

The superiority of HTST steam sterilization for spices and herbs

1. Introduction: the need for sterilization in spices and herbs

Spices and herbs, but also nuts and dried vegetables are agricultural products naturally exposed to a wide range of environmental conditions during cultivation, harvesting, drying, and storage. As a result, they are frequently contaminated with microorganisms such as *Salmonella* spp., *Escherichia coli*, *Bacillus cereus*, *Clostridium perfringens*, molds, and yeasts. These organisms may survive through conventional drying and handling processes and enter the food chain through spice-containing formulations.

Foodborne outbreaks linked to contaminated spices have been reported worldwide. This has led to increased regulatory attention from agencies such as the FDA and EFSA, which require validated decontamination or sterilization procedures to ensure microbial safety. At the same time, spices and herbs derive their commercial and sensory value from delicate volatile compounds that define their aroma, color, and flavor. Any sterilization method must therefore achieve a dual objective: ensure microbial safety while preserving sensory quality.

Steam sterilization has emerged as one of the most effective and natural methods to meet these requirements. It provides a physical means of microbial destruction without chemical additives, making it both consumer friendly and environmentally acceptable.

2. Overview of sterilization technologies for spices and herbs

Several technologies are currently used for microbial reduction in spices and herbs. Each method operates through a different mechanism and has specific advantages and limitations.

Method	Description	Advantages	Limitations
Steam treatment	Uses saturated or pressurized steam to inactivate microorganisms through protein denaturation and membrane disruption.	Natural, chemical-free, highly effective, and broadly accepted by regulators and consumers.	Requires careful control to limit loss of volatile components.

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Ethylene oxide (EO) treatment	Uses gaseous ethylene oxide as a chemical sterilant penetrating deep into the product.	Highly effective even at low temperatures.	Leaves toxic residues, is banned in the European Union, and faces strong consumer resistance.
Irradiation	Uses ionizing radiation such as gamma or electron beam to destroy microbial DNA.	Effective in sealed packaging and independent of product temperature.	Causes oxidative changes in volatiles, limited consumer acceptance, and regulatory restrictions.

3. Steam as the most effective natural sterilization method

3.1 Steam as an efficient heat carrier

Steam has superior heat transfer properties compared to air. When steam condenses on the surface of a spice particle, it releases large amounts of latent heat. This rapid transfer of energy results in efficient microbial destruction by denaturing cellular proteins and disrupting cell membranes.

3.2 Limitations of air and steam-air mixtures

Dry air by itself is a poor medium for microbial inactivation because of its low heat transfer coefficient. When steam is mixed with air, the air acts as an insulating layer that reduces direct condensation on the product surface. This limits energy transfer and results in slower heating rates, incomplete sterilization, or the need for longer exposure times that may degrade product quality.

3.3 Advantages of pressurized steam

Pressurized steam, produced at temperatures above 100 degrees Celsius, contains more energy per unit mass than atmospheric steam. This additional energy allows for faster microbial inactivation while minimizing total process time. The principle of using high temperature for short exposure times is known as high temperature short time (HTST) sterilization and is well established in food thermal processing.

3.4 Microbial kinetics: D-value and z-value

The effectiveness of thermal sterilization can be quantified using microbial kinetic parameters known as D- and z-values.

- The D-value is the time required at a specific temperature to achieve a 90 percent (one log) reduction in a microbial population.
- The z-value is the temperature increase required to reduce the D-value by a factor of ten.

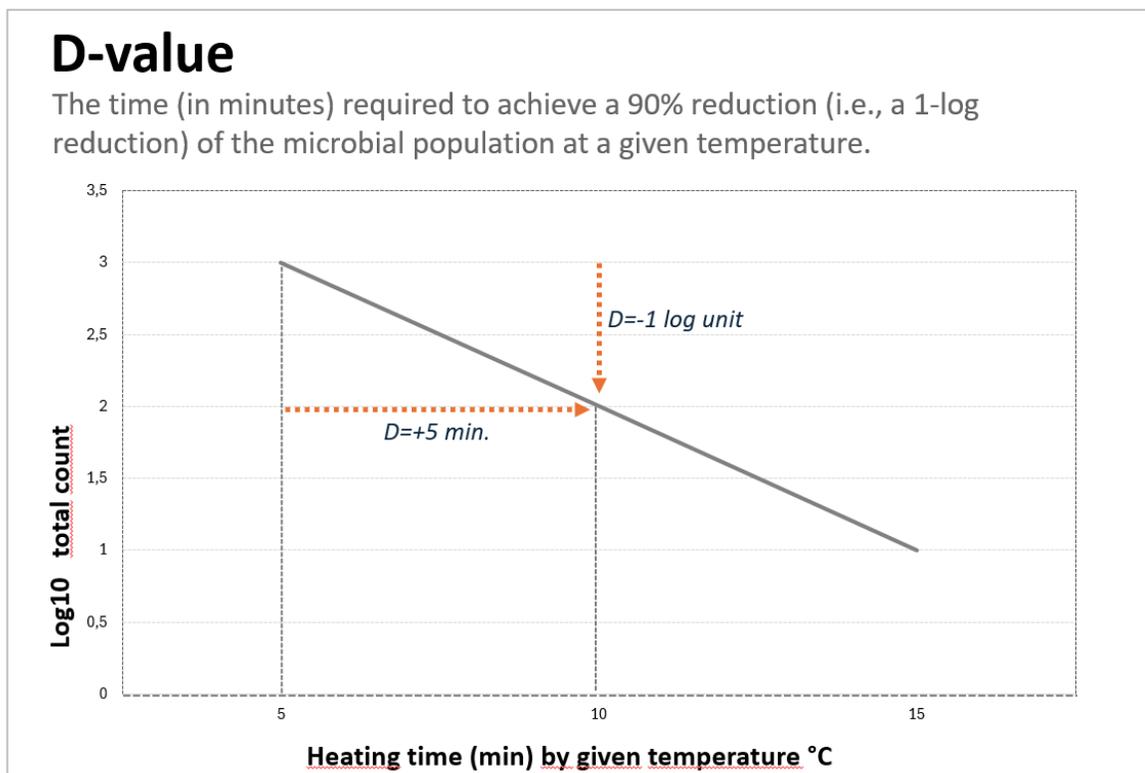


Figure 1: Predicted microbial reduction versus exposure time based on D- and Z-value kinetics.

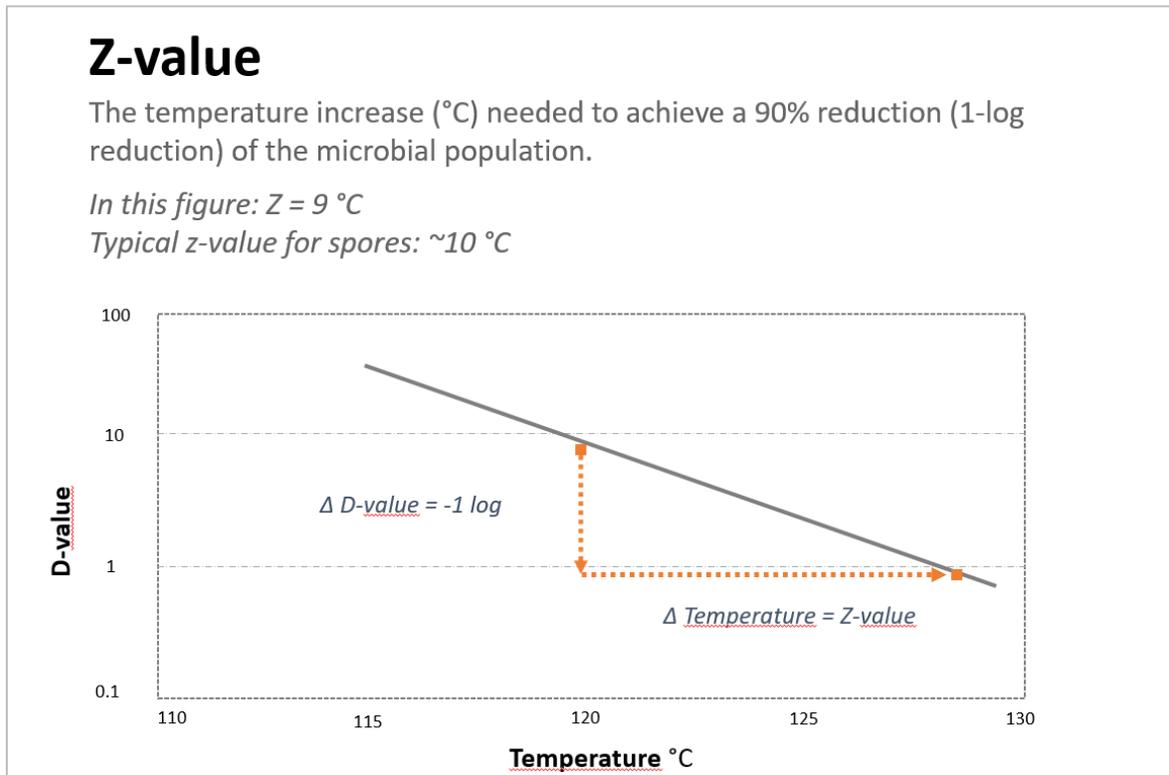


Figure 2: Predicted microbial reduction versus exposure temperature based on D- and Z-value kinetics.

For example, if the z-value of a microorganism is 10 degrees Celsius, increasing the process temperature by 10 degrees Celsius will shorten the D-value tenfold. These values are characteristic for each organism and are critical for designing a controlled sterilization process.

Table 1: Example of D-values of a micro-organism at different temperatures, assuming a Z-value of 10°C.

Temperature (°C)	D-value (min)	Equivalent time
85	32	32 min
95	3	3 min
105	0.3	18 s
115	0.03	2 s

What is the practical relevance of the D- en z-value kinetics for the treatment of spices with steam? A spice is often containing spores which has a D-value as mentioned in the above table, like e.g. the sporeformer *Bacillus cereus*. According to the table, a 10-fold reduction at 95 C will take 3 minutes. This will be the case if a steam treatment is done with non-pressurized steam at 95 C. In pressurized steam 115 °C can easily be reached and at this temperature the 10-fold reduction of these spores will be just 0,03 minutes (2 seconds). This is under the assumption that the z-value is 10 C, which is often the case for spores like *B. cereus*.

4. Atmospheric steam versus high-pressure steam sterilization

4.1 Atmospheric steam sterilization

Atmospheric steam sterilization operates at approximately 100 degrees Celsius, corresponding to the boiling point of water at normal atmospheric pressure. Although effective in reducing microbial loads, it requires prolonged exposure times, often several minutes, to achieve sufficient lethality.

Such extended heating negatively affects product quality. Volatile oils that define the characteristic aroma and flavor of spices tend to evaporate or oxidize during long thermal treatments. Color changes may occur due to pigment degradation or non-enzymatic browning reactions. Therefore, while atmospheric steam sterilization improves microbial safety, it often compromises sensory properties.

4.2 High-pressure steam sterilization and the HTST principle

High-pressure steam is generated under pressures greater than one atmosphere, allowing it to reach temperatures between 110 and 130 degrees Celsius. The higher energy content enables rapid microbial destruction within seconds rather than minutes. The HTST principle uses this property to combine high lethality with minimal exposure time, resulting in better product quality retention.

A practical example demonstrates this relationship. If *Bacillus cereus* has a D-value of approximately 0.03 minutes (2 seconds) at 115 degrees Celsius (see table 1), and the initial contamination level is 5,000 cfu per gram, at least a three-log reduction is required to bring the count below 100 cfu per gram. This corresponds to approximately six seconds at 115 degrees Celsius. Including the time needed to heat the product to the target temperature, a total exposure time of fifteen seconds is typically sufficient to achieve both safety and quality objectives.

4.3 Preservation of volatile compounds and product quality

Volatile oils such as eugenol, piperine, carvacrol and curcumin are responsible for the aroma, color, and flavor of spices. Their retention strongly depends on the total thermal load, which can be expressed as the product of temperature and time. Atmospheric steam processes, which last several minutes, expose the product to excessive thermal energy and promote loss of volatiles through evaporation and oxidation.

HTST treatment minimizes this effect by shortening the total exposure time to only a few seconds. Because heat transfer is rapid and uniform, the product reaches the sterilization temperature quickly, and cooling immediately follows. This minimizes chemical and physical degradation and maintains the natural appearance and sensory profile of the spice.

4.4 Comparative summary

Parameter	Atmospheric steam	High-pressure steam (HTST)
Operating temperature	~100 °C	110–130 °C
Exposure time	Several minutes	Few seconds
Microbial inactivation	Moderate	Excellent
Volatile oil retention	Moderate to poor	Excellent
Color and aroma preservation	Variable	Very good
Process predictability	Limited	Highly controllable via D/z modelling

5. Conclusion

HTST steam sterilization represents the most effective and scientifically validated approach for ensuring the microbiological safety of spices and herbs while maintaining their natural sensory attributes. By applying elevated temperatures for very short durations, this process achieves rapid microbial destruction according to well-established D- and Z-value kinetics.

Compared to atmospheric steam or chemical treatments such as ethylene oxide and irradiation, HTST sterilization provides a natural, residue-free, and controllable process that preserves the integrity of volatile oils and pigments. Its efficiency, reproducibility, and compliance with modern food safety standards make it the preferred technology for high-quality spice processing.