Predictive microbiology study of *Salmonella* spp. in chicken meat packaged with active antimicrobial packaging systems

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Abstract
Contamination of chicken meat by *Salmonella* spp. remains a major challenge for food safety and shelf-life preservation. In the present study, an exploratory quantitative analysis based on literature-derived datasets was conducted to investigate the application of essential oils and natural extracts incorporated into antimicrobial packaging systems for controlling *Salmonella* spp in chicken meat. In addition, an exploratory bibliometric visualization using VosViewer was performed to contextualize thematic relationships associated with essential oils, food packaging, and antimicrobial technologies. Experimental microbial kinetic datasets obtained from published studies were fitted using predictive microbiology models, including the Baranyi-Roberts model for microbial growth, the Geeraerd-Herremans-Van Impe model for microbial inactivation, and the Paganini and coworkers model for the Phoenix phenomenon. The fitted models adequately described microbial growth, inactivation, and regrowth behaviors under different antimicrobial treatments and storage conditions. Overall, packaging systems containing encapsulated or nanoencapsulated compounds tended to promote more sustained antimicrobial effects compared with non-encapsulated formulations, suggesting that controlled-release mechanisms may significantly influence microbial kinetic behavior during refrigerated storage. The bibliometric visualization indicated increasing scientific interest in active packaging, encapsulation, nanocomposites and controlled-release systems, whereas predictive microbiology approaches remain underrepresented in this research field. Despite the exploratory nature of the literature search and the heterogeneity among experimental conditions, the results demonstrate that secondary quantitative analysis combined with predictive microbiology tools can provide relevant insights into the microbial dynamics of *Salmonella* spp. in packaged chicken meat. The integration of antimicrobial packaging technologies with mathematical modeling approaches may contribute to the development of more effective food preservation strategies and improved microbiological safety in poultry products.
Keywords: controlled release; essential oils; food safety; microbial kinetics; plant extracts.

Estudo por microbiologia preditiva de Salmonella *spp. em carne de frango embalada em sistemas de embalagens antimicrobianas ativas*

Resumo
A contaminação da carne de frango por Salmonella *spp. continua representando o maior desafio para a segurança de alimentos e a preservação da vida útil. No presente estudo, uma análise quantitativa*

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exploratória baseada em conjuntos de dados da literatura foi conduzida para investigar a aplicação de óleos essenciais e extratos naturais incorporados em sistemas de embalagens antimicrobianas para o controle de Salmonella *spp. em carne de frango. Além disso, uma visualização bibliométrica exploratória utilizando o software VosViewer foi realizada para contextualizar as relações temáticas associadas a óleos essenciais, embalagens alimentícias e tecnologias antimicrobianas. Conjuntos de dados cinéticos microbianos obtidos de estudos publicados foram ajustados utilizando modelos de microbiologia preditiva, incluindo o modelo de Baranyi-Roberts para crescimento microbiano, o modelo de Geeraerd-Herremans-Van Impe para inativação microbiana e o modelo de Paganini e colaboradores para o fenômeno Phoenix. Os modelos ajustados descreveram adequadamente os comportamentos de crescimento, inativação e recrescimento microbiano sob diferentes tratamentos antimicrobianos e condições de armazenamento. De forma geral, sistemas de embalagens contendo compostos encapsulados ou nanoencapsulados tenderam a promover efeitos antimicrobianos mais sustentados quando comparados a formulações não encapsuladas, sugerindo que mecanismos de liberação controlada podem influenciar significativamente o comportamento cinético microbiano durante o armazenamento refrigerado. A visualização bibliométrica indicou crescente interesse científico em embalagens ativas, encapsulação, nanocompósitos e sistemas de liberação controlada, enquanto abordagens de microbiologia preditiva mostraram-se sub-representadas neste campo de pesquisa. Apesar da natureza exploratória da busca bibliográfica e da heterogeneidade entre as condições experimentais, os resultados demonstram que análises quantitativas secundárias combinadas com ferramentas de microbiologia preditiva podem fornecer informações relevantes sobre a dinâmica microbiana de* Salmonella *spp. em carne de frango embalada. A integração entre tecnologias de embalagens antimicrobianas e abordagens de modelagem matemática pode contribuir para o desenvolvimento de estratégias mais eficazes de conservação de alimentos e para o aumento da segurança microbiológica de produtos avícolas.*
Palavras-chave: *cinética microbiana; extratos de plantas; liberação controlada; óleos essenciais; segurança de alimentos.*

1 Introduction

Brazil is currently the world's largest exporter and the second-largest producer of chicken meat, behind only the United States, according to the Brazilian Association of Animal Protein (ABPA, 2026). Brazil produced and exported 15.3 and 5.3 million tons, respectively, of chicken meat in 2025 (ABPA, 2026). Due to the high global consumption of poultry products, ensuring microbiological safety throughout processing and storage has become a major challenge for the food industry. Among foodborne pathogens, *Salmonella* spp. represents one of the most important concerns associated with poultry products due to its frequent involvement in salmonellosis outbreaks and its significant economic and public health impacts (Mota *et al*., 2025).

According to the World Health Organization (WHO, 2025), foodborne diseases affect approximately 600 million people annually worldwide, with diarrheal diseases accounting for a large proportion of these cases. Among the main bacterial agents associated with foodborne illnesses, *Salmonella* spp. is particularly relevant in poultry production systems because the microorganism can naturally colonize birds and contaminate meat products during slaughtering, processing and storage (Brito *et al*., 2019). Consequently, the development of preservation technologies capable of controlling microbial growth in chicken meat remains an important scientific and industrial challenge.

Packaging systems and storage conditions play a fundamental role in determining the microbiological stability and shelf life of meat products (Marcelli; Osimani; Aquilanti, 2024). Conventional preservation methods, including refrigeration, modified-atmosphere packaging, thermal processing, and synthetic preservatives, are widely used to control microbial proliferation and delay spoilage (Zhang *et al*., 2022). However, growing consumer concern regarding the use of synthetic additives such as nitrites, nitrates, sorbates, and benzoates has stimulated the search for natural antimicrobial alternatives for food preservation (Yu; Chin; Paik, 2021). Recent studies have associated the excessive intake of some synthetic preservatives with adverse health effects, including allergic reactions, metabolic alterations, and potential carcinogenic risks (Mafe; Büsselberg, 2025).

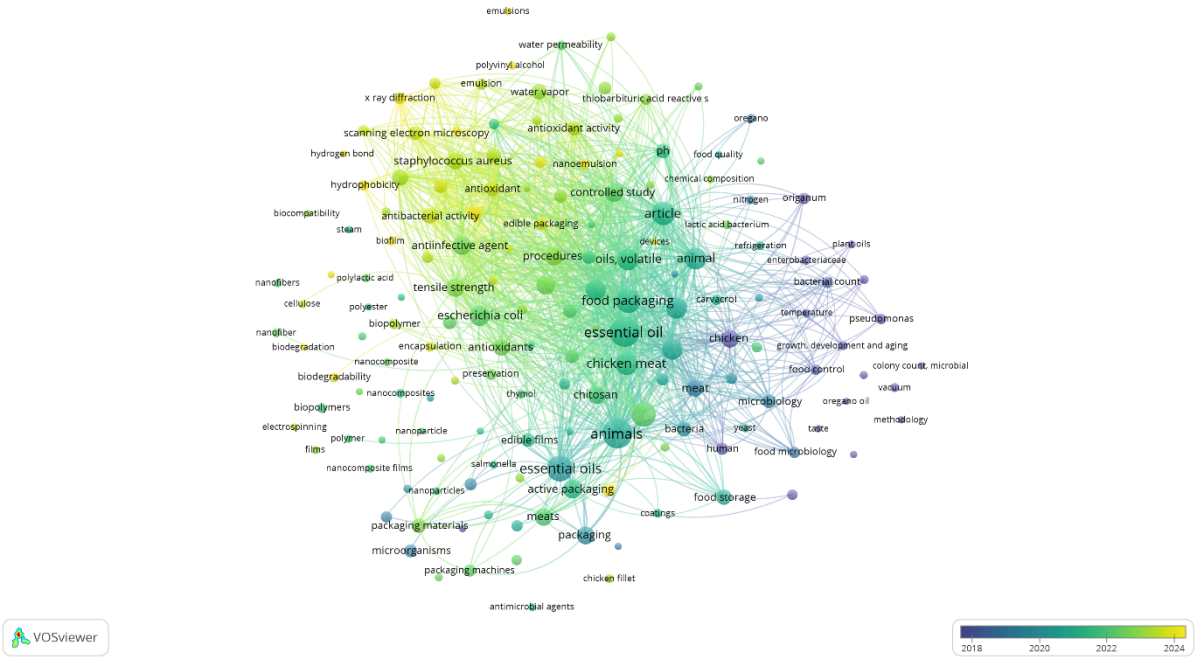
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In this context, plant-derived compounds, such as essential oils and natural extracts, have received increasing attention for their antimicrobial and antioxidant properties (Teshome *et al*., 2022). Essential oils obtained from aromatic plants, including oregano, rosemary, thyme, sage, mint, garlic, and turmeric, have shown considerable potential in meat preservation by inhibiting microbial growth, enhancing oxidative stability, and extending shelf life (Al-Hijazeen; Ibrahim, 2024). The antimicrobial activity of these compounds is primarily attributed to secondary metabolites that interact with bacterial cell membranes, altering permeability, disrupting membrane integrity, and promoting leakage of intracellular components (Jackson-Davis *et al*., 2023).

More recently, the incorporation of natural antimicrobial compounds into active packaging systems has emerged as a promising strategy to improve food preservation. Unlike conventional packaging, active packaging interacts both with the packaged product and its surrounding environment, enabling the controlled release of antimicrobial compounds during storage (Kashiri *et al*., 2019; Metha; Pawar; Suvarna, 2024). The gradual migration of active substances from the packaging matrix to the food surface may prolong antimicrobial activity and improve microbiological stability over time (García-Anaya; Sepúlveda; Acosta-Muñiz, 2025).

To provide an exploratory overview of the thematic relationships involving essential oils, chicken meat, and food packaging systems, a bibliometric co-occurrence map of keywords was generated using VosViewer software (van Eck; Waltman, 2010) (Figure 1). The analysis revealed strong thematic connections between essential oils, antimicrobial activity, food packaging, microbiology, and chicken meat preservation. The most recent keywords were associated with encapsulation, nanocomposites, electrospinning, nanoparticles, and active packaging systems, indicating increasing scientific interest in controlled-release technologies for food preservation. In contrast, predictive microbiology and kinetic modeling approaches did not emerged as central interconnected topics in the network, suggesting that quantitative microbial modeling has not been widely incorporated into studies involving antimicrobial packaging systems.

Figure 1 – Bibliometric overlay visualization showing thematic relationships and temporal trends among keywords associated with essential oils, chicken meat preservation, and active food packaging systems



Source: elaborated by the authors.

Predictive microbiology seeks to describe and predict the behavior of microorganisms under varying environmental and processing conditions using mathematical models (Baranyi; Rockaya; Ellouze, 2024). Primary models, such as those proposed by Baranyi and Roberts (1994) and Geeraerd, Herremans, and Van Impe (2000), are widely used to describe microbial growth and inactivation kinetics in foods. These models enable the estimation of biologically meaningful parameters, including maximum specific growth or inactivation rates, lag phases, and residual microbial populations, thereby providing a quantitative understanding of microbial behavior during food storage (Milkievicz *et al*., 2020, 2021).

Although several studies have investigated the antimicrobial effects of essential oils and extracts incorporated into active packaging systems for chicken meat preservation, most studies remain primarily experimental and descriptive, with limited application of predictive microbiology approaches and kinetic mathematical modeling. Furthermore, comparative analyses based on datasets from different studies under the perspective of microbial kinetics are still scarce in the literature.

Therefore, the present study aimed to compile experimental datasets from published studies involving essential oils and extracts applied to packaged chicken meat and to apply predictive microbiology tools to evaluate the effects of these antimicrobial treatments on the growth and inactivation kinetics of *Salmonella* spp. during refrigerated storage. In addition, the study also sought to investigate the influence of controlled-release technologies on antimicrobial effectiveness and microbiological stability in poultry products.

Section 2 describes the research materials and methods, detailing the article search strategies, data acquisition, mathematical modeling, and statistical aspects. Subsequently, Section 3 outlines the results of the article search and the parameters estimated by fitting the mathematical models to the data, discussing the results in the context of the literature. Finally, Section 4 presents the conclusion, summarizing the study's key findings and objective.

2 Materials and methods

An exploratory literature search was conducted using the ScienceDirect database[1] to identify studies involving essential oils, chicken meat, and food packaging systems that reported experimental microbial kinetic data suitable for predictive microbiology analyses. ScienceDirect was selected because it indexes a substantial number of journals in food science, food packaging, food microbiology, and active packaging technologies relevant to the scope of this study.

The keywords used in the advanced search were essential oil, chicken, and packaging. The retrieved studies were initially screened to identify publications related to antimicrobial applications in packaged chicken meat. Subsequently, the abstracts and methodological details were evaluated to identify studies presenting experimental microbial kinetic data that were suitable for secondary quantitative analysis and mathematical modeling. For the kinetic analyses performed in the present study, priority was given to studies published between 2019 and 2024 that contained experimental datasets suitable for modeling microbial growth and/or inactivation, reflecting recent advances in encapsulation technologies, nanocomposite materials, and active packaging systems.

To provide an exploratory overview of the thematic structure associated with essential oils, active packaging, and chicken meat preservation, an overlay visualization of keyword co-occurrence was generated using VosViewer software. The visualization was used solely to contextualize the scientific landscape associated with antimicrobial packaging systems and did not constitute a formal bibliometric analysis.

The selected studies were compiled into a Microsoft Office Excel spreadsheet (Microsoft Corporation, 2021) including the following information: type of chicken meat cut, microorganism species and serotype, packaging composition, essential oil or extract incorporated into the packaging system, antimicrobial concentration, storage conditions, and availability of experimental kinetic data with or without mathematical modeling. The primary inclusion criterion was the availability of sufficient experimental information to populate all variables included in the spreadsheet and to enable kinetic modeling. Studies with incomplete datasets were excluded.

[1] www.sciencedirect.com/search

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Experimental microbial kinetic data, expressed as microbial concentration (log CFU/g) as a function of storage time (h), were obtained directly from tables or digitized from graphs using the WebPlotDigitizer software (Rohatgi, 2010). Subsequently, mathematical models commonly applied in predictive microbiology were fitted to the experimental datasets using R software version 4.3.3 (R Core Team, 2024).

The logarithm of microbial concentration as a function of time was described using primary growth and inactivation models. The Baranyi and Roberts (1994) model, described by Equations 1 (complete form), 2 (without lag phase), and 3 (without stationary phase), was applied to describe microbial growth curves according to the kinetic behavior observed in each dataset. In these equations, μ_{max} (1/h) represents the maximum specific growth rate, λ (h) is the lag phase duration, and Y_0 and Y_{max} (log CFU/g) represent the initial and maximum microbial populations, respectively.

Microbial inactivation curves were described using the Geeraerd, Herremans, and Van Impe (2000) model, represented by Equations 4 (complete form), 5 (without shoulder), and 6 (without tail). In these equations, k_{max} (1/h) represents the maximum specific inactivation rate, S_1 (h) represents the shoulder duration, and Y_{res} (log CFU/g) represents the residual microbial population.

For datasets presenting microbial inactivation followed by regrowth (Phoenix phenomenon), the model proposed by Paganini *et al*. (2022), described by Equation 7, was applied. In this model, R_0 is defined as the ratio between the initial concentration of the growing subpopulation ($N_{g,0}$), to the total microbial population ($N_{t,0}$), i.e., $R_0 = N_{g,0}/N_{t,0}$.

Model fitting was carried out using the "minpack.lm", "nlsMicrobio", and "modelr" packages in R software. Parameter estimates were evaluated based on their biological coherence, confidence intervals, and goodness-of-fit indicators.

The residual sum of squares (RSS) was calculated according to Equation 8, where $\hat{y}$ denotes to the values predicted by the mathematical models and y represents the experimentally observed values.

$$Y(t) = Y_{max} + \log log\left(\frac{-1+e^{\mu_{max}\lambda}+e^{\mu_{max}t}}{e^{\mu_{max}t}-1+e^{\mu_{max}\lambda}\left(10^{Y_{max}-Y_0}\right)}\right) \quad (1)$$

$$Y(t) = Y_{max} - \log log\left(1 + \left(10^{Y_{max}-Y_0} - 1\right)e^{-\mu_{max}t}\right) \quad (2)$$

$$Y(t) = Y_0 + \frac{\mu_{max}t}{ln(10)} + \log log\left(e^{-\mu_{max}t}\left(1 - e^{-\mu_{max}t}\right) + e^{-\mu_{max}t}\right) \quad (3)$$

$$Y(t) = \begin{cases} Y_0 - \frac{k_{max}t}{\log log\,(10)}; & se\ t \leq \frac{\left(Y_0-Y_{res}\right)\log log\,(10)}{k_{max}} \\ Y_{res} + \log l & \end{cases} \quad (4)$$

$$Y(t) = Y_{res} + \log log\left(1 + \left(10^{\left(Y_0-Y_{res}\right)-1}\right)e^{\left(-k_{max}t\right)}\right) \quad (5)$$

$$Y(t) = Y_0 - \frac{k_{max}t}{\log log\,(10)} + \log log\left(\frac{k_{max}S_l}{e^{\left(1+\left(e^{\left(k_{max}S_l\right)}-1\right)e^{\left(-k_{max}t\right)}\right)}}\right) \quad (6)$$

$$Y(t) = \log log\left((1 - R_0)10^{Y_0+\frac{k_{max}}{\ln ln\,(10)}t} + R_0 10^{Y_0+ln\left(1+e^{\frac{\mu_{max}}{\ln ln\,(10)}(t-\lambda)}-e^{-\frac{\mu_{max}\lambda}{\ln ln\,(10)}}\right)}\right) \quad (7)$$

$$RSS = \sum\left(\hat{y} - y\right)^2 \quad (8)$$

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The estimated kinetic parameters, confidence intervals, and residual sum of squares obtained from model fitting were comparatively analyzed using Microsoft Office Excel spreadsheets. Because of the exploratory nature of the literature search and the considerable heterogeneity among the selected studies, the results were interpreted from a comparative predictive microbiology perspective rather than as a formal meta-analysis.

3 Results and discussion

The exploratory literature search retrieved 1,994 articles associated with the keywords *essential oil*, *chicken*, and *packaging*. After screening the abstracts and assessing the availability of experimental microbial kinetic datasets suitable for predictive microbiology, 17 studies on antimicrobial packaging systems applied to chicken meat were selected. Most of the remaining studies were excluded because they did not provide experimental microbial concentration data over time, focused on food matrices other than chicken meat, evaluated non-antimicrobial packaging applications, or presented insufficient information for kinetic mathematical modeling.

The studies included different essential oils, extracts, encapsulation strategies, packaging materials, and microbial targets (Table 1).

Table 1 – Summary of the studies selected from the exploratory literature search conducted using the ScienceDirect advanced search tool

Reference	Cut	Species and Serotype	Packaging system	Compounds
Wang *et al.* (2021)	Chicken breast	Total viable microorganism count (TVC) and *Pseudomonas deceptionensis*	Sterile stomacher plastic bag	Cinnamon essential oil nanoemulsions
Porter, Morey, and Monu (2020)	Ground boneless chicken thighs with skin	*Salmonella* Typhimurium, *S.* Heidelberg, *S.* Montevideo, *S.* Kentucky, and *S.* Enteritidis	Polyethylene film sealed on Styrofoam trays	White mustard essential oil and carvacrol
Dewi *et al*. (2021)	Chicken thighs and breast fillets	*Salmonella* Heidelberg (466 and 1904)	Sterile bag	Lemongrass essential oil
Surendhiran, Cui, and Lin (2019)	Chicken	*Salmonella* Enteritidis	Wrapped in a nanofiber film containing polyethylene oxide/sodium alginate/florotanino nanofibers	10% phlorotanin encapsulated with alginate
Yaghoubi *et al*. (2021)	Breast fillet	Counts of coliforms, fungi, and yeasts	Low-density polyethylene bags	*Artemisia fragrans* essential oil coated with chitosan
Rahnemoon *et al*. (2021)	Chicken breast	*Staphylococcus aureus*, *Listeria monocytogenes*, *Escherichia coli*, and *Salmonella enterica*	Packaged in sterile containers	Nanoencapsulated pomegranate peel extract; sodium alginate: 2% w/v and PPE or PPE; nanoencapsulated: 20% w/v

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Qiu *et al*. (2022)	Chicken burgers	*Staphylococcus aureus*, *Escherichia coli*, and *Bacillus subtilis*	Sterile polyethylene bags	Nanoemulsion with cinnamon essential oil and rosemary extract
Molaveisi, Taheri, and Dehnad (2022)	Chicken	Coliforms and *Staphylococcus aureus*	Meat covered with active films	Phytosomes of *Echinacea purpurea* (L.) extract-phospholipid incorporated in Alyssum homolocarpum seed gum film
Kaya, Kahyaoglu, and Sumnu (2022)	Chicken breast	Psychrotrophic bacteria count	Common plastic films and active films with extracts	Composite films incorporated with curcumin based on chitin and glucan complexes extracted from *Agaricus bisporus*
Afroz Ali *et al*. (2023)	Chicken breast fillet	*Escherichia coli*, *Listeria monocytogenes*, and *Salmonella enterica*	Composite films placed in sterile polyethylene plastic bags	Pectin-chitosan composite films incorporated with quercetin-loaded nanocargos
Lin *et al*. (2023)	Chicken breast	*Staphylococcus aureus*	Gelatin film and nanocomposite film	Gelatin film loaded with eugenol nanoparticles
Mirsharifi *et al*. (2023)	Chicken breast	*Escherichia coli*, *S.* Typhimurium, *Staphylococcus aureus*, *Bacillus cereus*	Fillets covered with a film with and without 4% thyme essential oil. Samples stored in polystyrene container	Composite films of almond gum/polyvinyl alcohol/chitosan containing nanoemulsion of thyme essential oil
Ceylan *et al*. (2023)	Chicken and salmon	Total mesophilic count	Nanofibers	Nanofibers obtained from sesame oil
Ali *et al*. (2023)	Chicken	*Salmonella enterica*	Active nanocomposite film gelatin/carrageenan/zein/oil, wrapped with Ge/Car film as control	Films incorporated with turmeric essential oil
Hematizad *et al*. (2021)	Chicken breast	Total aerobic bacteria, psychrotrophic bacteria, lactic bacteria, *Pseudomonas* spp., enterobacteria	Samples covered with active films	Gelatin-nanochitosan films incorporated with *Zataria multiflora* Boiss essential oil

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Sheerzad *et al*. (2024)	Chicken breast fillets	Total aerobic bacteria, psychrotrophic bacteria, *Pseudomonas* spp., lactic acid bacteria, *Staphylococcus aureus*, Enterobacteriaceae, fungi and yeasts	Sterile bags	Coating with whey protein isolate, nanocellulose, bacterial nanocellulose and cinnamon essential oil
Laein *et al*. (2024)	Chicken breast fillet	*Salmonella* Enteritidis, *Listeria monocytogenes*	Sterile zip bags	*Zataria multiflora* Boiss and solid lipid nanoparticles

Source: elaborated by the authors.

The keyword co-occurrence visualization generated using VosViewer (Figure 1) revealed strong thematic relationships between essential oils, antimicrobial activity, food packaging, microbiology, and chicken meat preservation. More recent terms were associated with active packaging, nanocomposites, electrospinning, nanoparticles, and encapsulation technologies, indicating growing scientific interest in controlled-release systems for food preservation. In contrast, predictive microbiology and kinetic mathematical modeling did not emerge as central interconnected themes, suggesting that quantitative microbial kinetic approaches remain insufficiently underexplored in studies involving antimicrobial packaging systems.

Although the selected studies presented high-quality experimental microbiological data, most investigations focused primarily on the development of antimicrobial films and evaluating microbial reductions descriptively, with limited use of predictive microbiology tools for quantitative kinetic interpretation. Therefore, this study sought to perform a secondary quantitative analysis of literature-derived datasets to better understand the microbial kinetic behavior of *Salmonella* spp. in chicken meat packaged with natural antimicrobial systems.

Among the 17 selected studies, six studies involving *Salmonella* spp. were considered suitable for predictive kinetic modeling because they provided experimental microbial concentration data over time under refrigerated conditions. The selected studies investigated different antimicrobial compounds, including white mustard essential oil, carvacrol, phlorotannins, pomegranate peel extract, quercetin, turmeric essential oil, and *Zataria multiflora* essential oil incorporated into active packaging systems.

The kinetic parameters obtained from model fitting are summarized in Table 2. Depending on the kinetic behavior observed, microbial growth, inactivation, or inactivation followed by regrowth (Phoenix phenomenon) was described using the Baranyi and Roberts (1994), Geeraerd, Herremans and Van Impe (2000), and Paganini *et al*. (2022) models, respectively. The estimated parameters included maximum specific growth or inactivation rates, lag phases, residual populations, and goodness-of-fit indicators.

The kinetic parameters estimated for the control treatments demonstrated that *Salmonella* spp. behavior varied considerably among studies (Figure 2). In most control treatments stored at refrigeration temperatures, positive growth rates were predominated, indicating that packaging systems without antimicrobial compounds were generally insufficient to suppress microbial proliferation. However, substantial variability among the estimated parameters was observed, likely attributable to differences in microbial serotypes, inoculum preparation, storage temperatures, packaging materials, and food matrix characteristics.

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Table 2 – Estimated kinetic parameters obtained from the fitting mathematical models to experimental *Salmonella* spp. datasets in chicken meat packaged with natural extracts and essential oils

Study	T[a]	Treatment	Resp.[b]		Eq.	μ_{max} or k_{max}		λ or S_l		Y_0		Y_{max} or Y_{res}		RSS[d]
						1/h	CI[c]	h	CI	log UFC/g	CI	log UFC/g	CI	
Porter, Morey, and Monu (2020)	4 ºC	Control	I	5	0.047	± 0.070	–	–		5.41*	± 0.11	5.12*	± 0.05	0.0068
Porter, Morey, and Monu (2020)	4 ºC	0.75% White mustard essential oil (EO)	I	5	0.032*	± 0.020	–	–		5.38*	± 0.22	4.57*	± 0.12	0.0248
Porter, Morey, and Monu (2020)	4 ºC	0.5% White mustard EO	I	5	0.023	± 0.031	–	–		5.36*	± 0.38	4.68*	± 0.25	0.0798
Porter, Morey, and Monu (2020)	4 ºC	0.75% White mustard EO + 0.1% Carvacrol	I	5	0.009	± 0.038	–	–		4.68*	± 0.55	4.31*	± 0.56	0.0156
Porter, Morey, and Monu (2020)	4 ºC	0.5% White mustard EO + 0.1 Carvacrol	I	5	0.023*	± 0.022	–	–		4.90*	± 0.26	4.58*	± 0.03	0.00053
Porter, Morey, and Monu (2020)	4 ºC	0.1% Carvacrol	I	5	0.025*	± 0.018	–	–		5.41*	± 5.30	5.12*	± 0.33	0.00326
Porter, Morey, and Monu (2020)	10 ºC	Control	G	3	0.030*	± 0.012	37.0	± 84.6		5.17*	± 0.50	–	–	0.027
Porter, Morey, and Monu (2020)	10 ºC	0.75% White mustard EO	G	3	0.023	± 0.031	–	–		5.36*	± 0.38	4.68*	± 0.25	0.0798
Porter, Morey, and Monu (2020)	10 ºC	0.5% White mustard EO	G	3	0.054	± 0.032	109.4*	± 46.7		5.29	± 0.35	–	–	0.0278
Porter, Morey, and Monu (2020)	10 ºC	0.75% White mustard EO + 0.1% Carvacrol	G	3	0.060*	± 0.045	139.6*	± 39.2		5.07*	± 0.27	–	–	0.021
Porter, Morey, and Monu (2020)	10 ºC	0.5% White mustard EO + 0.1 Carvacrol	G	3	0.044*	± 0.019	92.9*	± 41.4		5.12*	± 0.29	–	–	0.015
Porter, Morey, and Monu (2020)	10 ºC	0.1% Carvacrol	G	3	0.039*	± 0.007	1.2	± 31.7		5.17	± 0.29	–	–	0.00912
Surendhiran, Cui, and Lin (2019)	4 ºC	Control	G	1	0.041*	± 0.008	7.8	± 27.1		3.33*	± 0.24	6.32*	± 0.21	0.0784
Surendhiran, Cui, and Lin (2019)	4 ºC	Polyethylene oxide + Sodium alginate + Phlorotannins	I	4	0.031*	± 0.007	–	–		3.27*	± 0.13	2.18*	± 0.06	0.0374

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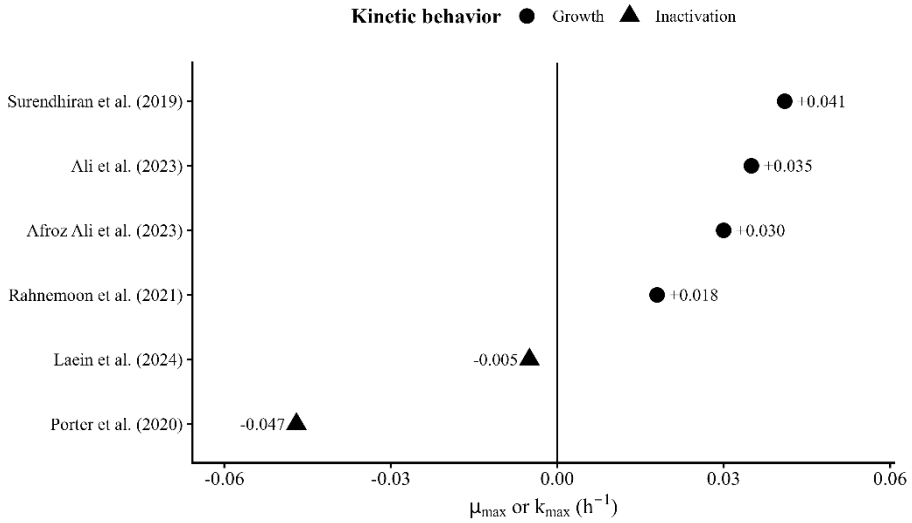
Surendhiran, Cui, and Lin (2019)	25 ºC	Control	G	2	0.201*	± 0.047	–	–	3.28*	± 0.61	8.57*	± 0.30	0.334
Surendhiran, Cui, and Lin (2019)	25 ºC	Polyethylene oxide + Sodium alginate + Phlorotannins	I	4	0.091	± 0.529	10.1	± 108.7	3.25*	± 0.37	2.64*	± 0.18	0.0729
Rahnemoon *et al*. (2021)	4 ºC	Sodium alginate (Control)	G	3	0.018*	± 0.003	21.3	± 59.3	4.24*	± 0.21	–	–	0.0818
Rahnemoon *et al*. (2021)	4 ºC	Sodium alginate + Pomegranate extract	G	3	0.03*	±0.0088	161.1*	± 54.6	4.95*	± 0.19	–	–	0.749
Rahnemoon *et al*. (2021)	4 ºC	Pomegranate extract nanosphere	G	3	0.025*	± 0.011	83.0	± 109.5	4.96*	± 0.51	–	–	0.749
Afroz Ali *et al*. (2023)	4 ºC	Positive Control	G	3	0.030*	± 0.006	78.2*	± 75.8	4.21*	± 0.69	–	–	0.607
Afroz Ali *et al*. (2023)	4 ºC	Pectin + chitosan	G	3	0.025*	± 0.011	83.0	± 109.5	4.96*	± 0.51	–	–	0.749
Afroz Ali *et al*. (2023)	4 ºC	Pectin + chitosan + Quercetin	I	4	0.018*	± 0.003	21.3	± 59.3	4.24*	± 0.21	–	–	0.0818
Afroz Ali *et al*. (2023)	4 ºC	Pectin + chitosan + Nanoquercetin	I	4	0.172*	± 0.105	15.0	± 47.6	7.24*	± 2.20	–	–	0.529
Ali *et al*. (2023)	4 ºC	Control	G	3	0.035*	± 0.008	87.0*	± 57.5	3.15*	± 0.46	–	–	0.262
Ali *et al*. (2023)	4 ºC	Gelatin/Carrageenan + Zein + Turmeric EO	P	7	0.0158 0.043	–	116.5	–	3.33	–	–	–	0.207
Ali *et al*. (2023)	4 ºC	Gelatin/Carrageenan + Nano Zein / Turmeric EO	I	6	0.032	± 0.164	240.0	± 157.6	3.49*	± 0.38	2.80*	± 1.70	0.258
Laein *et al*. (2024)	7 ºC	Control	I	3	0.005*	± 0.003	562.1*	± 550.6	5.45*	± 0.13	-	-	0.00925
Laein *et al*. (2024)	7 ºC	Sodium alginate	I	5	0.019*	± 0.004	-	-	5.79*	± 0.12	4.19*	± 0.24	0.0147
Laein *et al*. (2024)	7 ºC	Sodium alginate + Zataria multiflora EO	I	6	0.0124*	± 0.002	34.9	± 42.2	5.62*	± 0.07	–	–	0.00188
Laein *et al*. (2024)	7 ºC	Sodium alginate + nano *Zataria multiflora* EO	I	5	0.040	± 0.059	–	–	5.01*	± 0.56	4.07*	± 0.35	0.194

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[a]T = Temperature; [b]Resp. = Response, where I = Inactivation, G = Growth, and P = Phoenix (inactivation followed by growth); [c]CI = 95% Confidence Interval; [d]RSS = Residual Sum of Squares. Estimates marked with an asterisk (*) are statistically significant at the 95% confidence level ($p < 0.05$). Source: elaborated by the authors.

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Figure 2 – Estimated values for the maximum specific rate parameter (growth or inactivation) of *Salmonella* spp. in packaged chicken meat in control treatments without natural extract or essential oil across different studies



Source: elaborated by the authors.

The incorporation of essential oils and natural extracts into packaging systems generally promoted microbial inactivation or reduced microbial growth rates compared with control treatments. In several studies, encapsulated or nanoencapsulated systems showed more pronounced antimicrobial effects than non-encapsulated formulations, suggesting that controlled-release mechanisms may substantially influence microbial kinetic behavior during refrigerated storage.

The study by Porter, Morey, and Monu (2020) reported that white mustard essential oil reduced *Salmonella* spp. populations in refrigerated ground chicken meat. The antimicrobial effect was influenced by essential oil concentration, with higher concentrations generally associated with greater reductions in *Salmonella* spp. populations. Interestingly, the combination of white mustard essential oil and carvacrol did not necessarily produce synergistic effects, suggesting possible antagonistic interactions between antimicrobial compounds that may influence their effectiveness.

Surendhiran, Cui, and Lin (2019) observed microbial growth in the control samples, whereas inactivation occurred in chicken meat coated with nanofibers containing encapsulated phlorotannins. The results suggest that encapsulation favored a more sustained release of antimicrobial compounds throughout storage, maintaining antimicrobial activity against *Salmonella* Enteritidis over time.

A similar trend was observed in studies involving nanoencapsulated pomegranate peel extract (Rahnemoon *et al*., 2021), quercetin-loaded nanofilms (Afroz Ali *et al*., 2023), and encapsulated turmeric essential oil (Ali *et al*., 2023). In these studies, nanoencapsulation appeared to enhance antimicrobial activity by reducing volatilization and allowing the gradual migration of active compounds into the food matrix. This behavior is consistent with the controlled-release hypothesis, whereby encapsulation slows the diffusion of bioactive compounds from the packaging matrix, thereby maintaining inhibitory concentrations over extended storage periods. In contrast, direct incorporation of antimicrobial compounds into films without encapsulation tended to produce stronger initial antimicrobial effects but less sustained antimicrobial activity during prolonged storage.

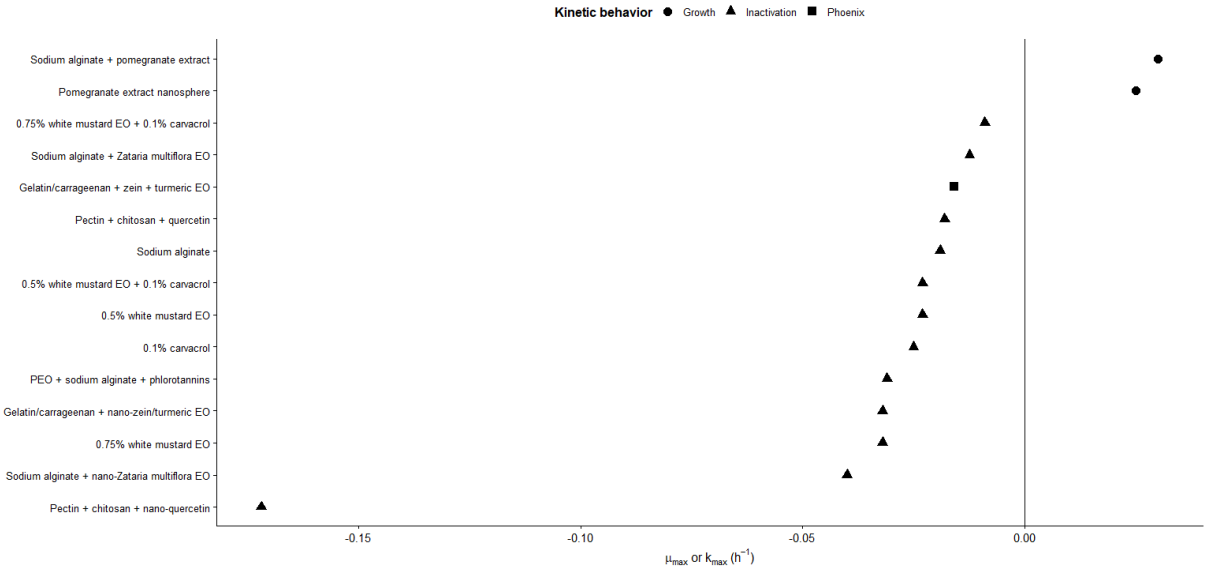
Among the selected studies, Ali *et al*. (2023) provided a particularly interesting example of the Phoenix phenomenon, characterized by microbial inactivation followed by regrowth. This behavior may be associated with the depletion of bioactive antimicrobial compounds, adaptive bacterial responses, or heterogeneity within the microbial population. The Paganini *et al*. (2022) model adequately described this kinetic behavior, highlighting the importance of mathematical approaches capable of representing non-monotonic microbial responses in food systems containing natural antimicrobials.

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The results obtained by Laein *et al*. (2024) also highlighted the importance of encapsulation technologies. Although microbial inactivation was observed even in the control samples stored at 7 °C, treatments containing *Zataria multiflora* essential oil showed substantially greater antimicrobial effectiveness. Encapsulation likely reduced volatilization losses and contributed to maintaining effective antimicrobial concentrations throughout refrigerated storage.

Overall, the kinetic analyses suggest that antimicrobial packaging systems containing encapsulated natural compounds may modify microbial kinetic behavior not only by reducing microbial populations but also by modifying microbial kinetic parameters such as maximum growth and inactivation rates (Figure 3). This observation is particularly relevant because microbial shelf-life and food safety predictions are strongly dependent on kinetic behavior rather than solely on endpoint microbial concentrations.

Figure 3 – Estimated maximum specific growth or inactivation rates of *Salmonella* spp. in chicken meat treated with different antimicrobial compounds and stored below 10 °C



Source: elaborated by the authors.

An important finding of the present study was the apparent relationship between controlled-release systems and prolonged antimicrobial effectiveness. Encapsulation technologies, nanocomposite films, and electrospinning materials appear to contribute to maintaining antimicrobial activity over time by regulating the release and the migration of active compounds from the packaging matrix to the food surface. In contrast, the immediate availability of antimicrobial compounds may promote rapid initial microbial reductions but potentially shorter antimicrobial persistence during storage.

These findings are consistent with previous reports describing the protective role of encapsulation against degradation and volatilization of bioactive compounds (Abandansarie; Ariaii; Langerodi, 2019). Controlled-release systems therefore represent a promising strategy for improving microbiological stability and extending the shelf life of poultry products. Nevertheless, direct quantitative comparisons among studies should be interpreted cautiously due to substantial heterogeneity among experimental conditions, including differences in microbial strains, inoculum preparation, storage temperatures, packaging materials, antimicrobial concentrations, and analytical methodologies. Furthermore, some parameters estimated exhibited relatively wide confidence intervals, possibly reflecting the limited number of sampling time points and differences in experimental designs among the selected studies.

Despite these limitations, the present study demonstrates that secondary quantitative analyses of literature-derived datasets combined with predictive microbiology modeling tools can provide relevant

insights into the microbial kinetic behavior of *Salmonella* spp. in antimicrobial packaging systems. The integration of active packaging technologies with mathematical modeling approaches may contribute to a more quantitative understanding of microbial dynamics in refrigerated poultry products and support the rational design of more effective food preservation systems.

4 Conclusion

The present study demonstrated that predictive microbiology models can be successfully applied to literature-derived experimental datasets to quantitatively characterize the behavior of *Salmonella* spp. in chicken meat packaged with active antimicrobial systems. The mathematical models adequately described microbial growth, inactivation, and regrowth under different packaging conditions and antimicrobial treatments.

Overall, antimicrobial packaging systems containing essential oils and natural extracts reduced microbial growth or enhanced microbial inactivation compared with the corresponding control treatments. Encapsulation and nanoencapsulation strategies appeared particularly promising because they promoted more sustained antimicrobial activity through controlled-release mechanisms, reducing volatilization and maintaining effective antimicrobial concentrations during refrigerated storage.

The exploratory bibliometric visualization indicated increasing scientific interest in active packaging technologies involving encapsulation, nanocomposites, and electrospinning. In contrast, predictive microbiology and kinetic modeling approaches remain relatively underexplored within this research field, highlighting the need for a broader integration of mathematical modeling into studies on antimicrobial packaging systems.

Although direct quantitative comparisons among studies should be interpreted cautiously due to differences in experimental conditions, microbial strains, packaging materials, and storage parameters, the present study demonstrates the potential of secondary quantitative analyses of literature-derived datasets to provide valuable insights into microbial kinetic behavior in food systems.

The integration of active packaging technologies with predictive microbiology approaches may contribute to improving microbiological safety, extending shelf life, and supporting the development of more rational and quantitatively based preservation strategies for poultry products. Future studies incorporating broader literature searches, larger datasets, and multivariate statistical approaches may further improve the understanding of the factors governing microbial kinetic behavior in antimicrobial packaging systems.

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Conflict of interest

The authors declare no conflict of interest.

Note

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Author contributions

OLIVEIRA, A. E.: data analysis and interpretation, methodology, writing of the original article. **KIELING, D. D.:** data analysis and interpretation, final review with critical and intellectual contribution to the manuscript. **ROBAZZA, W. S.:** análise e interpretação dos dados, revisão final

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com participação crítica e intelectual no manuscrito. **LONGHI, D. A.:** study conception, methodology, data analysis and interpretation, and final review with critical and intellectual contribution to the manuscript. All authors participated in the writing, discussion, reading, and approval of the final version of the article.

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