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THE GROWTH BEHAVIOR OF *SALMONELLA* IN PARSLEY STORED AT DIFFERENT TEMPERATURES

Basri OMAC

Munzur University, Tunceli Vocational School, Department of Food Processing, Tunceli, Türkiye

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ABSTRACT

This study investigated the growth dynamics of *Salmonella* spp. on parsley under three storage temperatures (15°C, 25°C, and 35°C) using the Baranyi primary model and relevant secondary models. Growth parameters, including maximum specific growth rate (μ_{max}), lag time (t_{lag}), and maximum population density (y_{max}), were significantly influenced by temperature. At 35°C, *Salmonella* exhibited rapid proliferation (μ_{max} =1.40 h⁻¹), minimal lag (t_{lag} =1.79 h), and high population density (y_{max} =7.05 log CFU/g), reaching hazardous levels in less than 24 hours. These findings highlight the critical importance of maintaining cold chain integrity to limit *Salmonella* growth on parsley. The application of predictive models provides a valuable tool for microbial risk assessment and can inform food safety management strategies, particularly in settings with inadequate refrigeration.

Keywords: Pathogens, food safety, predictive microbiology, fresh produce

FARKLI SICAKLIKLARDA DEPOLANAN MAYDANOZDA *SALMONELLA*'NIN GELİŞME DAVRANIŞI

ÖZ

Bu çalışma, maydanoz üzerinde Salmonella spp.'nın üç farklı depolama sıcaklığında (15°C, 25°C ve 35°C) gelişme dinamiklerini, Baranyi birincil modeli ve ilgili ikincil modeller kullanarak incelemiştir. Çalışmada, maksimum özgül büyüme hızı (μ_{max}), gecikme süresi (t_{lag}) ve maksimum popülasyon yoğunluğu (y_{max}) gibi büyüme parametrelerinin sıcaklıktan önemli ölçüde etkilendiği belirlenmiştir. 35°C'de, *Salmonella*'nın hızlı çoğalma gösterdiği (μ_{max} =1.40 sa⁻¹), en kısa gecikme süresine sahip olduğu (t_{lag} =1.79 sa) ve yüksek popülasyon yoğunluğuna ulaştığı (y_{max} =7.05 log kob/g) saptanmıştır; bu koşullar altında bakterinin 24 saatten kısa sürede tehlikeli seviyelere eriştiği görülmüştür. Elde edilen bulgular, maydanoz üzerinde *Salmonella* gelişimini sınırlamak için soğuk zincirin bütünlüğünün korunmasının kritik önemini vurgulamaktadır. Ayrıca, tahmine dayalı modellerin kullanımı, mikrobiyal risk değerlendirmesi için değerli bir araç sağlayarak, özellikle yetersiz soğutma koşullarına sahip ortamlarda gıda güvenliği yönetimi stratejilerinin geliştirilmesine katkıda bulunabilir.

Anahtar kelimeler: Patojenler, gıda güvenliği, prediktif mikrobiyoloji, taze meyve ve sebzeler

Yazışmalardan sorumlu yazar / Corresponding author: Basri OMAC
ORCID No: 0000-0001-6956-2720 **E-posta:** basriomac@munzur.edu.tr

INTRODUCTION

Fresh herbs, such as Italian parsley (*Petroselinum crispum*), are highly valued for their distinctive flavor, aroma, and nutritional benefits (Bahramsoltani et al., 2024; Fernandes et al., 2020). However, similar to other types of fresh produce, parsley may act as a vehicle for foodborne pathogens, particularly when consumed raw or subjected to minimal processing (Dittrich et al., 2021; Faour-Klingbeil et al., 2016a; Finger et al., 2021; Usanmaz et al., 2024). Contamination can occur at various stages of the supply chain, including cultivation, harvesting, processing, and transportation (Faour-Klingbeil et al., 2016b; Fatemi et al., 2023; FDA, 2024; Fernandez-Cassi et al., 2017). Pathogenic microorganisms that adhere to the surface of the herb are often difficult to remove using conventional washing methods, even when antimicrobial agents such as chlorine or hydrogen peroxide are applied (Dittrich et al., 2021; Usanmaz et al., 2024). Moreover, pathogens embedded within biofilms exhibit increased resistance and are not effectively eliminated by standard sanitizing treatments (Faour-Klingbeil et al., 2016a; Lapidot et al., 2006). Among the various foodborne pathogens, *Salmonella* spp. remains one of the most critical public health concerns globally, with numerous outbreaks traced back to fresh produce, including leafy herbs (Mkangara, 2023; Schwensohn et al., 2022).

In recent decades, fresh parsley has been repeatedly implicated in foodborne illness outbreaks (Naimi et al., 2003; Sewell and Farber, 2001; Spencer, 2024; Whitworth, 2025) and product recalls due to microbial contamination. Notably, in 1998, eight restaurant-associated outbreaks of shigellosis caused by a common strain of *Shigella sonnei* were reported in the United States (US) and Canada. Epidemiological investigations identified the consumption of parsley as the source of these outbreaks (Naimi et al., 2003). In this case, it was reported that the parsley had been washed prior to chopping; however, both washing and chopping were typically performed in the morning, and the prepared herb was stored at room temperature for several hours before being served to customers (Sewell and Farber, 2001). In 2010, a U.S.-based company voluntarily recalled multiple parsley and cilantro products following the detection of *Salmonella* by regulatory authorities (Caywood, 2010). Subsequent recalls occurred in 2011 and 2014 in response to suspected *Salmonella* contamination in several batches of fresh parsley (EFSA, 2011; Herman et al., 2015; Sheng and Zhu, 2021). In 2020, another company in the United States recalled its parsley products due to potential *Salmonella* contamination (FDA, 2020). Similarly, in 2021, two companies recalled parsley distributed across six U.S. states due to concerns about contamination with Shiga toxin-producing *Escherichia coli* (STEC) (Marler, 2021). More recently, in 2023, the Swedish Food Agency reported a foodborne outbreak linked to the consumption of parsley contaminated with enterotoxigenic *E. coli* (ETEC) (RASFF Window, 2024). In the same year, a Canadian company recalled its parsley products from the market due to potential *Salmonella* contamination (Government of Canada, 2023). Additionally, parsley imported from Mexico was recalled in the United States after testing confirmed *Salmonella* contamination (Food Safety News, 2023). Collectively, these incidents underscore the susceptibility of fresh parsley to microbial contamination at multiple points along the supply chain, including harvesting, processing, and distribution.

The ability of *Salmonella* to survive and proliferate on plant surfaces is influenced by factors such as leaf morphology, moisture content, surface chemistry, and environmental parameters-particularly temperature (Dittrich et al., 2021; Duffy et al., 2005; Faour-Klingbeil et al., 2016a; Lang et al., 2004; Namli et al., 2021). Several structural and physicochemical characteristics of the leaf environment influence *Salmonella* attachment to plant surfaces (Kowalska, 2023; Lapidot et al., 2006). The cuticle layer, composed of waxes and cutin, provides a hydrophobic surface that can facilitate bacterial adhesion and protect attached cells from desiccation (Grivokostopoulos et al., 2022). Natural openings such as stomata, hydathodes, and trichome bases can serve as micro-niches where bacteria may become lodged and protected from external stresses (Lenzi et al., 2022). In addition, the irregular topography of leaf surfaces-characterized by grooves, depressions, and vein structures-creates sheltered sites that enhance initial attachment and subsequent persistence (Grivokostopoulos et al., 2022). Interactions with the resident epiphytic microbiota and plant exudates further influence *Salmonella* attachment dynamics, potentially promoting survival under fluctuating environmental conditions (Kim et al., 2023). These factors collectively underscore the complexity of pathogen–plant surface interactions and highlight the need to understand how such mechanisms may contribute to bacterial survival and growth on fresh herbs.

Temperature also plays a critical role: while refrigeration is commonly used to restrict microbial growth, storage or handling at ambient or elevated temperatures may promote *Salmonella* replication (Kaur and Yemmireddy, 2023; Omac, 2024). Italian parsley, often stored and marketed under ambient conditions in retail or distribution chains, presents a potential risk if contamination occurs (Finger et al., 2021). Despite its widespread culinary use, data on the growth kinetics of *Salmonella* on parsley at different storage temperatures are limited (Likotrafiti et al., 2014; Posada-Izquierdo et al., 2016). Most herb-safety research has focused on leafy greens or basil, leaving parsley less studied in terms of pathogen behavior under non-refrigerated storage.

This study aimed to investigate the growth behavior of *Salmonella* on Italian parsley stored at three temperatures-15°C, 25°C, and 35°C-representing cool but non-refrigerated storage, typical ambient conditions, and elevated temperatures that may occur from improper handling or transportation. The results will contribute to improved risk assessments and guidelines for the safe handling and storage of fresh herbs, offering insight into how temperature influences pathogen persistence and growth on leafy herbs such as parsley.

MATERIALS AND METHODS

Bacterial strains and culture preparation

Five *Salmonella enterica* subsp. enterica serovars, kindly provided by Dr. Soyer from Middle East Technical University (METU), were used in this study: Newport (MET S1-670), Infantis (MET S1-674), Kentucky (MET S1-675), Enteritidis (MET S1-411), and Typhimurium (MET S1-625). Prior to inoculation, each strain was individually activated from frozen stocks in tryptic soy broth (TSB; Oxoid, UK) and incubated at 37°C for 18-24 hours. The cultures were then centrifuged (4000 × g, 10 minutes, 4°C), washed twice with sterile 0.1 % peptone water (PW), and resuspended in 9 ml of 0.1% PW (Omac, 2024). Equal volumes of each strain were combined to prepare a five-strain cocktail. The final cocktail concentration was approximately 9.0 log CFU/mL and was confirmed by plate counting on xylose-lysine deoxycholate (XLD) agar. Finally, the samples were inoculated with the diluted inoculum, diluted with sterile 0.1% PW to reach the required inoculum level (10^3 CFU/mL).

Sample preparation and inoculation

Fresh Italian parsley (*Petroselinum crispum*) was purchased from a local market on the day of the experiment. The parsley was visually inspected to remove damaged or decayed leaves and then gently rinsed under sterile distilled water to remove surface debris. The washing procedure applied to parsley leaves was carefully controlled to standardize experimental conditions. Leaves were gently rinsed under sterile distilled water at room temperature (approximately 25°C) using a consistent water volume of 5000 mL per 1000 g sample. The wash duration was set to 1 minute, with gentle agitation, to remove surface debris and loosely attached microorganisms without causing physical damage to the leaves. After washing, the samples were allowed to drain for 30 minutes under sterile conditions before inoculation. These standardized washing conditions ensured reproducibility of the experiments and minimized variability in initial microbial counts on the leaf surfaces. Parsley samples (5.0±0.4 g per replicate) were placed in sterile stomacher bags and inoculated with 0.5 ml of the *Salmonella* cocktail (103 log CFU/g) using a micropipette, ensuring even distribution across the leaves. The samples were gently massaged for 1 minute to facilitate uniform contact between the bacteria and plant surfaces. Two samples were prepared for each time point, and the experiment was repeated twice.

Storage conditions and sampling

Following inoculation, parsley samples were stored at three different temperatures: 15°C (cool storage), 25°C (ambient room temperature), and 35°C (elevated temperature), each in independent incubators (Stik, BI-150A, Shanghhai, China). At predetermined time intervals (0, 2, 4, 6, 8, 10, 12, 24, 36, and 48 hours), samples were collected for bacterial enumeration. At each sampling point, 5 g of parsley was transferred to a stomacher bag containing 45 mL of buffered peptone water (BPW) and homogenized for 2 minutes using a stomacher (BagMixer, Interscience, France). Serial dilutions were prepared using 9 ml of 0.1 % PW and plated on XLD agar, followed by incubation at 37°C for 24 hours. Colonies exhibiting typical *Salmonella* morphology were counted, and results were expressed as log CFU/g.

Primary and secondary modeling

The Baranyi growth model (Eqs. 1-2) was used as the primary model to fit bacterial growth curves and estimate kinetic parameters, including the lag phase duration (t_{lag}), the maximum specific growth rate (μ_{max}), and the maximum population density (y_{max}) (Baranyi and Roberts, 1995). Model fitting was performed using the Integrated Pathogen Modeling Program (IPMP, 2013), which was created by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) as a software tool for predictive microbiology data analysis and model creation (Huang, 2014).

$$y(t) = y_o + \mu_{max}A(t) - \ln\left(1 + \frac{\exp(\mu_{max}A(t)-1)}{\exp(y_{max}-y_0)}\right) \quad (1)$$

$$A(t) = t + \frac{1}{\mu_{max}}\ln\left(\exp(-\mu_{max}t) + \exp(-\mu_{max}t_{lag}) - \exp\left(-\mu_{max}t - (\mu_{max}t_{lag})\right)\right) \quad (2)$$

Herein, y_0 and t refer to the initial cell density (ln CFU/g) and time (h), respectively.

To evaluate the effect of temperature on the maximum specific growth rate, the suboptimal Ratkowsky square-root model was employed as the secondary model. The relationship between temperature and μ_{max} values was modeled using Eq. 3:

$$\sqrt{\mu_{max}} = a(T - T_{min}) \quad (3)$$

where T is the storage temperature (°C), T_{min} is the theoretical minimum temperature for growth (°C), and a is a constant.

Parameter estimation and model fitting were performed using non-linear regression analysis in the IPMP software (Huang, 2014).

The effects of temperature on the lag phase (t_{lag}, Eq. 4) and the maximum population density (y_{max}, Eq. 5) were determined using a second-order polynomial model (Omac, 2024). The data obtained from this analysis were modeled using SigmaPlot software (version 11.0, San Jose, CA, USA).

$$t_{lag} = A_1 + \frac{A_2}{T} + \frac{A_3}{T^2} \quad (4)$$

$$y_{max} = A_1 + A_2T + A_3T^2 \quad (5)$$

In these equations, A_1, A_2, and A_3 represent the regression coefficients.

Statistical analysis

All experiments were conducted in triplicate, and data were expressed as mean ± standard deviation. Analysis of variance (ANOVA) was performed using SPSS (version 20.0; IBM Corp.) to assess significant differences in growth parameters across temperatures, with $P<0.05$ considered statistically significant. The mean separation was then performed using Tukey's multiple range test.

RESULTS AND DISCUSSION

The growth behavior of *Salmonella* enterica on Italian parsley was effectively described using the Baranyi primary model at 15°C, 25°C, and 35°C. The model demonstrated a strong fit to the experimental data, as indicated by low error metrics-sum of squares error (SSE), mean square error (MSE), and root mean square error (RMSE)-across all temperature conditions (Table 1). RMSE values ranged from 0.08 to 0.11, reflecting close agreement between observed and predicted bacterial counts. The high coefficient of determination (R^2=0.99) further confirmed the model's accuracy. These evaluation metrics are commonly used to validate the performance of microbial growth models (Ndraha et al., 2022; Omac, 2024; Park et al., 2019; Sant'Ana et al., 2012; Yoon et al., 2014). According to Ndraha et al. (2022), models with low RMSE and R^2 values approaching 1 are considered highly reliable. Collectively, these findings support the applicability of the Baranyi model for predicting *Salmonella* growth on parsley under varying temperature conditions, consistent with its use in other fresh produce studies (Dey et al., 2025; Omac, 2024).

At 15°C (Figure 1), the estimated maximum specific growth rate (μ_{max}) was 0.19 h^{-1}, accompanied by a relatively long lag phase (t_{lag}) of 12.83 h (Table 1). The t_{lag} value at 15°C was not significantly different from that observed at the other temperatures (*P*>0.05). However, the μ_{max} at 15°C was substantially lower than the value at 35°C (*P*<0.05), whereas it did not differ significantly from the μ_{max} observed at 25°C (*P*>0.05). The maximum population density (y_{max}) reached 3.92 log CFU/g, indicating limited bacterial proliferation under cool storage. The prolonged t_{lag} at this temperature likely reflects a stress response to suboptimal conditions, delaying the onset of exponential growth. Similar trends were observed by Son et al. (2024), who also reported suppressed *Salmonella* growth on leafy greens at low temperatures, consistent with the reduced growth rates found in our study. In contrast, Likotrafiti et al. (2014) detected no growth of *S.* Typhimurium on parsley at 20°C. Differences in initial inoculum levels may explain this discrepancy; their study used a considerably higher starting concentration (10^5-10^6 CFU/g), whereas the maximum population densities in our study remained lower (~10^4

CFU/g). Besides, the longer lag times we recorded are in line with previous reports showing extended tlag under low-temperature conditions (Koseki and Isobe, 2005; Park et al., 2019; Puerta-Gomez et al., 2013; Sant'Ana et al., 2012; Yoon et al., 2014). Conversely, several studies have reported no detectable lag phase within comparable temperature ranges (Ndraha et al., 2022; Tarlak et al., 2020), highlighting that tlag can vary considerably between studies. Such variation may stem from strain-specific responses, differences in food matrices, or methodological differences in experimental design (Xiao et al., 2021).

Table 1. Baranyi model parameters for *Salmonella* in parsley

Temperature (°C)/ Parameters	Initial counts (y0, log CFU/g)	Maximum growth rate (μ_{max}, h^{-1})	Lag phase (t_{lag}, h)	Maximum population density (y_{max}, log CFU/g)	RSS	MSE	RMSE	R2
15	2.31^a (0.29)	0.19^a (0.13)	12.83^a (10.00)	3.92^a (0.32)	0.04	0.01	0.11	0.95
25	2.25^a (0.24)	0.26^a (0.06)	5.88^a (5.43)	5.23^b (0.21)	0.05	0.01	0.1	0.99
35	2.22^a (0.20)	1.40^b (0.22)	1.79^a (0.66)	7.05^c (0.10)	0.01	0.01	0.08	0.99

^{a,b,c}: Means within a column, which are not followed by a letter, are significantly different (P<0.05)

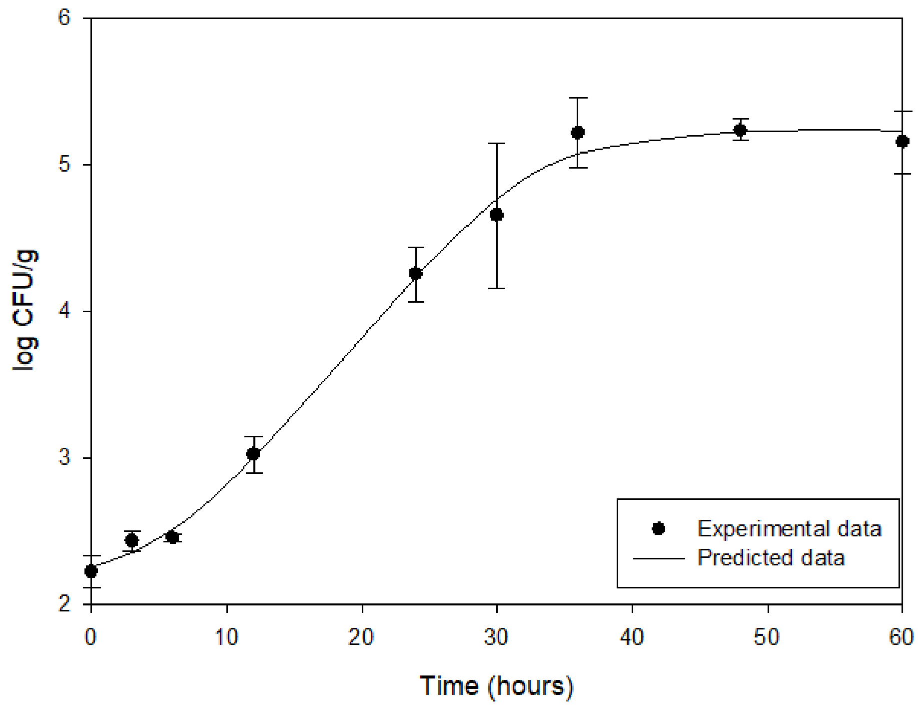

Figure 1. The growth behaviour of *Salmonella* on parsley stored at 15°C.

At 25°C (Figure 2), *Salmonella* exhibited a higher growth rate (μ_{max} =0.26 h^{-1}) and a notably shorter lag phase (5.88 h), indicating increased metabolic activity and quicker adaptation to the environment (Table 1). The μ_{max} value at 25°C was not significantly different from that at 15°C but remained substantially lower than that measured at 35°C ($P<0.05$). In contrast, the tlag at 25°C was considerably shorter than at 15°C ($P>0.05$), indicating more rapid initiation of growth. The y_{max} value at 25°C was significantly different from those at the other temperatures; specifically, it was higher than the y_{max} at 15°C ($P<0.05$) but lower than the y_{max} at 35°C ($P<0.05$), demonstrating a temperature-dependent pattern in maximum population density. The final population density reached 5.23 log CFU/g, confirming enhanced proliferation at this temperature. Comparable values have been reported by Yoon et al. (2014) and Sant'Ana et al. (2012) for *Salmonella* on cabbage and lettuce, respectively, at the same temperature. These results underscore the elevated microbiological risk associated with ambient storage of parsley, particularly during extended periods at room temperature. Similar patterns have been noted in fresh produce exposed to ambient or retail conditions (Ndraha et al., 2022; Omac, 2024; Posada-Izquierdo et al., 2016; Veys et al., 2016).

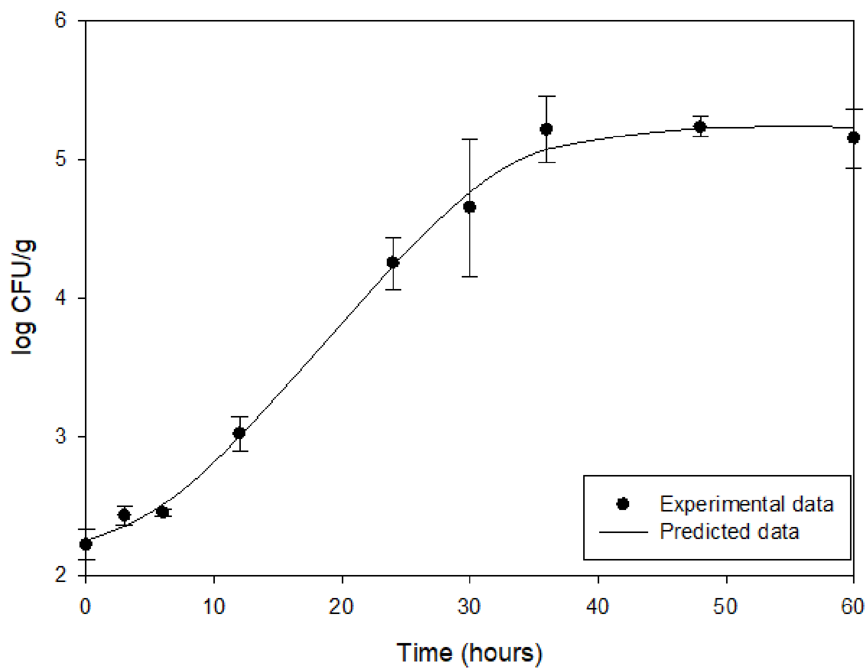

Figure 2. The growth behaviour of *Salmonella* on parsley stored at 25°C

At 35°C (Figure 3), conditions were highly favorable for Salmonella growth, as indicated by a μ_{max} of 1.40 h^{-1}, more than fivefold higher than at 25°C. The lag time was shortest at 1.79 h, demonstrating rapid adaptation and immediate transition into exponential growth. The maximum population density (y_{max}) also reached its highest level at this temperature (7.05 log CFU/g), indicating pronounced proliferation under warm conditions. These findings align with previous studies reporting accelerated *Salmonella* growth under elevated temperatures (Sant'Ana et al., 2012; Posada-Izquierdo et al., 2016; Son et al., 2024). The rapid growth observed under thermal abuse conditions underscores the increased food safety risks posed by inadequate temperature control during storage and transport, particularly in warmer climates.

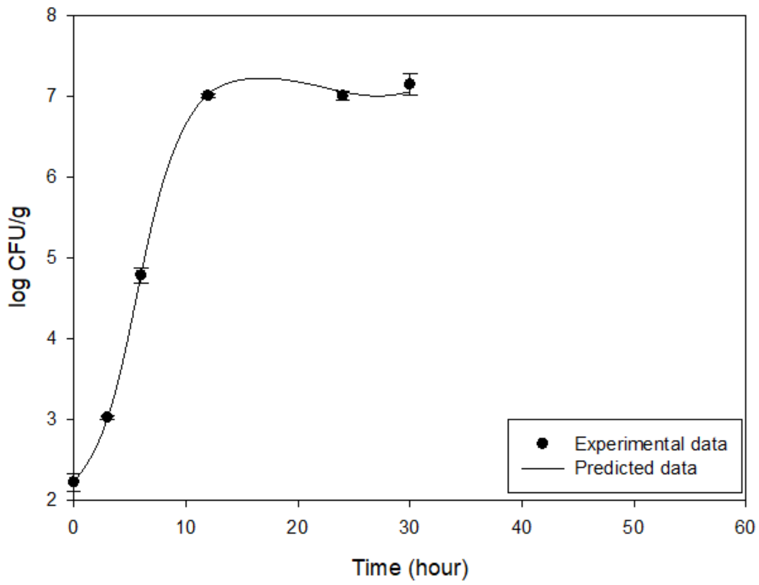

Figure 3. The growth behaviour of *Salmonella* on parsley stored at 35°C

To model the effect of temperature on μ_{max}, the Ratkowsky square-root model was applied. The estimated parameters included a slope (b) of 0.035 and a theoretical minimum growth temperature (T_{min}) of 5.679°C. The model displayed moderate goodness-of-fit (R^2 =0.70; RMSE = 0.43), suggesting it captured the general trend of increasing μ_{max} with temperature (Table 2). While some deviations between observed and predicted values were present, potentially due to experimental variability or primary model limitations, the estimated T_{min} falls within the expected range for Salmonella spp., as reported by others (Koseki and Isobe, 2005; Ndraha et al., 2022; Puerta-Gomez et al., 2013). Despite the moderate RMSE, the Ratkowsky model remains a valuable tool for describing the temperature dependence of bacterial growth rates in predictive microbiology applications (Baranyi et al., 2024).

Table 2. Secondary model parameters for *Salmonella* in parsley

Parameters	b	T_{min}	RMSE	R2	
Maximum growth rate (μ_{max})	0.035 (0.03)	5.68 (14.99)	0.43	0.70	
Parameters	A1	A2	A3	RMSE	R2
Lag phase (t_{lag})	-10.61	488.375	-1903.13	0.10	1.00
Maximum population density (y_{max})	2.9112	0.029	0.0025	0.02	1.00

The temperature dependence of lag time (t_{lag}) was described using an inverse second-order polynomial model, with parameters A_1=-10.61, A_2=488.375, and A_3=-1903.13 (Table 2). This model provided an excellent fit (R^2=1; RMSE=0.1), indicating strong predictive accuracy. As expected, t_{lag} decreased with increasing temperature, reflecting enhanced metabolic activity and reduced adaptation time at higher temperatures (Son et al., 2024; Zwietering et al., 1992). This result supports the widely accepted understanding that temperature is a key determinant of lag phase duration. The precise model fit further suggests that temperature alone was sufficient to predict t_{lag} under the conditions tested, underscoring the importance of time–temperature control to minimize Salmonella proliferation in fresh produce (Navarro-Pérez et al., 2022; Schultz and Kishony, 2013).

A quadratic model was used to describe the relationship between temperature and maximum population density (y_{max}), with coefficients A_1=2.9112, A_2=0.029, and A_3=0.0025 (Table 2). The model fit the data exceptionally well (R^2=1; RMSE=0.02), indicating that temperature had a measurable, although small, effect on final bacterial population size. The positive coefficients suggest a slight increase in y_{max} with rising temperature, possibly due to improved nutrient uptake and metabolic activity under warmer conditions (Cuggino et al., 2023; Zwietering et al., 1991). However, this trend is expected to plateau or decline beyond the organism's optimum temperature range (Huang et al., 2011). The modest change in y_{max} suggests that other factors-such as oxygen levels, substrate limitations, or competing microflora-may also influence the carrying capacity of *Salmonella* populations on fresh parsley (Carrasco et al., 2012; Son et al., 2024).

Overall, the results clearly demonstrate that temperature significantly influences the growth kinetics of *Salmonella* on Italian parsley. As temperatures increased, growth rates accelerated, lag phases shortened, and population densities rose, with potentially hazardous levels reached within 24 hours at 35°C. These findings highlight the critical importance of maintaining appropriate cold chain conditions to prevent microbial proliferation during the distribution, storage, and display of fresh herbs (Cuggino et al., 2023; Huang et al., 2019; Ndraha et al., 2022). The risks are particularly acute in open-market and food service environments, where refrigeration may be inconsistent (Naimi et al., 2003; Ndraha et al., 2018). From a food safety and risk management perspective, integrating predictive models, such as the Baranyi model, into hazard analysis and critical control point (HACCP) systems can provide a valuable tool for anticipating microbial risks and designing more effective temperature control strategies (Kumar et al., 2024). Furthermore, quantitative microbial risk assessment (QMRA) could be applied to estimate potential exposure to Salmonella from contaminated parsley and to evaluate the associated public health risks. Incorporating QMRA into predictive modeling frameworks would provide a more comprehensive understanding of microbial hazards and support more effective food safety management strategies (Kumar et al., 2024).

CONCLUSION

This study successfully applied the Baranyi primary model to describe the growth kinetics of Salmonella enterica on Italian parsley across a range of storage temperatures (15 °C, 25°C, and 35°C). The model demonstrated excellent predictive performance, supported by high R^2 values and low error metrics, confirming its suitability for modeling pathogen behavior on parsley. Temperature was found to be a critical factor influencing all growth parameters. As storage temperature increased, μ_{max} rose significantly, t_{lag} decreased, and y_{max} increased moderately. Notably, at 35°C, Salmonella reached hazardous levels within 24 hours, underscoring the heightened food safety risks associated with temperature abuse. In addition, secondary models-Ratkowsky, inverse second-order polynomial, and quadratic-further characterized the temperature dependence of μ_{max}, t_{lag}, and $y_{max,}$ respectively. These models exhibited strong fits and provided valuable tools for integration into predictive microbiology frameworks.

Overall, the findings emphasize the importance of strict temperature control during the storage, transport, and handling of fresh parsley to limit *Salmonella* proliferation. Incorporating predictive models into food safety management systems, such as HACCP, can support more proactive risk assessment and the development of targeted mitigation strategies, especially in environments where cold chain integrity is compromised.

DECLARATION OF CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHOR CONTRIBUTIONS

Basri Omaç: Investigation, methodology, analysis, writing-original draft, review & editing.

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