *Salmonella* Virchow was present in 2 different semi-dried tomato sources that the cases had been traced back to. The only common ingredient of the two semi-dried tomato products was garlic imported from China (Bennett et al., 2003). *S.* Virchow could not be isolated from this garlic, presumably because of the antibacterial properties of the garlic (allicin).

## Difficulties and Developments in Detection of Pathogens in Dried Onion and Garlic

### Antimicrobial properties of garlic

Garlic on its own has been supported to have antimicrobial effects. These antimicrobial effects may be strong enough to limit recovery of microorganisms from these products with current techniques, but the effects are not likely strong enough to eliminate the need for preventive controls. Some studies have demonstrated the use of garlic as an ingredient to inhibit growth of pathogens and spoilage microorganisms in certain food systems. These include products such as sauces, meat, and other products in which garlic is normally added as part of its recipes. Ma et al. (2010) observed that adding fresh garlic and lime juice to salsa inactivated *Salmonella* cocktail from 3 log

CFU/g to undetectable levels after 7 days storage at 4°C. Leuschner et al. (2022) found that increasing concentration of dried garlic (1% garlic) in a nutrient broth, decreased the survival of *S.* enteritidis and *E. coli* O157 by 1 log and 3 log CFU/g, respectively over 3 days storage, suggesting that *E. coli* was more sensitive to the effect of garlic than *Salmonella*. In the same study, 1% garlic was added to mayonnaise inoculated with the same pathogens. Populations of both pathogens decreased by 1 log CFU/g after 3 days storage at 25°C. After 4 days of storage, both pathogen populations were below detection level (<100 CFU) but *S.* Enteritidis could still be recovered by enrichment even after 10 days of storage (Leuschner et al., 2022).

Uhart et al. (2006) explored the effect of garlic paste on *S.* Typhimurium survival in different media. The study found lower antimicrobial efficacy of garlic when introduced to complex media (i.e., food) compared to simple media such as nutrient broth. Specifically, *Salmonella* survival decreased by 3.4 and 1.5 log CFU/g in garlic paste and garlic paste + buffered peptone water respectively, compared to control samples after 10 days of storage; however, garlic paste was not able to decrease populations of *Salmonella* in ground beef when stored over the same number of days. This decreased antimicrobial effect of garlic in food as compared to simple media was also observed in Leuschner et al. (2002). Lastly, a study noted that the antimicrobial efficacy of garlic was also enhanced at elevated temperature (Adler et al., 2022). They found that a 4-log CFU/g reduction of *Salmonella* was achieved faster when raw garlic was added to butter and stored at 37°C, as compared to 21°C (24 h versus 6 h). The study also noted that incorporating raw garlic to butter reduced *L. monocytogenes* to non-detectable levels (ca. 5-log CFU/g reduction).

It is not surprising to observe that the method in which garlic is processed also has an impact on its antimicrobial efficacy. Najjaa et al. (2020) noted that the reduction in populations of *E. coli*, anaerobes and total mesophilic bacteria were higher when meat was treated with raw and freeze-dried garlic alone, as compared to oven dried garlic. This is consistent with the fact heat degrades allicin content—one of the main antimicrobial components in garlic (Li et al., 2020). Similar results were also found in a study by Rahman et al. (2006), where the study noted the largest inhibition diameter on bacteria plate treated with fresh garlic, followed by frozen dried garlic, and oven dried garlic. Higher temperature and longer drying time of garlic powder significantly decreased inhibition diameter. This trend was found in lactic acid bacteria, *S. aureus*, *S.* Typhimurium and *B. cereus*. Additionally, Sasaki et al. (2000) found that garlic powder from old garlic (i.e., open air dried for one year before milling) was able to reduce populations of *E. coli* O157 but its effect was less as compared to powder made from fresh garlic (i.e., processed immediately after harvest). These studies stressed that the antimicrobial substance in garlic powder is greatly affected by processing parameters, such as drying temperature and duration.

## Improved Detection Methods

While the benefits of antimicrobial properties of onion and garlic have been noted, the consequences of these properties can result in undetectable microbial populations. Some bacterial populations may not be detectable with typical testing methods in these foods because the antimicrobial properties inhibit the normal growth and isolation. Though undetected, these microorganisms can still survive and cause illness. There are two main methods for detection of microorganisms in spices: pre-enrichment in broths and diluents that dilute or counter antimicrobial components followed by traditional plating and isolation, and incorporation of ingredients to allow rapid detection using Real-Time Polymerase Chain Reaction (RT-PCR). Both methods have their own efficiencies and limitations.

The Bacteriological Analytical Manual (BAM) is the current FDA standard detection and isolation procedure for *Salmonella* in spices (FDA, 2015; FDA, 2023). Chapter 5 of BAM (*Salmonella*) provides various pre-enrichment procedures, dependent on the type of spice. The current FDA BAM approach is intended to dilute these compounds beyond their hazardous concentrations for the identification and isolation of *Salmonella* from spices containing antimicrobial properties. Allspice, cinnamon, and oregano, for example, are pre-enriched at a sample/broth ratio of 1:100, while cloves are pre-enriched at a sample/broth ratio of 1:1000. None of the current approaches, however, completely neutralize the antibacterial compounds found in spices like allspice, cinnamon, and cloves. Onion flakes, onion powder, and garlic flakes are recommended to be pre-enriched with TSB supplemented with 0.5% $K_2SO_3$ (adjusted to pH 6.8 if necessary) for 24 hours at 35°C (25 g into 225 mL). Following the pre-enrichment, 0.1 mL of the mixture is transferred to Rappaport Vassiliadis broth and 1.0 mL to tetrathionate broth for 24-h incubation. Positive tubes are streaked for isolation on a selective agar medium for 24 hours for observation and identification of colonies. Testing spices for foodborne pathogens can be time-consuming and labor-intensive, since it may require a sample-to-broth ratio up to 1:100 or 1:1000 (Barrere et al., 2020; FDA, 2023). This requirement makes it difficult to fulfill the BAM sampling plan, which typically prescribes for an analysis of 15 25-g samples (FDA, 2015). The time, resources, and physical space required to execute this procedure highlights the difficulty encountered in following this procedure. Furthermore, the dilution to neutralize antimicrobial properties subsequently diminishes the sensitivity of detection.

In the study done by Barrere et al. (2020), *Salmonella* was recovered from onion samples incubated in buffered peptone water (BPW), but only when the sample to broth ratio was greater than 1:9 due to a lack of buffering capacity. Similarly, 2x BPW had no effect on the pH of onion enrichments, and *Salmonella* could only be recovered by increasing the sample to broth ratio. *Salmonella* could not be recovered from garlic regardless of sample to broth ratio or broth (BPW, 2x BPW) used. Allicin is a bioactive component in garlic with antibacterial effects that work against a wide variety of microbes (Fujisawa et al., 2009). These substances may prevent *Salmonella* from proliferating or interfere with its ability to recover in enrichment media.

As mentioned in the study done by Barrere et al. (2020), when L-cysteine was introduced to 2x BPW in the previous experiment, turbidity (OD600) was measured in test tubes (1:100 ratio) with and without L-cysteine. Turbidity was seen exclusively in the tubes with a 1:9 ratio of garlic spice and broth containing L-cysteine, meaning *Salmonella* could proliferate and survive in a 1:9 garlic to broth ratio in the presence of L-cysteine at 30mmol/L in 2x BPW. Real-Time Polymerase Chain Reaction (RT-PCR) and electrophoresis verified the observation. A similar observation was made for onion powder at a sample-to-broth ratio of 1:9. Assays employing 25g of garlic in 225 mL of broth supported the prior observations (Barrere et al., 2020). The reason for this may be that the addition of an SH-compound, such as cysteine or glutathione, fully abolished the antimicrobial properties of allicin. All of the SH-compounds examined, including cysteine, glutathione, and coenzyme A, demonstrated a blocking action that reduced the antibacterial effectiveness of allicin (Fujisawa et al., 2009; Kyung et al., 2002).

Castelijn et al. (2023) also studied the effect of different spices on growth and detection of *Salmonella* and STEC in ISO standard methods and found that by replacing BPW with Tryptic Soy Broth (TSB), antimicrobial activity in onion powder was successfully neutralized, but not garlic. This was possibly due to the higher content of allicin or the presence of other antimicrobial inhibitors in garlic as compared to onion. However, when 0.5% $K_2SO_3$ was added to TSB, $K_2SO_3$ counteracted the antimicrobial activity of onion, mustard seed, galanga, garlic and cinnamon powder, as both *Salmonella* and STEC were detected after incubation. Although this is true for onion, garlic, and cinnamon powders (Wilson & Andrew 1976; Lins, 2018b) and is in line with other investigations, the precise mechanism by which $K_2SO_3$ inhibits antimicrobial substances is unknown (Barrere et al., 2020; Kim et al., 2004; Lins, 2018a). It is thought that sulfite reacts with disulfide bonds (Kim et al., 2004; Lins, 2018a), but not all antimicrobial substances derived from onion, mustard seed, galanga, garlic, and cinnamon contain sulfur. Also, increasing the dilution factor by 100 times (rather than 10 times) in the primary enrichment with $K_2SO_3$ managed to neutralize onion powder but not garlic powder. Moreover, PCR inhibitors were not present in onion and garlic powder with the current detection method or when the primary enrichment was altered.

The second method is a Real-Time Polymerase Chain Reaction (RT-PCR) method. After 18 hours of incubation, Qiagen instruments detected *Salmonella*. QIAsymphony and QIAcube enabled the extraction of DNA from dried *Salmonella* in spice samples in a timely and accurate manner. A signal (Ct value) was obtained for onion (and other spices) at 3000 and 300 CFU, but only at 3000 CFU for garlic. For 15 CFU, a signal could not be detected by RT-PCR for garlic and onion. Based on the chemical characteristics of DL-serine and L-cysteine, *Salmonella* growth occurred in 18 hours of incubation with a sample to broth ratio of 1:9 (and 1:20). RT-PCR allowed rapid detection of *Salmonella* in less than 24 hours, including the incubation of 150 cells found in 25 g of food sample (Barrere et al., 2020). The DNA extraction was done with Qiagen tools and did not require any professional support during the 40-45-minute process, a particular improvement over the other labor-intensive method. Another advantage to the method was that the DNA extracts did not include any PCR inhibitors when employing 400 µL of elution volume with QIAsymphony or 150 µL of elution volume with QIAcube. The authors concluded that the investigated approach is faster and easier to perform than BAM for *Salmonella* (Barrere et al., 2020; FDA, 2007).

In conclusion, there is no universal enrichment or molecular detection assay to detect *Salmonella* or STEC across spice varieties; methods must be specific to each food product (Castelijn et al., 2023). Utilizing the Most Probable Number method of quantifying microorganism can be a preferred and appropriate method used by the food industry when low concentrations of microorganisms are expected. However, this method utilizes stepwise enrichments and statistical calculations based on the dilutions to provide an estimated number of growth units (as opposed to bacterial colony forming units) within a 95% confidence interval. The application of this method to detect and quantify pathogens in dried onion and garlic powders would be limited and is not commonly used by researchers in studies or for testing prevalence levels.

## Reducing Microbial Contamination in Dried Onion and Garlic

There are many points in spice production that contamination can occur. In the event that pathogens enter the system, mitigation practices should be investigated and optimized so they can be implemented to address the contamination. Preventive controls and the identification of critical control points could be utilized to reduce contamination risks of dried garlic and onion productions.

### Thermal Treatments

Drying is one of the oldest, most common, and cheapest methods of food preservation. Although the terms drying and dehydration have distinct meanings, they are often used interchangeably (Saravacos & Kostaropoulos, 2022). By lowering water activity of food, microorganism growth, oxidative and enzymatic reactions are inhibited, thereby prolonging the shelf life of products. Moreover, the high temperature used in most drying/dehydration technologies has the potential to inactivate microorganisms. There is increasing evidence that spores and vegetative cells of pathogens are more likely to develop heat resistance as the water activity of a product decreases (Smelt & Brul, 2014; Syamaladevi et al., 2016). Therefore, the ability of different types of drying and dehydration technologies to inactivate pathogens in dried garlic and onion products must be considered.

Zhang et al. (2017) investigated the survival of a *Salmonella* cocktail in garlic during oven drying and found that higher *Salmonella* inactivation was correlated with higher drying temperature and lower starting inoculum level. At a medium inoculum level (4-5 log CFU/g), *Salmonella* was not detected after 420 min and 150 min when dried at 80°C and 90°C, respectively. At a high inoculum level (7-8 log CFU/g), *Salmonella* remained at 3.5 log CFU/g after 8 hours of drying and was not detected after 360 min when dried at 80°C and 90°C, respectively. However, higher temperature and longer drying time significantly decreased antimicrobial compounds and changed the volatile profile of garlic powder (Rahman et al., 2006; Li et al., 2020).

Interest in radiofrequency (RF) heating of spices is growing due to faster heating, better quality products, and higher energy efficiency. Liu et al. (2002) found that onion powder processed using a combination of RF and then oven heating at 66°C for 210 s and 38 h, respectively reduced 3.4 log of *Salmonella* Enteritidis in onion powder. This reduction is approximately 1.3 log CFU/g higher, compared to onion powder that is subjected to the hot air control (48 h at 66°C). Moreover, it took much shorter time for RF to heat the cold spot of 500 g onion powder to 66°C, compared to hot air alone (190 s versus 2.3 h), suggesting that the rapid heating rate may prevent the development of heat shock proteins from developing in *S.* enteritidis. Additionally, it was also noted that the volatile retention of RF processed onion powder was superior, compared to those processed by hot air. There is minimal inactivation study on RF processed garlic powder, but Ozturk et al. (2018) found that garlic powder took a relatively longer time to heat up by RF, compared to other spices due to its low dielectric constant. Both studies discussed the challenge of uniform heating in RF which highlights the need for process optimization for the application of this technology in spice powders.

Superheated steam drying has also been investigated to inactivate pathogens in dried garlic and onion powder. Jo et al. (2019) found that combining germinant compounds with superheated steam completely inactivated *B. cereus* spores without evidence of sublethal injury. Phungamngoen et al. (2011) attributed low pressure superheated steam with higher *Salmonella* inactivation rate compared to convective air drying due to higher heating rate. There are other drying technologies being used for spice production; however, studies using those technologies on garlic and onion powder are minimal. Nevertheless, it should be noted that freeze drying alone is not a good pathogen inactivation strategy regardless of food product as it has high bacteria survivability (Bourdoux et al., 2016).

Another factor for consideration is how a flow agent, such as silicon dioxide ($SiO_2$) could impact efficacy of thermal treatments. The difference in particle size and conductivity would likely affect the transfer of heat throughout a product during a thermal treatment, but the extent to which it might reduce heat transfer is unknown. Some dried spice products, particularly mixes and blends, are more likely to contain flow or anti-caking agents, which might be accounted for in benchtop laboratory studies investigating pathogen reduction from individual dried spices. This emphasizes the need for in-plant validations with products in their final form and proportion.

## Non-Thermal Treatments

There is an increasing demand for non-thermal processing of spices, which will potentially allow the inactivation of pathogen and spoilage microorganisms without compromising the sensory quality and nutritional properties of food products. The use of irradiation, cold plasma, high pressure processing, ozone, and UV-LED on the microbiological quality of garlic and onion powder have been investigated in multiple studies.

Approximately one-third (175 million pounds) of the commercial spices consumed in the United States are irradiated annually (Eustice & Bruhn, 2012). Irradiation damages the genetic material of microorganisms in food products thereby inactivating them with minimal impact to product's sensory quality. Farkas (1998) suggested a minimum gamma ray dose of 3–10 kGy to improve the microbiological safety of spices. The American Society for Testing and Materials (ASTM International, 2010) suggested minimum gamma ray dose of 7–12 kGy for onion powder. Multiple studies explored the capability of gamma ray radiation to inactivate pathogens in garlic and onion powder. Arias-Rios et al. (2019) found a minimum absorbed dose of 8.5 kGy would be required to achieve a 5-log10 reduction in population based on the largest D10-value reported in talc inoculated spices. Moreover, *Enterococcus faecium* was supported to be a suitable surrogate for *Salmonella* in talc-inoculated spices and could be adopted for industrial validation study. Pezzutti et al. (2005) and Oh et al. (2003) enumerated total aerobic bacteria on garlic and onion powder before and after irradiation treatment. A 2.3 and 1.9 log CFU/g reduction of total aerobic bacteria was observed in garlic and onion powder, respectively after 10 kGy radiation exposure (Oh et al., 2003). Similarly, Pezzutti et al. (2005) noted an approximate 4.0-4.6 and 3.0-3.2 log reduction in garlic and onion powder after 10 kGy radiation treatment. The higher sensitivity of aerobic bacteria to radiation in garlic powder is attributed to the presence of allicin, a natural antimicrobial substance in garlic. Additionally, Pezzutti et al. (2005) also demonstrated that the 15 kGy treatment was able to inactivate spores of aerobic bacteria, *Clostridia* spp., and *Bacillus* spp. to non-detectable levels. Although irradiation claimed to have minimal change in sensory quality, a study by Duncan et al. (2017) found that sensory panelists were able to detect significant differences between the color and odor of irradiated and non-irradiated onion powder, with the irradiated powder being redder as compared to non-irradiated control powder. Conversely, gas chromatography mass spectroscopy (GC-MS) analysis did not reveal significant differences in volatiles. Irradiation seems to be a promising technology to ensure the safety of these spice powders; however, challenges concerning it include high adoption cost and inconsistent consumer acceptability.

Studies have also been done on cold plasma to inactivate pathogens in onion powder. Won et al. (2016) treated onion powder with dielectric barrier discharge-cold plasma (DBD-CP; 9 kV, 20 minutes) and found 2 log CFU/cm$^2$ reduction of *S.* enteritidis, and 1 log CFU/cm$^2$ reduction of *Escherichia coli* (*E. coli*) O157:H7 and *Listeria monocytogenes* without significant change in product's color. The study also noted that increasing a powder's particle size reduced the pathogen reduction by the same cold plasma treatment (1 log difference for *L. monocytogenes and E. coli* O157:H7; 0.5 log difference for *S.* enteritidis). Another study by Kim and Min (2017) supported that combining moisture vaporization to DBD-CP at 15 kHz for 20 min resulted in higher log reduction of pathogens than DBD-CP alone, specifically 3.1, 1.4, and 1.1 log CFU/cm$^2$ for *S.* Enteritidis, *E. coli* O157:H7, and *L. monocytogenes*, respectively. Microwave powered cold plasma at 400 W for 40 minutes was also found to inactivate spores of B. cereus and Aspergillus by 2.3 log spores/g and 1.5 log spores/cm$^2$, respectively (Kim et al., 2017). The same study also noted that high density plasma was more effective at inactivating these spores as compared to low density plasma, especially at longer treatment time due to higher formation of reactive oxygen species. Quality analysis conducted on the plasma treated on samples showed no difference in color, moisture content, and functional substances compared to non-treated samples; however, volatile profile was affected (Kim & Min, 2018; Kim et al., 2017). Minimal inactivation studies were found on cold plasma treated garlic powder.

Individual and combined treatments of ozone and UV have also gained popularity in ensuring food safety in spices. Darra et al. (2021) showed that individual treatments of ozone, ultraviolet (UVC) and far infrared (IR) on dried onion flakes were able to reduce *E. coli* by 2.8-3.4 log CFU/g to non-detectable levels after 30 minutes. The same study also found that the sequential treatments of ozone with UVC and IR combined gave improved results than individual treatments alone by stimulating more damage to the cell envelope. Specifically, the reductions achieved by combined treatment was 2.69 log higher, compared to each of the individual treatments. However, it should be noted that this study enumerated laboratory strain *E. coli* (K12 derivative without temperate bacteriophage lambda and F plasmid), which might skew the results. A study by Nyhan et al. (2021) explored the use of UV-LED, a more economical and sustainable alternative than UVC, to inactivate pathogens in garlic and onion powder. The study found that *L. monocytogenes*, *E. coli*, *B. subtilis*, and *S.* Typhimirium were reduced by 2.0 – 2.5 logs CFU/g when exposed to 270 nm UV-LED for 40 seconds. No significant differences between reductions were observed between onion and garlic powder at multiple sampling points. Furthermore, smaller particle size and higher water activity were also not associated with increased inactivation by UV-LED (Nyhan et al., 2021). Unfortunately, no quality testing was conducted on any of the ozone and UV studies mentioned. This study supported that the use of UV-LED is an efficient and cost-effective way to ensure food safety of spices, as compared to conventional UVC.

Treating garlic products with high hydrostatic pressure processing (HPP) has also been explored in multiple studies as an alternative to thermal processing. However, it is important to note that all studies concerning HPP used wet ground garlic or or garlic paste, instead of a dry powder. For HPP to work effectively, the food product needs to have high content of free water available ($a_w$> 0.96) to transmit the pressure, which makes HPP a challenging to be implemented on low water activity products (Garcia, 2021). Regardless, Park et al. (2019) found that wet garlic powder treated with HPP (600 MPa for 5 min) exhibited a 2 and 1 log CFU/g reduction of total aerobic bacteria and yeast and mold, respectively. The treatment also maximized the antioxidant substances in the product, while minimized the diallyl disulfide content responsible for the undesirable pungent odor of garlic. Eroman Unni et al. (2012) found similar results in which the study compared the effectiveness of thermal pasteurization (90°C for 5 min) versus HPP (600 MPa, 30°C, 5 min) on microbial activation and sensory quality of garlic paste. They found that the microbial inactivation between both were comparable—2-log CFU/g reduction for total aerobic count, 1-log CFU/g reduction of coliform and yeast and mold until non detectable level. Interestingly, sensory panelists rated HPP-treated samples to be superior compared to their thermally treated counterpart. In addition to the unsuitability of HPP on spices, there are also concerns about its low efficacy in inactivating spores.

## Conclusions

With the Food Safety Modernization Act's Preventive Controls for Human Foods Rule, many food industry members must implement preventive controls. Determining the parameters around this process include understanding contamination routes, prevalence levels, and pathogen resistance to interventions. Prevalence studies of dried garlic and onion products indicate a wide, and sometimes high, range of contamination levels. Many studies determine presence/absence because quantification can be challenging and expensive, but the studies that quantify contamination note up to 3-4 log CFU/g of aerobic bacteria, spore-formers, and *Enterobacteriaceae*. Several other food industries are required or advised to achieve 5-log reductions with preventive controls, but because dried herbs and spices can be delicate and easily degraded by thermal and nonthermal treatments, the industry would benefit from extensive investigation with evidence defending a lower reduction requirement. However, no such evidence or justification currently exists. Furthermore, current detection method constraints limit how much confidence can be placed in abilities to detect presence/absence of pathogens and even study effective preventive controls. While progress has been made in this particular area of research, there are still many gaps that require investigation in order to advise dried onion and garlic producers on best practices to increase food safety of their products.

## References


1. Adler, B. B., & Beuchat, L. R. (2002). Death of *Salmonella*, *Escherichia coli* O157:H7, and *Listeria monocytogenes* in garlic butter as affected by storage temperature. *Journal of Food Protection*, *65*(12), 1976–1980. https://doi.org/10.4315/0362-028X-65.12.1976
2. Arias-Rios, E. V., Acuff, G. R., Castillo, A., Lucia, L. M., Niebuhr, S. E., & Dickson, J. S. (2019). Identification of a surrogate to validate irradiation processing of selected spices. *LWT*, *102*, 136–141. https://doi.org/10.1016/j.lwt.2018.12.018
3. ASTM International. (2010). *Standard guide for irradiation of dried spices, herbs, and vegetable seasonings to control pathogens and other microorganisms*. https://allcivilstandard.com/wp-content/uploads/2019/02/F-1885.pdf Accessed Feb. 13, 2024.
4. Baixin Machinery. (2022). *Onion Powder Processing Process, Onion Powder Processing Machinery-Henan Baixin Machinery*. https://www.bxdryer.com/news/industry-news/onion-powder-processing-machinery.html Accessed Feb. 13, 2024.
5. Banerjee, M., and Sarkar, P. K. (2003). Microbiological quality of some retail spices in India. *Food Research International* 36, 469–474. doi: https://doi.org/10.1016/S0963-9969(02)00194-1.
6. Barrere, V., Tompkins, E., Armstrong, M., Bird, P., Bastin, B., & Goodridge, L. (2020). Optimization of *Salmonella* detection in garlic, onion, cinnamon, red chili pepper powders and green tea. *International journal of food microbiology*, *316*, 108440. https://doi.org/https://doi.org/10.1016/j.ijfoodmicro.2019.108440
7. Bennett, C. M., Dalton, C., Beers-Deeble, M., Millazo A., Kraa, E., Davos, D., et al. (2003). Fresh garlic: a possible vehicle for *Salmonella* Virchow. *Epidemiology & Infection* 131, 1041–1048. doi: 10.1017/S0950268803001158.
8. Bourdoux, S., Li, D., Rajkovic, A., Devlieghere, F., & Uyttendaele, M. (2016). Performance of drying technologies to ensure microbial safety of dried fruits and vegetables. *Comprehensive Reviews in Food Science and Food Safety*, *15*(6), 1056–1066. https://doi.org/10.1111/1541-4337.12224
9. Brown, J. C., and Jiang, X. (2008). Prevalence of antibiotic-Resistant Bacteria in Herbal Products. *Journal of Food Protection* 71, 1486–1490. doi: https://doi.org/10.4315/0362-028X-71.7.1486.
10. Castelijn, G. A. A., de Lange, L., & van der Voort, M. (2023). Effect of spices on the growth and detection of *Salmonella* and Shiga toxin-producing *Escherichia coli* in ISO standard methods. *Available at SSRN 4473501*. Accessed Feb. 13, 2024.
11. Centers for Disease Control and Prevention (CDC). (2010). Montevideo infections linked to red and black pepper/Italian-style meats. https://www.cdc.gov/*salmonella*/2010/montevideo-5-4-2010.html Accessed Feb. 13, 2024.
12. Centers for Disease Control and Prevention (CDC). (2023). *Salmonella* outbreak linked to fresh diced onions. https://www.cdc.gov/salmonella/thompson-10-23/index.html. Accessed Feb. 19, 2024.
13. Duncan, S., Moberg, K., Amin, K., Wright, M., Newkirk, J., Ponder, M., Acuff, G., & Dickson, J. (2017). Processes to preserve spice and herb quality and sensory integrity during pathogen inactivation. *Journal of Food Science*, *82*. https://doi.org/10.1111/1750-3841.13702
14. El Darra, N., Xie, F., Kamble, P., Khan, Z., & Watson, I. (2021). Decontamination of *Escherichia coli* on dried onion flakes and black pepper using infra-red, ultraviolet and ozone hurdle technologies. *Heliyon*, *7*(6), e07259. https://doi.org/10.1016/j.heliyon.2021.e07259

15. Eroman Unni, L., Chauhan, O. P., & Raju, P. S. (2014). High pressure processing of garlic paste: Effect on the quality attributes. *International Journal of Food Science & Technology*, *49*(6), 1579–1585. https://doi.org/10.1111/ijfs.12456
16. Eustice, R. F., & Bruhn, C. M. (2006). Consumer acceptance and marketing of irradiated foods. In *Food Irradiation Research and Technology* (2nd ed.). Wiley-Blackwell. https://onlinelibrary.wiley.com/doi/10.1002/9781118422557.ch10
17. Farkas, J. (1998). Irradiation as a method for decontaminating food: A review. *International Journal of Food Microbiology*, *44*(3), 189–204. https://doi.org/10.1016/S0168-1605(98)00132-9
18. FAO Statistics (2023). https://www.fao.org/statistics/en/ Accessed Feb. 13, 2024.
19. Food Safety News. (2023, June 9). *21 tons of onion powder recalled because of Salmonella*. Food Safety News. https://www.foodsafetynews.com/2023/06/21-tons-of-onion-powder-recalled-because-of-salmonella/ Accessed Feb. 13, 2024.
20. Food Safety News (2023). Ground cinnamon suspected as 30 sick in Spain. Available at: https://www.foodsafetynews.com/?s=*Clostridium+perfringens*+outbreak+cinnamon. Accessed Feb. 13, 2024.
21. Fujisawa, H., Watanabe, K., Suma, K., Origuchi, K., Matsufuji, H., Seki, T., & Ariga, T. (2009). Antibacterial potential of garlic-derived allicin and its cancellation by sulfhydryl compounds. *Bioscience, biotechnology, and biochemistry*, *73*(9), 1948-1955. https://doi.org/https://doi.org/10.1271/bbb.90096
22. García, O. (2021, July 23). *Products not suitable for High Pressure Processing (HPP).* https://www.hiperbaric.com/en/products-not-suitable-for-high-pressure-processing-hpp/
23. Gelgoog. (n.d.). *Complete Garlic Powder Production Processing Plant*. Accessed August 4, 2023, from https://www.gelgoogdryer.com/solution/garlic-powder-production-equipment.html
24. Gyorgy, E., Laslo, E., Antal, M., and Andras, C. D. (2021). Antibiotic resistance pattern of the allochthonous bacteria isolated from commercially available spices. *Food Science & Nutrition* 9, 4550–4560. https://doi.org/https://doi.org/10.1002/fsn3.2433
25. Hara-Kudo, Y., Ohtsuka, K., Onoue, Y., Otomo, Y., Furukawa, I., Yamaji, A., et al. (2006). *Salmonella* prevalence and total microbial and spore populations in spices imported to Japan. *Journal of Food Protection* 69, 2519–2523. doi: https://doi.org/10.4315/0362-028X-69.10.2519.
26. J. De La Cruz Medina & H.S. Garcia. (2007). *Garlic Post-harvest Operations*. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/av002e/av002e.pdf Accessed Feb. 13, 2024.
27. Jo, Y., Bae, H., Kim, S.-S., Ban, C., Kim, S. O., & Choi, Y. J. (2019). Inactivation of *Bacillus cereus* ATCC 14579 spore on garlic with combination treatments of germinant compounds and superheated steam. *Journal of Food Protection*, *82*(4), 691–695. https://doi.org/10.4315/0362-028X.JFP-18-401
28. Karam, L., Salloum, T., Hage, R. E., Hassan, H., and Hassan, H. F. (2021). How can packaging, source and food safety management system affect the microbiological quality of spices and dried herbs? The case of a developing country. *International Journal of Food Microbiology* 353, 109295. doi: https://doi.org/10.1016/j.ijfoodmicro.2021.109295.
29. Kim, J. E., Oh, Y. J., Won, M. Y., Lee, K.-S., & Min, S. C. (2017). Microbial decontamination of onion powder using microwave-powered cold plasma treatments. *Food Microbiology*, *62*, 112–123. https://doi.org/10.1016/j.fm.2016.10.006
30. Kim, J. H., & Min, S. C. (2018). Moisture vaporization-combined helium dielectric barrier discharge-cold plasma treatment for microbial decontamination of onion flakes. *Food Control*, *84*, 321–329. https://doi.org/10.1016/j.foodcont.2017.08.018

31. Kim, J. W., Huh, J. E., Kyung, S. H., & Kyung, K. H. (2004). Antimicrobial activity of alk(en)yl sulfides found in essential oils of garlic and onion. *Food Science and Biotechnology*, *13*(2), 235-239.
32. Klebukowska, L., Zadernowska, A., and Chajęcka-Wierzchowska, W. (2015). Microbiological contamination of dried and lyophilized garlic as a potential source of food spoilage. *Journal of Food Science and Technology* 52, 1802–1807. doi: 10.1007/s13197-013-1169-6.
33. Kyung, K. H., Kim, M., Park, M., & Kim, Y. S. (2002). Alliinase-independent inhibition of *Staphylococcus aureus* B33 by heated garlic. *Journal of food science*, *67*(2), 780-785. https://doi.org/https://doi.org/10.1111/j.1365-2621.2002.tb10676.x
34. Leuschner, R. G. K., & Zamparini, J. (2002). Effects of spices on growth and survival of *Escherichia coli* 0157 and *Salmonella enterica* serovar Enteritidis in broth model systems and mayonnaise. *Food Control*, *13*(6), 399–404. https://doi.org/10.1016/S0956-7135(02)00051-8
35. Lins, P. (2018a). Antimicrobial activities of spices and herbs against *Salmonella* Oranienburg. *Food Control*, *83*, 123-130. https://doi.org/https://doi.org/10.1016/j.foodcont.2017.05.041
36. Lins, P. (2018b). Detection of *Salmonella* spp. in spices and herbs. *Food Control*, *83*, 61-68. https://doi.org/https://doi.org/10.1016/j.foodcont.2017.05.040
37. Liu, S., Xiong, H., Qiu, Y., Dai, J., Zhang, Q., & Qin, W. (2022). Radiofrequency-assisted low-temperature long-time (LTLT) pasteurization of onion powder. *LWT*, *170*, 114002. https://doi.org/10.1016/j.lwt.2022.114002
38. Ma, L., Zhang, G., Gerner-Smidt, P., Tauxe and, R. V., & Doyle, M. P. (2010). Survival and growth of *Salmonella* in salsa and related ingredients. *Journal of Food Protection*, *73*(3), 434–444. https://doi.org/10.4315/0362-028X-73.3.434
39. Mathot, A. G., Postollec, F., & Leguerinel, I. (2021). Bacterial spores in spices and dried herbs: The risks for processed food. *Comprehensive Reviews in Food Science and Food Safety*, *20*(1), 840-862. https://doi.org/https://doi.org/10.1111/1541-4337.12690
40. Moreira, P. L., Lourenção, T. B., Pinto, J. P. A. N., and Rall, V. L. M. (2009). Microbiological quality of spices marketed in the city of Botucatu, São Paulo, Brazil. *Journal of Food Protection* 72, 421–424. doi: https://doi.org/10.4315/0362-028X-72.2.421.
41. Najjaa, H., Chekki, R., Elfalleh, W., Tlili, H., Jaballah, S., & Bouzouita, N. (2020). Freeze-dried, oven-dried, and microencapsulation of essential oil from *Allium sativum* as potential preservative agents of minced meat. *Food Science & Nutrition*, *8*(4), 1995–2003. https://doi.org/10.1002/fsn3.1487
42. Nyhan, L., Przyjalgowski, M., Lewis, L., Begley, M., & Callanan, M. (2021). Investigating the use of ultraviolet light emitting diodes (UV-LEDs) for the inactivation of bacteria in powdered food ingredients. *Foods (Basel, Switzerland)*, *10*(4), 797. https://doi.org/10.3390/foods10040797
43. Oh, K. N., Lee, S. Y., Lee, H. J., Kim, K. E., & Yang, J. S. (2003). Screening of gamma irradiated spices in Korea by using a microbiological method (DEFT/APC). *Food Control*, *14*(7), 489–494. https://doi.org/10.1016/S0956-7135(02)00108-1
44. Ozturk, S., Kong, F., Singh, R. K., Kuzy, J. D., Li, C., & Trabelsi, S. (2018). Dielectric properties, heating rate, and heating uniformity of various seasoning spices and their mixtures with radio frequency heating. *Journal of Food Engineering*, *228*, 128–141. https://doi.org/10.1016/j.jfoodeng.2018.02.011
45. Park, I., Kim, J., Shahbaz, H., Jung, D., Jo, M., Lee, K., Lee, H., & Park, J. (2018). High hydrostatic pressure treatment for manufacturing of garlic powder with improved microbial safety and antioxidant activity. *International Journal of Food Science & Technology*, *54*. https://doi.org/10.1111/ijfs.13937

46. Pezzutti, A., Marucci, P. L., Sica, M. G., Matzkin, M. R., & Croci, C. A. (2005). Gamma-ray sanitization of Argentinean dehydrated garlic (*Allium sativum* L.) and onion (*Allium cepa* L.) products. *Food Research International*, *38*(7), 797–802. https://doi.org/10.1016/j.foodres.2005.03.007
47. Phungamngoen, C., Chiewchan, N., & Devahastin, S. (2011). Thermal resistance of *Salmonella enterica* serovar Anatum on cabbage surfaces during drying: Effects of drying methods and conditions. *International Journal of Food Microbiology*, *147*(2), 127–133. https://doi.org/10.1016/j.ijfoodmicro.2011.03.019
48. Saravacos, G., & Kostaropoulos, A. E. (2016). *Handbook of Food Processing Equipment* (G. Saravacos & A. E. Kostaropoulos, Eds.). Springer International Publishing. https://doi.org/10.1007/978-3-319-25020-5_7
49. Sasaki, J.-I., KITA, T., ISHITA, K., UCHISAWA, H., & MATSUE, H. (2000). Antibacterial activity of garlic powder against *Escherichia coli* O-157. *Journal of Nutritional Science and Vitaminology*, *45*, 785–790. https://doi.org/10.3177/jnsv.45.785
50. Shafiur Rahman, M., Ibrahim Al-Sheibani, H., Hamad Al-Riziqi, M., Mothershaw, A., Guizani, N., & Bengtsson, G. (2006). Assessment of the anti-microbial activity of dried garlic powders produced by different methods of drying. *International Journal of Food Properties*, *9*(3), 503–513. https://doi.org/10.1080/10942910600596480
51. Smelt, J. P. P. M., & Brul, S. (2014). Thermal inactivation of microorganisms. *Critical Reviews in Food Science and Nutrition*, *54*(10), 1371–1385. https://doi.org/10.1080/10408398.2011.637645
52. Syamaladevi, R. M., Tang, J., Villa-Rojas, R., Sablani, S., Carter, B., & Campbell, G. (2016). Influence of water activity on thermal resistance of microorganisms in low-moisture foods: A review. *Comprehensive Reviews in Food Science and Food Safety*, *15*(2), 353–370. https://doi.org/10.1111/1541-4337.12190
53. Tancinova, D., Mokry, M., Barborakova, Z., and Maskova, Z. (2014). Mycobiota of spices and aromatic herbs. *Potravinarstvo Sci. J. Food Ind.* 8, 172–177.
54. Uhart, M., Maks, N., & Ravishankar, S. (2006). Effect of spices on growth and survival of *Salmonella* Typhimurium Dt 104 in ground beef stored at 4 and 8 °C. *Journal of Food Safety*, *26*(2), 115–125. https://doi.org/10.1111/j.1745-4565.2006.00036.x
55. U.S. Food and Drug Administration (2017). *Risk Profile on Pathogens and Filth in Spices*. https://www.fda.gov/media/108126/download?attachment Accessed Feb. 13, 2024.
56. U.S. Food and Drug Administration (2023). Lipari foods recalls ground cumin because of possible health risk. Available at: https://www.fda.gov/safety/recalls-market-withdrawals-safety-alerts/lipari-foods-recalls-ground-cumin-because-possible-health-risk. Accessed Feb. 13, 2024.
57. U.S. Food and Drug Administration. 2023. Lipari Foods Recalls Ground Cumin Because of Possible Health Risk. https://www.fda.gov/safety/recalls-market-withdrawals-safety-alerts/lipari-foods-recalls-ground-cumin-because-possible-health-risk Accessed Feb. 13, 2024.
58. U.S. Food and Drug Administration. 2021. Outbreak Investigation of *Salmonella* Oranienburg: Whole, Fresh Onions.https://www.fda.gov/food/outbreaks-foodborne-illness/outbreak-investigation-salmonella-oranienburg-whole-fresh-onions-october-2021 Accessed Feb. 13, 2024.
59. U.S. Food and Drug Administration. 2015. *Salmonella*, chap. 5. In Bacteriological analytical manual. Available at: https://www.fda.gov/media/166699/download. Accessed Feb. 13, 2024.
60. U.S. Food and Drug Administration. 2023. *Salmonella*, Chap. 5. In Bacteriological Analytical Manual. Available at: https://www.fda.gov/media/166699/download. Accessed Feb. 13, 2024.

61. U.S. Food and Drug Administration. (2021). FDA In Brief: FDA Releases Investigation Report Following 2020 Salmonella Outbreak Linked to Red Onions. Available at: https://www.fda.gov/news-events/press-announcements/fda-brief-fda-releases-investigation-report-following-2020-salmonella-outbreak-linked-red-onions. Accessed Feb. 19, 2024.
62. U.S. Food and Drug Administration. 2015. Food sampling and preparation of sample homogenate, chap. 1. In Bacteriological analytical manual. Available at: Bacteriological Analytical Manual (BAM) | FDA Accessed Feb. 13, 2024.
63. U.S. Food and Drug Administration. 2007. Bacteriological Analytical Manual: *Salmonella*. https://www.fda.gov/media/166699/download. Accessed Feb. 13, 2024.
64. Van Doren, J. M., Kleinmeier, D., Hammack, T. S., and Westerman, A. (2013). Prevalence, serotype diversity, and antimicrobial resistance of *Salmonella* in imported shipments of spice offered for entry to the United States, FY2007–FY2009. *Food Microbiology* 34, 239–251. doi: https://doi.org/10.1016/j.fm.2012.10.002.
65. Wilson, C. R., & Andrews, W. H. (1976). Sulfite compounds as neutralizers of spice toxicity for *Salmonella*. *Journal of food protection*, *39*(7), 464-466. https://doi.org/https://doi.org/10.4315/0022-2747-39.7.464
66. Won, M. Y., Choi, H. Y., Lee, K. S., & Min, S. C. (2016). Helium dielectric barrier discharge-cold plasma treatment for microbiological safety and preservation of onion powder. *Korean Journal of Food Science and Technology*, *48*(5), 486–491. https://doi.org/10.9721/KJFST.2016.48.5.486
67. Zhang, G., Hu, L., Pouillot, R., Tatavarthy, A., Van Doren, J. M., Kleinmeier, D., et al. (2017). Prevalence of *Salmonella* in 11 spices offered for sale from retail establishments and in imported shipments offered for entry to the United States. *Journal of Food Protection* 80, 1791–1805. doi: 10.4315/0362-028X.JFP-17-072.
68. Zhang, H., Qi, Y., Wang, L., Zhang, S., & Deng, X. (2017). *Salmonella* survival during thermal dehydration of fresh garlic and storage of dehydrated garlic products. *International Journal of Food Microbiology*, *263*, 26–31. https://doi.org/10.1016/j.ijfoodmicro.2017.10.010