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Quantifying bacterial thermal resistance for drying and roasting processes using a novel low-humidity control method

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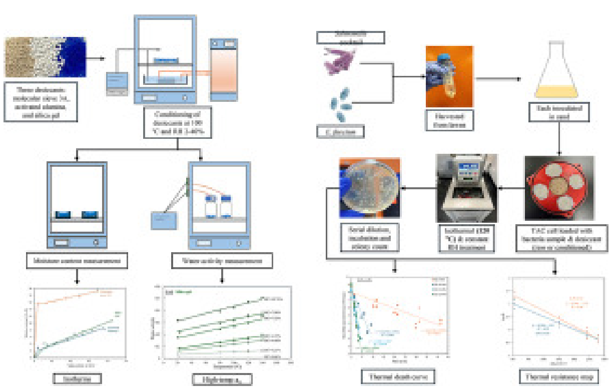
Highlights

- A novel method using desiccants to control humidity for thermal inactivation studies at >100°C was developed.
- Molecular sieve 3A is superior for creating near-zero RH; silica gel is more effective for RH controlling.
- Thermal resistance data for *Salmonella* and *E. faecium* at 120°C and controlled RHs (0–40%) are reported.
- Microbial thermal resistance at 120°C is strongly dependent on humidity, decreasing log-linearly as RH increases.
- The method provides a critical tool to generate data for validating industrial drying and roasting processes.

Abstract

Accurate mathematical models are vital for validating the microbial safety of low-moisture food processes like high temperature drying and roasting. However, model development is hindered by a lack of thermal resistance data for pathogens such as *Salmonella* spp. under relevant high-temperature, low-humidity conditions. This study aimed to develop and validate a method using conditioned desiccants to control humidity at temperatures above 90°C. We evaluated three desiccants, silica gel, activated alumina, and molecular sieve 3A, for their ability to control relative humidity (RH) in a thermal a_w cell (TAC) at temperatures from 80 to 140°C. System equilibration was characterized, and the inactivation kinetics for a three-strain *Salmonella* cocktail and its surrogate *Enterococcus faecium* were determined at 120°C under various low-RH conditions. Results showed that molecular sieve 3A was most effective at creating extremely dry conditions (approaching 0% RH), due to its high monolayer moisture binding capacity. Temperature and humidity equilibration within the TDT cell headspace was rapid, occurring in under 3 min. Microbial inactivation for both *Salmonella* and *E. faecium* followed first-order kinetics. *D*-values at 120°C showed no significant difference when using the three unconditioned (or raw) desiccants (minimum RH) but was significantly dependent on RH in the 0–40% range, confirming the extreme protective effect of desiccation at elevated temperatures. *D*-values at 120 °C for the *Salmonella* cocktail, for example, plummeted 27-fold from 10.8±4.2 min at ~0.5% RH to 0.43±0.14 min at 29.7% RH, demonstrating a critical dependence on humidity. This work successfully demonstrates a reliable method for generating critical thermal inactivation data in previously difficult-to-study, high-temperature, low-humidity environments. The resulting kinetic parameters can be used to strengthen predictive models, enabling more robust process validation for the food industry.

Graphical abstract



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Graphical abstract introducing the methods and results of the research.

Introduction

Thermal processes such as high-temperature drying and roasting are fundamental to manufacturing low-moisture foods (LMFs), including nuts, spices, dehydrated fruits, and cereal products (Liu et al., 2022; Mohammadi-Moghaddam et al., 2024; Pedron, Jaouhari and Bordiga, 2025). These operations are designed to extend shelf life and develop desired sensory qualities like texture and aroma (Mohammadi-Moghaddam et al., 2024). During both drying and roasting, the product is exposed to high-temperature, low-humidity (HTLH) conditions. While these conditions were traditionally assumed to ensure microbial safety, recent evidence demonstrates that pathogens such as *Salmonella* spp. exhibit dramatically enhanced thermal resistance in dry environments, challenging the efficacy of these processes for pathogen control.

The thermal resistance of microorganisms is inversely related to the water activity (a_w) of the food matrix, particularly at the elevated temperatures used in processing (Xu et al., 2019). As the product's a_w decreases, moisture is expelled from bacterial cells through desorption, leading to desiccation (Syamaladevi et al., 2016). This lack of intracellular water restricts molecular mobility and stabilizes critical proteins and ribosomes, resulting in an exponential increase in the organism's heat tolerance (Potts, 1994; Xu et al., 2020). This phenomenon poses a significant food safety risk, as *Salmonella* can survive in LMFs for extended periods and cause illness even at low concentrations (Jarvis et al., 2016; Xu et al., 2019). Consequently, and in alignment with the Food Safety Modernization Act, the food industry requires robust, scientifically defensible methods to validate the lethality of their thermal processes. Among these, the development of mathematical models is highly desired, as such models correlate quantitative relationships between process parameters and the thermal resistance of target pathogens, providing a clear pathway for process optimization and control (Yang & Tang, 2023).

A major challenge in developing predictive thermal processing inactivation models for drying and roasting is the scarcity of microbial thermal resistance data under realistic HTLH conditions. Current laboratory methods, which often rely on saturated salt solutions (e.g., LiCl) to control humidity in thermal a_w cells (TACs), are not effective at temperatures above 100°C. The water activity of these solutions invariably increases with temperature, making it impossible to simulate those very dry conditions (<30% RH) characteristic of industrial drying and roasting operations (Tadapaneni, Syamaladevi, et al., 2017). This limitation creates a critical knowledge gap and is a primary barrier to developing accurate thermal inactivation models for these processes.

To address this gap, a new method is required to control humidity at very low levels under high temperatures. Commercial desiccants offer a potential solution. These materials are engineered with immense porosity and large surface areas, enabling them to adsorb significant quantities of water. Key candidates include silica gel (SiO_2), molecular sieve 3A ($K_{12}[(AlO_2)_{12}(SiO_2)_{12}]\cdot nH_2O$), and activated alumina (Al_2O_3). Silica gel, produced by acidifying sodium silicate, possesses a high specific surface area and can adsorb up to 37% of its weight in water (ChemicalBook. Silica gel, 2025). Activated alumina is generated via calcination of aluminum hydroxide, creating a highly porous structure with a surface area that can exceed 300 m^2/g (AGM Container Controls Inc, 2025). Molecular sieve 3A is synthesized hydrothermally and then subjected to ion exchange, resulting in a crystalline aluminosilicate with uniform 3-Å pores ideal for selectively adsorbing water molecules (Sigma-Aldrich, 2025). The thermodynamic properties of these materials, governed by the Clausius-Clapeyron relationship, mean that their equilibrium water activity at a given temperature is determined by their moisture content and net isosteric heat of sorption (Yang, Guan, et al., 2020). By pre-conditioning these desiccants to specific moisture levels, it may be possible to create and maintain the stable, well-defined HTLH environments needed to generate relevant microbial inactivation data.

This study aimed to develop and evaluate a method using these desiccants as humidity-controlling agents for determining microbial thermal resistance under conditions pertinent to food drying and roasting. The specific objectives were: (1) to characterize the water activity of silica gel, molecular sieve 3A, and activated alumina when conditioned to various moisture contents and exposed to temperatures ranging from 20 to 140°C; (2) to determine the temperature and humidity equilibration profiles within a TAC using these desiccants; and (3) to demonstrate the application of this method by investigating the thermal inactivation kinetics of a *Salmonella* cocktail and its surrogate, *Enterococcus faecium*, at 120°C under controlled low-humidity conditions.

E. faecium is commonly used as a surrogate in validating industrial thermal treatments for control of *Salmonella* in low moisture foods. Although its application is well-documented in industrial process validation and research, the scarcity of microbial thermal resistance data under realistic HTLH conditions remains a critical knowledge gap. The primary novelty of this work is the development of a validated method using conditioned desiccants to precisely control humidity at temperatures above 100 °C and relative humidity levels below 30%. This approach overcomes a significant methodological barrier, providing a robust tool to generate the kinetic parameters required for accurate predictive models and the scientific validation of industrial drying and roasting processes.

Section snippets

Desiccant conditioning

Three desiccants, silica gel, molecular sieve 3A, and activated alumina (Wisesorbent Technology, Marlton, NJ, USA), were purchased from a commercial supplier. To achieve specific target moisture contents, the desiccants were conditioned in a controlled-humidity environment at 100°C, a temperature that accelerates moisture equilibration while allowing a broad relative humidity (RH) range to be achieved. The conditioning system (Fig. 1a) consisted of a convection oven (UF55Plus, Memmert USA, …

Desiccant sorption characteristics and high-temperature water activity

The moisture sorption isotherms define the relationship between desiccant moisture content (MC) and the equilibrium water activity (a_w) they can maintain, which is critical for their function as humidity-controlling agents at constant temperatures. The isotherms for all three desiccants at 100 °C (Fig. 3) revealed a two-stage sorption behavior distinct from the six classical types (Sing, 1985). In the initial stage (at a_w<0.05), a large amount of moisture was adsorbed with only a minimal …

Conclusions

This study successfully developed and validated a method using desiccants to control humidity in high-temperature, low-humidity (HTLH) thermal inactivation studies. It was established that molecular sieve 3A is superior for creating extremely dry conditions, while conditioned silica gel effectively controls a range of low RH levels.

The application of this method yielded the first kinetic data for *Salmonella* and *E. faecium* inactivation at 120°C under RH-controlled environments. The results …

CRediT authorship contribution statement

Rajesh Dangal: Writing – original draft, Investigation, Formal analysis. **Tejaswi Boyapati:** Investigation, Formal analysis. **Kasiviswanathan Muthukumarappan:** Writing – review & editing, Supervision. **Juming Tang:** Writing – review & editing, Resources. **Raghu Ramaswamy:** Writing – review & editing. **Ren Yang:** Writing – review & editing, Resources, Project administration, Methodology, Conceptualization. …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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