

REVIEW

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COMSOL multiphysics for food processing: advances, challenges, and future perspectives

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Abstract

COMSOL Multiphysics is an advanced numerical simulation platform increasingly applied in food engineering to model complex Multiphysics phenomena. This review summarizes recent advances in its application for simulating key food processing operations, including thermal treatments (pasteurization, drying, frying), novel heating technologies (microwave, radio frequency, ohmic heating), mass transfer processes (drying, extraction, packaging), microbial inactivation, and chemical reaction modeling. The ability of COMSOL to handle coupled Multiphysics enables predictive modeling of the temperature distribution, moisture migration, reaction kinetics, and microbial safety, thus reducing the reliance on costly and time-consuming experimental trials. However, wider implementation remains constrained by challenges such as variability of food material properties, lack of dedicated food-specific templates and material libraries, requiring customization of general modules, and difficulties in experimental validation. Recent advances, including AI-driven optimization, IoT-enabled real-time monitoring, and digital twin integration, are expanding its potential in food engineering. This review offers guidance for students, researchers, and industry professionals in leveraging computational modeling to accelerate innovation, improve safety, and enhance sustainability. Future perspectives emphasize interdisciplinary integration, multistage simulations, and advanced coupling strategies to overcome current limitations and expand applications in both research and industrial practice.

Keywords COMSOL multiphysics, Modeling, Food process, Optimization

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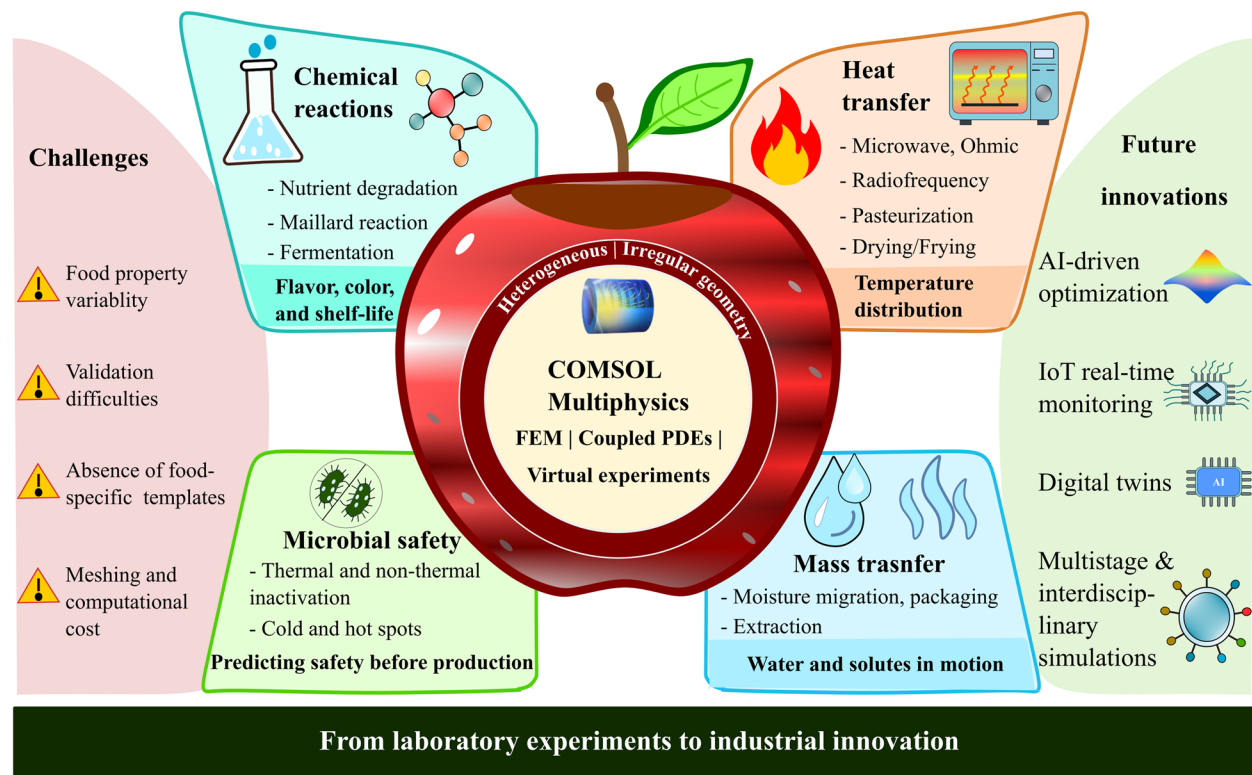
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Graphical Abstract

COMSOL Multiphysics: simulating food processing operations



Introduction

Multiphysics in food processing

Food processing involves a wide range of complex operations such as heating, cooling, mixing, drying, fermentation, separation and packaging unit operations. These operations require an integrated understanding of physical, chemical, and biological processes to achieve efficient production and maintain product quality (Deponte et al., 2020). Typically, governed by heat transfer, mass transfer, fluid dynamics, and reaction kinetics, these processes often occur simultaneously, defining the Multiphysics nature of food processing. For example, microwave (MW) heating, combines the absorption of electromagnetic energy with conductive and convective heat transfer at the food surface (Albahr et al., 2024; Jha & Tripathy, 2021); conversely, drying processes include moisture diffusion with shrinkage-related structural changes within a system of simultaneous heat, mass, and momentum transfer (Gao et al., 2024).

Mathematical modeling plays an important role in optimizing and developing food processing unit operations. In 1969, Teixeira (1969) conducted the first computational mathematical modeling study in food process engineering, employing finite difference methods to enhance nutrient retention in foods subjected to conduction heating. Since then, modeling approaches have been increasingly applied to study heat transfer, mass transfer, fluid flow, and microbial growth within food systems. These models offer a significant understanding of the fundamental process, facilitate the prediction of final product quality, and aid decision-making along the food chain by offering detailed data for process optimization (Emori et al., 2023).

For example, modeling heat transfer in food processing (Tepnatim et al., 2021), frying (Ghaderi et al., 2022), drying (Goud et al., 2022), cooling and smoking (Feyissa & Frosch, 2023), and thawing (Jiang et al., 2023) has proven instrumental in determining temperature distributions within food matrices, which is critical for maintaining product quality and ensuring microbial safety. Similarly,

mass transfer modeling has enhanced the understanding of moisture and solute movement (Rani & Tripathy, 2020; Tuly et al., 2023), which are important parameters influencing the texture, flavor, and shelf-life of food products.

Among mathematical modeling approaches, computational fluid dynamics (CFD) is one of the most widely employed tools for solving equations under various conditions (Tu et al., 2023). CFD integrates the principles of fluid mechanics, applied mathematics, and computer science, and focuses on describing the behavior of fluids in motion through mathematical formulations (Szpicier et al., 2023). COMSOL Multiphysics provides a versatile platform for solving finite element (FEM) and partial differential equation (PDE) problems, primarily for CFD analysis, and other coupled Multiphysics simulations relevant to food and bioprocess engineering.

Why COMSOL matters in food processing: advantages over empirical and data-driven models

Empirical and data-driven models, including those utilizing machine learning, are increasingly used in food engineering for predicting process kinetics in unit operations, such as drying, frying, baking, canning, extrusion, encapsulation, and fermentation (Khan et al., 2022; Liu et al., 2024). While they can be developed rapidly without extensive process knowledge, they are usually tailored to specific food products and operating conditions, which limits their extrapolation to other unit operations or product types (Rabeler, 2020). Moreover, issues related to data scarcity, quality, and the intrinsic heterogeneity of food systems, together with limitations in algorithm training and validation, restrict their broader utility. For example, AI can accurately predict the kinetics of apple drying; however, it cannot explain the mechanistic role of pore structure or thermal conductivity in driving moisture migration (Huang et al., 2022; Sağlam and Çetin, 2022). This limited physical interpretability hinders process scale-up, innovation, and industrial adoption.

Conversely, mechanistic models such as those developed in COMSOL Multiphysics, present several advantages. These methods enable predictions under conditions that have not been previously tested, including non-regular geometries such as shrimp (Abedini et al., 2022); provide physical interpretability, e.g., identifying hot and cold spots through simulated temperature fields; and allow the coupling of multiple phenomena such as microbial inactivation kinetics with novel food processing methods (Kim et al., 2020). COMSOL, as a versatile finite element platform, is distinguished by its ability to perform coupled simulations involving heat transfer, fluid flow, and chemical reactions (Hashemi et al., 2024). It can solve PDEs for complex food geometries, replace

trial-and-error experiments with virtual prototyping, and assist in optimizing processing parameters such as pasteurization conditions (Guo et al., 2020). By integrating these features within a unified modeling environment, COMSOL facilitates the process of translating laboratory findings into industrial-scale applications, making it an indispensable tool for advancing innovation and ensuring safety in food and bioprocess engineering (Fig. 1).

COMSOL interfaces and their applications in food processing

COMSOL Multiphysics is not limited to food processing operations; rather it is a general-purpose platform that integrates a wide range of physics interfaces. When applied to food materials these interfaces enable the simulation of complex behaviors by representing heat transfer, mass transfer, fluid flow, electromagnetic heating, chemical reactions, structural mechanics, and Multiphysics coupling. These are among the most common modules in food engineering.

The heat transfer interface is widely applied in thermal processing, such as pasteurization, drying, and frying. Modeling temperature distributions in baked foods using the heat transfer solid interface (Reddy et al., 2020) and modeling the sterilization of juice, soup, and milk using heat transfer in fluids interface are typical examples (Oishi et al., 2022). The non-isothermal flow interface, which couples fluid flow with heat transfer, and bioheat transfer are often used in microbial inactivation studies. Mass transfer processes are modeled using the Chemical Reaction Engineering and the Subsurface Flow Module. The Transport of Diluted Species interface is used in drying, fermentation, and packaging to simulate the diffusion and convection of water, salts, and solutes, such as the prediction of moisture profiles in dehydrated fruits (Kumar et al., 2022). Related interfaces include Transport of Concentrated Species and Free and Porous Media Flow. Fluid flow interfaces support modeling of mixing, pumping, and spray drying. Laminar and turbulent flow models describe fluid dynamics in pipes and tanks (Tao et al., 2024). In addition, multiphase flow models are used to study gas–liquid–solid interactions in fermentation (Miller et al., 2019), and thin-film flow models are used in coating processes (Bikos et al., 2023). Electromagnetic heating interfaces, including MW, radiofrequency, and ohmic heating, are increasingly applied in novel thermal technologies. Chemical reaction interfaces are used to model various reactions during food processing, such as vitamin C degradation (Yang et al., 2021) and the reactive transport of nutrients (Wang et al., 2024a, 2024b).

Finally, structural mechanics interfaces are useful for simulating food texture and packaging stresses, such as shrinkage during drying or thin-film deformation in

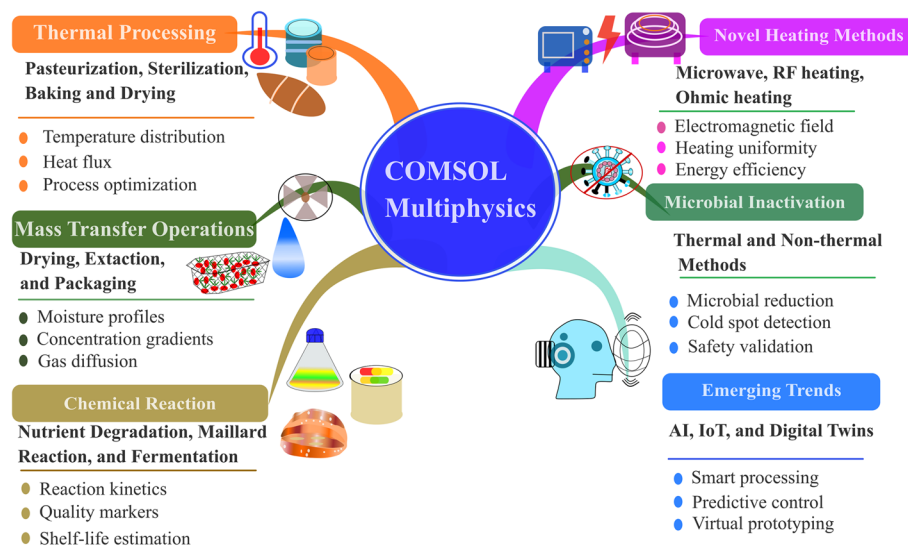


Fig. 1 Principal applications of COMSOL multiphysics in food processing

packaging. Multiphysics coupling interfaces integrate heat and mass transfer, electromagnetics and heat transfer, or fluid flow and chemistry, enabling realistic simulations of complex operations such as MW drying of shrimp, where electromagnetic absorption, heat transfer, moisture evaporation, and structural shrinkage can all be considered (Siguemoto et al., 2021; Teleken et al., 2025).

Governing equations underlying COMSOL-based food process modeling

Table 1 presents a summary of the fundamental governing equations used in food process simulations in COMSOL Multiphysics. These include Fourier's law for heat transfer, Fick's second law for mass diffusion, the Navier–Stokes equations for fluid flow, first-order kinetics for

Table 1 Governing equations and their corresponding COMSOL interfaces in food process modeling

Phenomenon	Governing equation	COMSOL module
Heat transfer	$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q$ (Fourier's law)	- Heat transfer in solids
	$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$ (Energy equation)	- Heat transfer in fluids
Mass diffusion	$\frac{\partial c}{\partial t} = \nabla \cdot (D \nabla c) + R$ (Fick's second law)	Transport of diluted species
Fluid flow	$\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) = -\nabla p + \mu \nabla^2 u + F$ (Navier–Stokes Equations)	Laminar Flow
Microbial inactivation	$\frac{dN(t)}{dt} = -k \cdot N(t)$ (First-Order Kinetics)	Chemical Reaction Engineering
MW heating	$\nabla \times (\mu_m^{-1} \nabla \times E) - \omega^2 \epsilon_c E = 0$ (Maxwell's Equations)	MW/RF
Porous Media Flow	$u = \frac{\kappa}{\mu} \nabla p$ (Darcy's Law)	Porous Media Flow
Viscoelastic Deformation	$\sigma_d = 2G \epsilon_d + 2\eta \frac{\partial \epsilon_d}{\partial t}$ (Kelvin–Voigt model)	Structural Mechanics
Biochemical Reactions	$k = A \left(\frac{T}{T_{ref}} \right)^n \exp \left(-\frac{E}{R_g T} \right)$ (Arrhenius Reaction Kinetics)	Chemical Reaction Engineering

ρ density, C_p heat capacity, k thermal conductivity, Q heat source, T absolute temperature, c concentration of the species, D diffusion coefficient, R reaction rate expression for the species, u velocity vector, p pressure, μ viscosity, F volume force vector, N number of microorganisms, t time, E electric field, ϵ_c permittivity, G shear modulus, η viscosity, ω angular velocity, κ permeability, ϵ_d deviatoric strain, δ_d deviatoric stress, A frequency factor, n temperature exponent, E activation energy, R_g gas constant

microbial inactivation, Maxwell's equations for MW/radio frequency heating, Darcy's law for porous media flow, the Kelvin-Voigt model for viscoelastic deformation, and the Arrhenius equation for temperature-dependent reaction kinetics (COMSOL, 2025). By integrating these governing equations within a finite element framework, COMSOL Multiphysics enables simultaneous solutions of coupled phenomena that are central to food engineering. This capacity facilitates innovation in new product development, process design and optimization, and the development of virtual experiments that can replace lab experiments which are difficult to handle practically.

COMSOL application builder and LiveLink

The application Builder and LiveLink suites are among its distinctive features, which make COMSOL effective in its usage. The application builder, which is included in the Windows® version of COMSOL Multiphysics®, is used to create simulation applications from COMSOL models. It includes a Form Editor and a Method Editor, where users can drag and drop to quickly create a custom user interface, and a programming environment for writing application-specific code, respectively (COMSOL, 2025). This feature has made an outstanding contribution to both academia and the food industry.

In academia, instructors can develop simulation applications from their modeling results to show their students, allowing students to interact with simplified interfaces to change parameters and run simulations. The simulation apps developed in COMSOL serve as virtual experiments, in which students can adjust process parameters and see their end results. For example, from an application developed for the thermal processing of foods, students can change geometry, food composition, and retort temperature to visualize cold spots. This approach shifts the food engineering classroom from a passive learning environment to an active simulation environment, helping students understand complex food processing systems (Erdogdu, 2023; Rivera & Jaeger, 2025). In the food industry, a customized application helps plant operators run pre-established models of various unit operations, such as heating, cooling, and drying. This supports informed decisions without interacting with the complete modeling interface, consequently enhancing process efficiency.

Furthermore, another critical component is the LiveLink suite, which enables COMSOL to integrate with external tools, such as MATLAB, Excel, and Simulink. With MATLAB, it facilitates automated parametric sweeps, optimization loops, and integration with machine learning scripts for real-time model updates. For example, in a study that combined COMSOL and MATLAB to model the heat and electric field distributions

in packaged sausage, the combined model reduced the computational time by 60%. MATLAB used initial COMSOL simulations to predict temperature changes, which avoided repeating full electromagnetic-thermal calculations at each rotation step. This allowed for easier parameter testing and optimization (Tepnatim et al., 2021). Additionally, Excel allows users to easily import data (i.e., parameters, variables, and functions) into COMSOL. Conversely, it can export simulation data from COMSOL to Excel, which helps with optimizing, calibrating, and comparing different scenarios or simulation results with experimental data. In addition, COMSOL can recognize and store material properties created and exported from Excel in its library. Unlike some other simulation tools that are highly reliant on user-defined functions (e.g., Ansys Fluent) or require coding (e.g., OpenFOAM), these unique COMSOL features lower the barrier for interdisciplinary teamwork, making advanced Multiphysics simulations possible for junior and senior food scientists with limited programming skills.

Technical comparison with other simulation tools

While promising for applications in food processing, COMSOL is not always the optimum or perfect choice from every perspective for food engineering simulations. There are other similar tools, each with its own unique nature and purpose. To compare these tools based on metrics such as solver foundation, Multiphysics coupling capability, geometry handling capability, user accessibility and expertise requirements, and their typical application in food processing, information collected from various sources (Ansys, 2025; GitHub, 2026; MathWorks, 2025; COMSOL, 2025) is summarized in Table 2. Selecting appropriate simulation software requires a foundational understanding of the architectural principles underlying each platform and their alignment with specific application domains. COMSOL Multiphysics is built upon a finite element method framework that is inherently designed to accommodate coupled systems of partial differential equations. This design renders it especially suitable for simulating Multiphysics phenomena characterized by bidirectional interactions across complex geometries, where the direct coupling of governing equations is critical (COMSOL, 2025).

In contrast, Ansys Fluent employs a finite volume method, which is highly optimized for CFD (Ansys, 2025). The platform has undergone rigorous validation for industrial-scale turbulent flows, establishing its position as a robust choice for applications dominated by fluid transport. Consequently, for various food engineering applications, such as analyzing airflow in cold storage facilities or fluid dynamics in piping networks, Fluent often has advantages in terms of computational efficiency

Table 2 Technical analysis of some computational platforms for food process simulation

Features	Simulation tools			
	COMSOL	MATLAB	OpenFOAM	Ansys Fluent
Solver foundation	FEM	ODE/PDE	Finite Volume Method (FVM)	FVM
Multiphysics coupling	Primary focus	Requires significant effort to robust solver convergence	Requires manual coding of coupling terms	Requires user-defined functions (UDFs) or coupled modules
Material library	Extensive, customizable	Does not have a single, general-purpose library	User-defined	Broad fluid/thermal libraries
Geometry handling	Strong	Not preferred for complex and industrial geometries	Moderate	Strong
User accessibility	High	High	Low (code-intensive)	Moderate
optimization	LiveLink for MATLAB, built-in parametric sweeps	One of its core focuses	Custom python	DesignXplorer
Typical food applications	MW heating, drying with shrinkage, coupled transport	System dynamics, control design, data-driven modeling, e.g., unstructured fermentation	Customized CFD, multiphase flows	Spray drying, mixing tanks
Target users	Researchers, Multiphysics specialists, academics	Control engineers, researchers, data scientists, algorithm developers	Researchers, CFD specialists, academics	Large enterprises, aerospace, automotive, energy industries
Pricing	Commercial; module-based pricing	Commercial; toolbox-based pricing	Free	Commercial; expensive
Strengths	Integrated Multiphysics, customizable PDEs, app deployment	Rapid prototyping, control integration, data analysis	Open-source, flexible, customizable	Industrial CFD validation, turbulence, scalability
Limitations	Steeper learning curve for advanced features, higher memory for 3D transient modeling	No native spatially-resolved Multiphysics	Steep learning curve, no native graphical user interface (GUI) for coupling	Multiphysics coupling less seamless, license cost

and scalability. However, integrating additional physics domains, such as electromagnetics or structural mechanics, demands external coupling strategies or the development of User-Defined Functions, potentially leading to significant procedural complexity.

OpenFOAM, a finite volume method library available as an open source, provides considerable flexibility for researchers engaged in developing custom numerical solvers or novel Multiphysics formulations (GitHub, 2026). The core advantages of this tool are its code transparency and its development model, which relies on community contributions. Nevertheless, these advantages are dependent upon a high level of proficiency in computational methods and programming, which may hinder their adoption within interdisciplinary teams in applied fields such as food science.

MATLAB/Simulink operates at a higher level of abstraction, concentrating on system dynamics, control logic, and data-integrated modeling. Although this environment is particularly well suited for control system design and empirical model calibration, it does not, by its nature, offer high-fidelity, spatially resolved solutions for coupled Multiphysics problems. Therefore, its most significant application lies in a situation where detailed

spatial resolution is less critical to system-level behavioral analysis or control integration (MathWorks, 2025).

Despite the growing number of CFD-oriented reviews (Erdogdu, 2023; Muktiarni et al., 2024; Szpicer et al., 2023), comprehensive analyses dedicated specifically to COMSOL-based modeling in food systems remain limited. This review therefore bridges that gap by systematically evaluating recent applications of COMSOL in heat transfer, mass transfer, microbial inactivation, and chemical reaction modeling, providing insights into its role in advancing innovation and efficiency in food engineering for both early-stage and seasoned researchers.

COMSOL multiphysics in heat transfer modeling

From a scientific and engineering perspective, optimizing food processing conditions and designing industrial equipment are highly dependent on an accurate understanding of the temperature distribution. Even though novel food processing methods such as infrared (IR), MW, and radio frequency (RF) methods are often more effective than conventional methods are, heat transfer still plays a critical role in both categories of processes (Ou et al., 2025; Patel et al., 2023; Savitha et al., 2025).

Therefore, the design and optimization of industrial-scale food processes require heat transfer modeling to accurately predict the temperature distribution over time and location, which is crucial for ensuring final product safety and quality (Erdogdu, 2023).

Conventional heating

A summary of the recent applications of COMSOL Multiphysics in heat transfer operations during food processing is presented in Table 3. Feyissa and Frosch (2023) developed a mathematical model to describe the drying, smoking, steam cooking, water and air-cooling unit operations involved in the production of salted-smoked loin pork, also known as "Hamburgerryg". Their simulations, which considered a 2D axisymmetric geometry

to represent the product, provided a complete spatial and temporal map of the temperature history. The main findings revealed that the product center was the most critical thermal point during heating, reaching 74.4 °C at 333.33 min, which met the 72 °C food safety standard. In contrast, the surface was the most critical during cooling, as shown in Fig. 2.

Mosalam (2021) also used FEM to study heat transfer during bread baking, but with some simplifications. These include ignoring crust formation and shrinkage and considering only water diffusion. The study showed that the initial moisture content and air humidity strongly affected water loss. The results also showed how the temperature and water concentration profiles changed across the bread matrix. These models provide

Table 3 Some examples of COMSOL Multiphysics modeling in heat transfer

Food type	Unit operation	Major objectives of the study	Reference
Juice	MW heating	- Numerical simulations of constant power MW heating (CPMH) and traditional MW heating (TMH) - Determining inner point temperature and surface temperature distributions for both methods - Validation of the simulation results experimentally	(Gao et al., 2024)
Potato	Deep frying	- Simulations of surface and center temperatures of the strips - Solve mathematical equations for oil and water transfer using Fick's law and Fourier's law	(Gargari et al., 2022)
Carrot slices	MW pasteurization	- Solve coupled 3D and transient form of heat and Maxwell's equations for determining temperature distribution within carrot slices - Propose inactivation modeling for <i>Enterococcus faecalis</i>, <i>Bacillus cereus</i>, <i>Staphylococcus aureus</i> and <i>Shigella flexneri</i> based on the cumulative exposure time to the elevated temperatures	(Roohi & Hashemi, 2020)
Paddy	Solar drying	- Optimize process parameters and develop 3D multilayered finite element model for predicting moisture and temperature profile during simulated solar drying of paddy - Validate the developed model	(Jha & Tripathy, 2021)
Hamburgerryg	- Drying - Smoking - Steam-cooking - Water-cooling - Air-cooling processes	- Develop mathematical model that describe the unit operations listed in the left column - Predict product temperature as function of position and time - Validate the developed model	(Feyissa & Frosch, 2023)
Bread	Baking	- Develop 1D CFD model for simultaneous heat transfer within a cylindrical bread	(Mosalam, 2021)
Liquid foods	MW heating	- Develop a mathematical model for MW processing of liquid foods, - Experimentally validate the developed model and demonstrate rotation on temperature uniformity	(Topcam et al., 2020)
Liquid foods	MW heating	- Propose a continuous-flow MW heating system based on a coaxial inner conductor structure - Develop mathematical model and optimize the parameters of continuous flow heating system - Experimental validation for the proposed model	(Xu et al., 2024)
Shrimp	Drying	- Develop a 3D mathematical model - Predict the temperature and moisture distributions in shrimp - Compare the proposed models with natural convection type of shrimp dryer	(Abedini et al., 2022)
White shrimp	RF	- Develop a simulation model to explore the uniformity of RF treatment on white shrimp - Experimental verification of the developed model	(Zhang et al., 2024)
Minced fish	Thawing	- Develop mathematical expressions and visualizations of temperature uniformity for the heating patterns of fish - Experimental validations for the proposed models	(Yang et al., 2019)

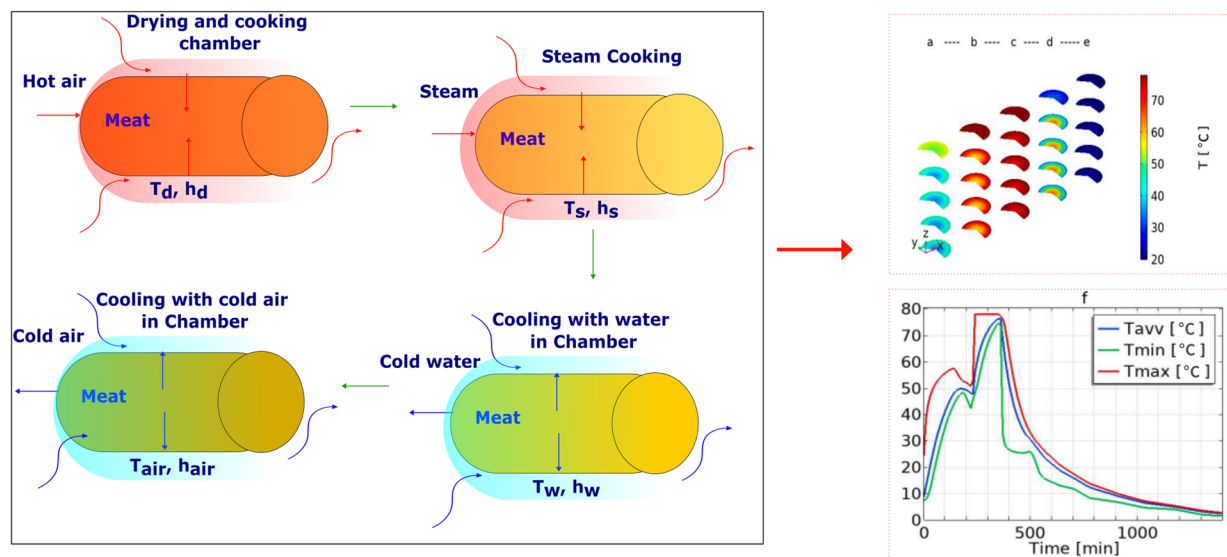


Fig. 2 Heat transfer process during salted-smoked loin pork processing and simulated temperature distributions (Feyissa & Frosch, 2023)

mechanistic insights into process that are often inaccessible through direct experiments. This helps improve safety, energy efficiency, and quality control in traditional food production (Fig. 3).

Novel heating methods

Compared with traditional techniques, novel food treatment methods, such as MW heating, have advantages, including a high rate of heating and selective heat application to specific materials. However, they also face significant challenges, such as uneven heating patterns (Sastry, 2023; Ye et al., 2021). COMSOL Multiphysics greatly contributes to overcoming the difficulties inherent to non-uniform heating, which is a characteristic of novel technologies such as MW, RF, and IR processing. These models which integrate electromagnetic, thermal, and mass transfer equations, enable researchers to visualize temperature gradients, evaluate microbial inactivation, and optimize equipment design and process parameters. Such mechanistic approaches provide a physics-based foundation for translating laboratory findings into scalable industrial applications, thus facilitating swift adoption of novel thermal technologies in food engineering.

Roohi and Hashemi (2020) developed a 3D computational model that couples Maxwell's equations with heat transfer equations to simulate the MW heating of carrot slices. The accuracy of the model in reproducing temperature distributions across power levels was commendable, with a maximum deviation of 7%, compared

with the experimental data. Furthermore, three distinct microbial inactivation phases for *S. aureus* and *S. flexneri* were successfully predicted. However, the study treated carrot slices as homogeneous with constant dielectric properties and overlooked the anisotropic cellular structure and the dynamic property changes that occur during the heating process. This simplification potentially compromises the accuracy of hotspot predictions and may restrict the applicability of the model to other vegetable matrices.

Zhang et al. (2023) investigated the MW heating of berry puree, which revealed three distinct heating stages and demonstrated the influence of edge effects, mainly the overheating observed at corners. A key challenge identified by the authors is that the dielectric properties of berry puree are dynamic and change with temperature and moisture content, which creates nonlinear heating behavior. Additionally, treating berry puree as a homogeneous substance was acknowledged as a major source of potential error. Material rotation was incorporated to improve uniformity, but the model does not account for particle settling or component separation in real berry puree.

Similarly, Xu et al. (2024) developed a continuous-flow MW system featuring a coaxial inner conductor, achieving 90% heating efficiency for liquid foods such as milk and juice. However, these studies focused primarily on liquids with low-dielectric-constants. Its suitability for high-viscosity fluids or those containing solid particulates has yet to be evaluated. Additionally, the incorporation

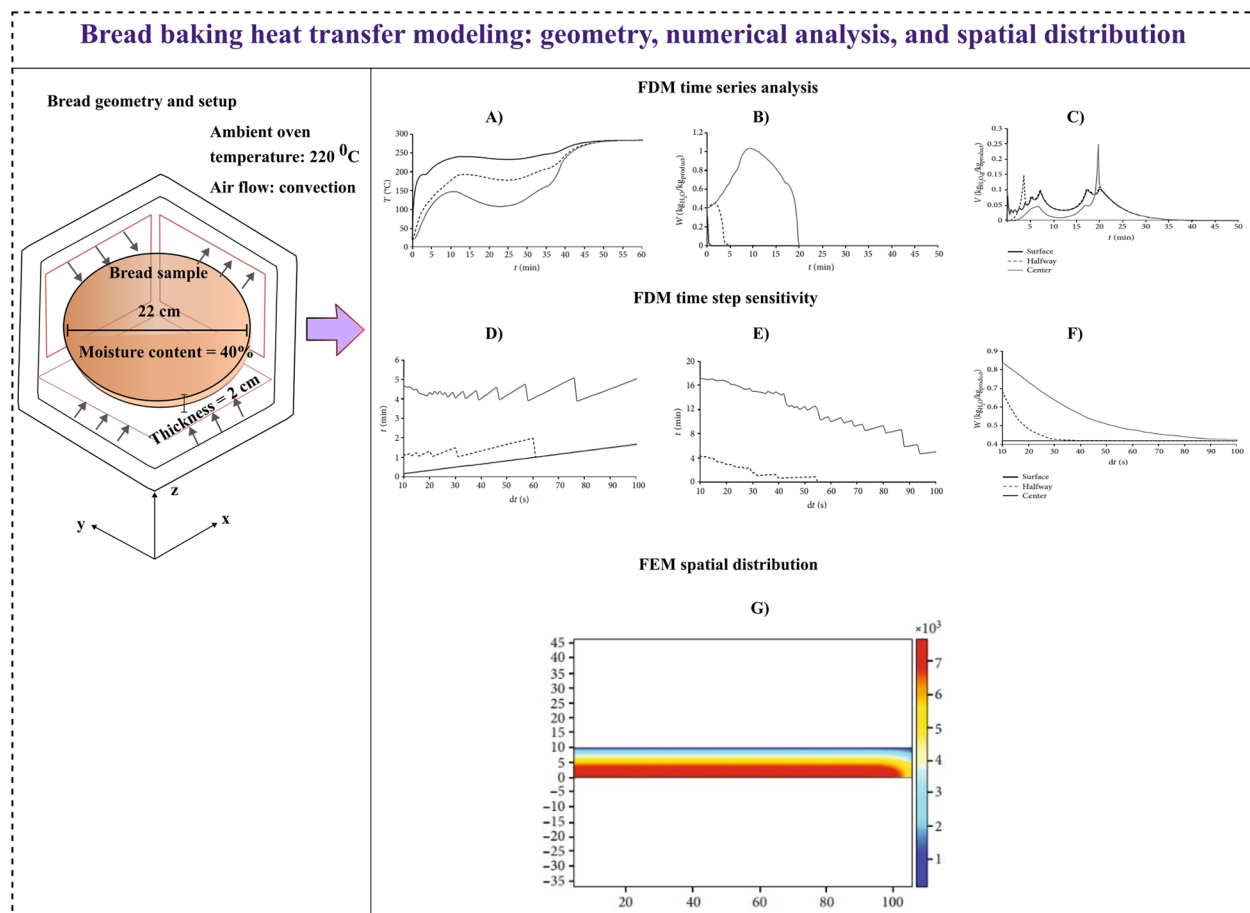


Fig. 3 Combined FDM-FEM baking simulation results for cylindrical bread sample heat and mass transfer analysis (Mosalam, 2021). Left panel: schematic of the cylindrical bread sample and oven environment. Right panel, top FDM results showing temporal evolution of (a) temperature, (b) liquid water content, and (c) vapor water content at the surface, midpoint, and center over 1800s. Right panel, middle FDM sensitivity analysis illustrating the effect of time step (Δt) on (d) time to reach 100 °C, (e) time of peak liquid content, and (f) peak liquid water content value. Right panel, bottom FEM results showing (g) a two-dimensional axisymmetric moisture concentration profile ($\frac{mol}{m^2}$) at $t = 1800$ s, revealing moisture gradients from the surface to the center

of a metal bar presents potential practical difficulties, including fouling, cleaning difficulty, and regulatory concerns for continuous food contact.

Similar to electromagnetic methods, IR heating has also been modeled. Jha and Tripathy (2021) used a 3D multilayer paddy model (husk, bran, endosperm) to simulate solar drying, demonstrating the importance of considering multilayer structures rather than simplified geometries to improve predictive accuracy. This study effectively quantified the effective diffusion coefficient for each layer, endosperm ($2.95 \times 10^{-11} \frac{m^2}{s}$) > bran ($8.66 \times 10^{-12} \frac{m^2}{s}$) > husk ($6.00 \times 10^{-12} \frac{m^2}{s}$), confirming that the husk and bran act as barriers to moisture migration. While the study integrates practical engineering optimization with advanced modeling techniques, the

model relies on simplifying assumptions. These include negligible paddy shrinkage, porosity, hygroscopicity, summed grain layer properties, and an adiabatic system boundary, which is a somewhat idealized representation of real-world conditions, and may not capture actual phenomena.

Furthermore, other researchers have broadened the application of COMSOL in frying, drying, and thawing operations (Gargari et al., 2022; Abedini et al., 2022; Oishi et al., 2022; Miran and Palazoglu, 2019; Yang et al., 2019). However, these studies share common constraints such as the use of constant or oversimplified material properties, idealized boundary conditions, a lack of experimental validation for complex geometries, and high computational costs.

Mass transfer: drying, extraction, and packaging

Heat transfer and mass transfer are fundamental to numerous food processing operations. These include drying, extraction, distillation, dehydration, infusion, and leaching, with water, salt, oils, proteins, and flavors being the most commonly transferred food components. Accurately predicting moisture and temperature distributions in the food matrix is mandatory for process efficiency in unit operations such as drying and dehydration (Heldman et al., 2018). Furthermore, food stability during storage depends on the transfer of various components, including water, oxygen, and carbon dioxide (Vatankhah & Ramaswamy, 2021). The temperature and moisture distribution of processed food significantly affect its appearance, structure, quality, and safety. Food materials are typically heterogeneous in terms of microstructure and physical properties, making accurate determination of the variable heat and mass transfer processes required to optimize thermal processing difficult. Mathematical modeling is commonly used to provide predictions of processing results (Farid, 2019).

Drying processes

A summary of the applications of COMSOL Multiphysics in mass transfer modeling is depicted in Table 4. Rani and Tripathy (2023) modeled pineapple drying in mixed-mode solar dryers that integrate flat plates and finned collectors. To achieve 10% (wb) moisture in pineapple slices, the dryer integrated with the flat plate collector (FPSC) required 2.5 h more drying time than the finned collector aided drier. Their simulations revealed that air-flow-induced vortices generated dead zones in the FPSC chamber, whereas the finned collector improved the air distribution and drying efficiency. The coupled CFD heat transfer model showed excellent agreement with the experimental results for temperature (mean absolute error of 2–3 °C). However, the standalone mass transfer model had greater deviation for moisture (25–30%), which the authors attributed to neglected factors. Limitations of this study include; lumping internal moisture transport mechanisms, specifically liquid diffusion, vapor diffusion, and capillary flow into a simplified approach. Furthermore, the governing equations were solved in a loosely coupled manner, which failed to capture an

Table 4 Typical examples of the application of COMSOL Multiphysics in mass transfer modeling

Product treated	Mass transfer unit operation	Study objectives	Reference
Potato slices	Dehydration	- Develop a 2D axisymmetric geometry - Predict the heat and mass transfer (HMT) in a disk-shaped potato slice - Predict non isotropic shrinkage - Validate the proposed model	(Das & Prasad, 2024)
Mango pulp	Drying	- Develop a 3D model and solve heat and mass transfer equations to understand and visualize the effect of different temperature combinations on temperature profile & their distribution	(Kumar et al., 2022)
Phenolics and carotenoids	Extraction	- Extraction kinetics modeling of yield, total phenolic content, and total carotenoids content - Optimizations and experimental validations of the developed extraction kinetics model	(Vélez-Erazo et al., 2021)
Tomato	Drying	- Determine a theoretical model to define tomato drying curves - Validations of the theoretical model	(Reppich et al., 2021)
Trans-resveratrol	Extraction	- Develop a mathematical model of coupled momentum and mass transfer including thermal degradation of trans-resveratrol from grape cane powder - Experimental validations of the proposed model	(Turgut et al., 2020)
Kiwifruit slices	Drying	- Establish a 3D multiphase porous model to describe heat and mass transfer within the kiwifruit slices subjected to combined RF and vacuum drying - Experimental validations of the proposed model	(Hou et al., 2020)
Bioactive compounds	Extractions	- Develop MW extractor by simulating the waves and electric fields in a heating chamber - Provide brief insights into MW heating to overcome technical challenges	(Nisoa et al., 2023a)
Naphthol blue black dye	Membrane distillation	- Develop a 3D CFD model to predict the permeate flux and interfacial temperature - Determine temperature polarization coefficient at different operating parameters	(Baghel et al., 2020)

accurate representation of the interactions between moisture loss and material properties. The semicircular loop solar collector dryer geometry requires an unstructured mesh with over 2.7 million elements, representing a high computational cost.

Chen and Pan (2021) investigated heat and moisture transfer in walnuts subjected to hot air drying in a fixed-bed column dryer through modeling. Their simulations revealed that walnuts positioned at lower column heights dried faster, resulting in a lower moisture content, whereas walnuts positioned at higher-columns retained more moisture. Increasing the air temperature improved the dryer efficiency more than increasing the air velocity. However, a slight decrease in efficiency was observed at column heights above 0.8 m. Several challenges were identified, including the need to determine parameters, i.e., moisture-dependent thermal conductivity, temperature-dependent vapor diffusivity, and moisture-dependent relative activation energy. Walnuts were treated as concentric spheres, which ignored a 3D geometric variation. Solving coupled transient multiphase equations for a deep-bed system requires a high computational cost, and the model does not account for volumetric shrinkage, which can alter moisture pathways and drying rates. Despite these limitations, the model provides a useful way to predict and optimize walnut drying.

Solomon et al. (2021) developed a convection drying model to simulate the drying process of *injera*, Ethiopian flat fermented bread. The simulations showed that drying started on the surface and then moved inward, with internal moisture leaving the bread more slowly. The drying rate was significantly affected by both the air temperature and velocity. Specifically, it took about 125 min to reduce the moisture ratio to 0.03 when the air temperature was 60 °C and the air velocity was 0.5 m/s. The model outputs agreed well with experimental data, with $R^2 > 0.95$. However, the model used a fixed geometry, ignoring the significant shrinkage that is highly probable for high-moisture products such as *injera*. Furthermore, the model simulated only a single piece of *injera* and did not extend to a tray with multiple pieces, where inter-sample airflow is critical for designing an effective dryer.

Considering structural changes during the processing of agricultural products is a major tool to accurately capture actual phenomena. Consequently, some researchers have integrated dynamic geometry into their models. For example, Dhalsamant (2021) developed a finite element (FE) model that integrates heat transfer, laminar flow, the transport of diluted species, and moving mesh modules to simulate the solar drying of potato cylinders with varying diameters. The predictions revealed that the temperature increased and that moisture migrated across different sample sizes. Furthermore, the model accounts for

shrinkage, providing realistic data comparable to those of physical experiments. However, the study uses a constant effective diffusivity, whereas in reality diffusivity depends on moisture content and temperature. In addition, this approach overlooks pressure-driven flow dynamics, although these limitations are not unique to this study.

To reveal more complex spatial variations within a product during drying, several researchers have employed 3D analysis, extending beyond one-dimensional (1D) analysis. Kumar et al. (2022) developed a 3D model of mango pulp drying, solving coupled heat and mass transfer equations. The simulations showed vertical temperature gradients ($T_{\text{bottom}} > T_{\text{middle}} > T_{\text{top}}$) and moisture content gradients ($MC_{\text{bottom}} > MC_{\text{middle}} > MC_{\text{top}}$), indicating that with surface areas dried faster than the central regions. The results aligned well with the experimental measurements, confirming the efficacy of 3D modeling in accurately capturing spatially heterogeneous drying behavior. Despite these strengths, several universal challenges remain. These include managing complex material properties and achieving process uniformity. Moreover, limitations in the empirical data required for the governing equations, alongside some simplified assumptions to ensure problem solvability, were also observed.

Extraction processes

The application of COMSOL to model extraction processes enables a detailed mechanistic understanding, as demonstrated by Vélez-Erazo et al. (2021) in their study on MW-assisted extraction from mango waste. Using a two-step kinetics modeling approach with a Box-Behnken design, the COMSOL model distinguishes between an initial washing stage (fast release of surface compounds) and a diffusion stage (release from within the plant matrix). Although the model does not account for thermal degradation effects, it provides insight into solvent polarity and process complexity, revealing that MWs negatively affect some compounds. Similarly, Turgut et al. (2020) developed a sophisticated model using COMSOL to simulate the extraction of trans-resveratrol by integrating fluid flow, heat transfer, and mass transfer with reaction equations. The model successfully predicted time-dependent extraction curves at various temperatures, flow rates, and ethanol concentrations. However, the authors acknowledged a slight deviation between the model predictions and experimental data at different flow rates, which was attributed to an oversimplified mass transfer mechanism. Additionally, the degradation model uses first-order single activation energy kinetics, which may not capture complex degradation pathways.

In addition to simulating the extraction process itself, COMSOL models are instrumental in designing and

optimizing the extraction hardware, as illustrated by Nisoa et al. (2023a), who combined numerical modeling with experimental validation to investigate MW-assisted extraction of bioactive compounds from *Kaempferia parviflora* rhizomes. The simulation aimed to optimize the MW chamber height and waveguide positions to improve the heating uniformity and electric field intensity. However, the authors focused mainly on Maxwell's equations and did not couple heat and mass transfer equations, indicating that the model was intended for hardware design rather than extraction process simulation. Furthermore, the optimum extraction conditions (83°C, 2.5 min) for peak yield ($258.1 \frac{\mu\text{gQE}}{\text{mL}}$, total flavonoids; $120.69 \frac{\mu\text{gGAE}}{\text{mL}}$, total phenolic contents) were determined empirically, and the kinetics of yield recovery over time, temperature, or power were ignored.

These case studies reflect a broader trend, as evidenced by additional research (Baghel et al., 2020; Hou et al., 2020; Kumar & Tripathy, 2024; Reche et al., 2021; Sujinda & Varith, 2025). Collectively, COMSOL-based extraction models integrate electromagnetic, thermal, and diffusion phenomena to provide mechanistic insights into solute release kinetics, supporting rational design and scale-up of bioactive compound extraction processes.

Food packaging

Following drying and extraction, food packaging is another critical area where mass transfer modeling supports material development and shelf-life prediction. COMSOL-based FEA has been increasingly used for this purpose. Yuan et al. (2019) presented a model of moisture migration in a multi-component food system (biscuits, hawthorn sheets, agar gel), each exhibiting different water activities. Using a 1D, unsteady-state diffusion model, which includes experimentally derived effective diffusivity values and sorption isotherms, the study successfully captured the discontinuous moisture distribution observed at the interfaces of the components. The water activity gradient was determined to be the principal driving force; consequently, the agar-biscuit system achieved equilibrium in 48 h, the hawthorn-biscuit system in 72 h, a difference attributable to the more pronounced initial water activity differences.

For gas-controlled packaging, González-Buesa and Salvador (2022) developed a model to simulate gas exchange within microperforated films, specifically for modified atmosphere packaging of products that respire. In their 3D model, the microperforation was represented as a distinct fluid domain, employing geometry derived from scanning electron microscopy (SEM) data; conversely, the unperforated film was modeled as an impermeable barrier, given the minimal gas permeation through the polymer. This model effectively integrates fluid dynamics

within the perforation, Maxwell–Stefan diffusion for multi-component gas transport, and respiration reaction kinetics, thereby enabling precise predictions of the internal package atmosphere under convective-diffusive conditions.

More recently, Nguyen et al. (2025) developed a numerical model for O_2/CO_2 transfer in cheese packaging using a 2D geometry. Unlike microperforated films, the tray and lid films were treated as separate diffusive domains, with explicitly defined material properties (permeability, diffusivity, solubility) governed by Fick's second law and Arrhenius-dependent parameters. Henry-type sorption/desorption at the food-headspace boundary and flux continuity at the food-tray interface were included as boundary conditions. The model successfully represented dual-regime dynamics, characterized by initial rapid alterations stemming from gas sorption within the food, followed by slower permeation-dominated transport through the packaging. Sensitivity analysis showed that the permeability a tray to O_2 and CO_2 was the primary determinant of the equilibrium concentration, surpassing the influence of diffusivity, solubility, and activation energy. Furthermore, the efficacy of COMSOL in predicting mass transfer phenomena in food packaging has been documented by other researchers (Dutta et al., 2024; Nisoa et al., 2023b). These case studies confirm that COMSOL accurately simulates complex mass transfer scenarios in packaging, from moisture migration in solid components and convective gas exchange in microperforated films to coupled diffusion through food and packaging materials. Model accuracy depends heavily on reliable input parameters such as permeability, diffusivity, and sorption properties, enabling a shift from empirical shelf-life testing toward physics-based packaging design that identify optimal materials and atmospheres to extend product shelf life.

Advanced multiphysics applications of COMSOL in food processing

Moving beyond traditional unit operations, COMSOL Multiphysics has become an indispensable tool for simulating advanced, interconnected phenomena where multiple physical processes occur simultaneously. A summary of some of the studies on advanced applications of COMSOL are presented in Table 5.

Advanced fluid flow and rheology in complex processes

The behavior of non-Newtonian fluids under dynamic conditions is a critical focus of numerous food processing techniques, including extrusion and 3D printing. For example, the modeling of a single-screw extruder requires the integration of laminar flow with temperature-dependent rheology and heat transfer, including the

Table 5 Advanced Multiphysics applications of COMSOL in food processing

Application	Key physics involved	Product treated	Reference
Whole milk spray drying	Turbulent fluid flow (k- ϵ model), heat and mass transfer, particle tracking (Euler Lagrange), droplet evaporation (4-stage model), species transport	Whole milk	(Sefidan et al., 2022)
Freezing of vacuum-packed beef	Conjugate heat transfer (solid and fluid), laminar fluid flow, phase change (apparent specific heat method), heat transfer in solids with variable composition	Beef	(Beltran et al., 2025)
Single-screw polymer extrusion	Laminar/non-Newtonian fluid flow, Heat transfer (conduction/convection/viscous dissipation), Species transport (with chemical reaction)	Polymer solutions	(Kousemaker et al., 2025)
3 d food printing	Non-Newtonian flow, heat transfer, fluid–structure interaction, solidification	Gelatin gels	(Tong et al., 2023)
Convective drying with shrinkage	Heat and mass transfer, fluid flow (air), solid mechanics (shrinkage), Arbitrary Lagrangian–Eulerian (ALE)	Banana slices	(Das et al., 2025)
Liquid–liquid two-phase flow heat transfer in microchannels	Fluid flow, interfacial tension, heat transfer, level set method (LSM), swirling intensity	Microdroplet systems	(Cao et al., 2025)
Refrigerated transport simulation of citrus fruits	Fluid flow (porous media), heat transfer, respiration kinetics, turbulent flow, convective heat transfer	Oranges and lemons	(Tobler et al., 2025)
Fluid–structure interaction (texture deformation)	Solid mechanics, heat transfer (Phase change)	Starch Gel	(Qin et al., 2024)
Multiphase flow (emulsification)	Fluid flow, interfacial tension	Oil-in-Water emulsions	(Adeyemi et al., 2023)
Freezing and ice crystal growth	Phase change, heat transfer	tylose gel	(Anwajler et al., 2024)
Convective drying with shrinkage	Mass transfer, heat transfer, solid mechanics	Cornstarch-alginate gel slabs	(Júnior et al., 2019)
3D food printing	Non-Newtonian flow, laminar flow, fluid dynamics, structural mechanics	Mashed potatoes, gels	(Guo et al., 2019)
Vacuum cooling with shrinkage	Heat transfer, mass transport, fluid flow, structural mechanics	Steamed bread, porous foods	(Ajani et al., 2023)
Spray drying atomization	Turbulent flow, heat and mass transfer, Particle tracking, droplet drying kinetics, crust formation	Colloidal suspensions	(Schweitzer et al., 2021)
Freezing and ice crystal growth	Phase change, heat transfer (conduction, forced/natural convection)	Raw potatoes	(El Achkar et al., 2021)

solid screw component itself (Kousemaker et al., 2025). This methodology facilitates accurate predictions of pressure drops and thermal profiles, which is essential when processing materials such as dough or protein mixtures that exhibit shear-thickening behavior. Similarly, in 3D food printing, the choice of extrusion mechanism greatly affects printability. Simulations comparing syringe-based and screw-based systems reveal that while syringe extrusion offers simple, controllable flow for high-viscosity inks such as mashed potatoes, screw-based systems generate complex patterns and backflow, making them less suitable for such materials (Guo et al., 2019). Consequently, these insights contribute to the customization of printer design and ink formulation, guided by the fundamental principles of fluid mechanics.

A key limitation of these modeling approaches is the simplification of rheological behavior. Conventional

models such as the Carreau-Yasuda equation can underestimate the pressure drop and viscous dissipation when applied to shear-thickening fluids (Kousemaker et al., 2025). Furthermore, the majority of simulations are predicated on idealized assumptions, including no-slip walls and isothermal flow, which are not representative of practical situations where wall slip or temperature variations are present. The computational costs also remain high due to the fine meshing required for complex geometries. In addition, simulation outcomes are material-specific; a design validated for polymers may not perform well for soft-solid food inks, necessitating careful calibration and revalidation.

Dynamic systems with moving geometries and interfaces

Real-world food processing often involves moving boundaries, such as rotating drums in dryers or products

on conveyors in MW ovens. The ALE method in COMSOL is key to simulating these challenges. It has been used, for instance, to model the rotation of materials during MW-assisted pyrolysis, coupling electromagnetics with heat transfer and reaction kinetics to minimize harmful hot spots (Ajani et al., 2023). This methodology translates directly to improving uniformity in processes such as RF pasteurization or baking. Furthermore, the ALE method proves valuable in predicting structural changes in food products. During vacuum cooling of steamed bread, the coupling of porous media flow with heat and mass transfer enables researchers to model shrinkage. Their findings indicated that moisture loss, rather than the viscoelastic properties of the material, was the primary factor driving deformation. This offers a more detailed understanding, thereby advancing texture prediction beyond empirical approaches.

Despite the efficiency of the ALE based conjugate modeling approach, significant challenges persist. The computational cost is high, as even the simplified 2D geometry requires hrs. of run time. Furthermore, the model's underestimation of moisture loss, as evidenced by the reported values of 9.18% and 10.28% for predicted and experimental outcomes, respectively, stemmed from material property simplifications, such as the assumption of constant porosity. The applicability of the model to other processes is constrained by the small deformation assumption, and validation attempts yielded a maximum shrinkage error of 13.51%. Sensitivity analysis revealed that the most influential parameter is empirical rather than predictive. Finally, the local thermal equilibrium assumption may breakdown under rapid evaporation, and the model was validated only for steamed bread.

Multiphase and particle-scale phenomena

From emulsification to spray drying, many food operations depend on interactions between different phases. For liquid–liquid systems, such as emulsions, COMSOL's Level Set method can track sharp interfaces between phases, helping optimize conditions to achieve the desired droplet sizes for product stability (Cao et al., 2025). Furthermore, in acoustic emulsification, simulations correlate ultrasonic pressure fields with droplet breakup regimes, functioning as a virtual laboratory to minimize surfactant utilization (Adeyemi et al., 2023). Spray drying represents a quintessential multiscale challenge. By integrating Eulerian airflow simulations with Lagrangian particle tracking, researchers can monitor individual droplets, such as those found in milk, throughout their entire drying process (Schweitzer et al., 2021; Sefidan et al., 2022). Consequently, this approach enables

the prediction of critical events, including crust formation and particle buckling, which ultimately dictate the final powder properties, such as morphology and solubility. This approach transforms spray dryer design from a trial-and-error methodology into a predictive science, particularly for high-value powders such as infant formula. However, even within this spray drying framework, several limitations persist. The limitations of single-droplet models, which cannot predict buckling without experimentally determined coefficients, are key issues. In addition, the acoustic levitator has a limited temperature range, and the range of 20–65 °C used for experimental validation poses a restriction. Moreover, CFD simulations often ignore the flow disturbances caused by the droplet itself (Schweitzer et al., 2021).

Phase change and preservation processes

Accurately simulating freezing, thawing, and drying is essential for preserving food quality. COMSOL's ability to model phase change using methods like the apparent heat capacity allows realistic prediction of freezing times for irregularly shaped foods, such as meat cuts or seafood (Beltran et al., 2025). Research on potato freezing has shown that asymmetric airflow within industrial freezers can displace the final freezing point from the geometric center (El Achkar et al., 2021). These findings challenge conventional sensor placement strategies and underscore the necessity of a process design that is specifically tailored to the application. Drying, often accompanied by shrinkage, is another coupled process. By integrating moisture transport with geometry deformation via the ALE method, models can predict final shapes and identify quality defects like cracking, which are simpler diffusive models that are missed (Júnior et al., 2019). Furthermore, for thawing, simulations that incorporate various packaging materials contribute to the design of improved insulation strategies, thus extending shelf life (Anwajler et al., 2024).

Despite these capabilities, significant modeling challenges have been observed. A primary limitation is the need for detailed, temperature-dependent thermophysical properties (e.g., for separate muscle and fat tissues), which are time-consuming to obtain and product-specific (Beltran et al., 2025; El Achkar et al., 2021). From a computational perspective, the coupling of phenomena like shrinkage with the ALE method is computationally demanding and susceptible to mesh distortion or convergence issues when subjected to substantial deformation. Moreover, the prevalent use of 2D geometries, while efficient, fails to fully account for 3D edge effects, limiting the predictive accuracy for actual products.

Microbial inactivation: thermal and nonthermal methods

Microbial safety remains a critical priority in food processing. Both conventional thermal methods and emerging nonthermal technologies face issues such as non-uniform energy delivery, suboptimal process parameters, and limited mechanistic insight into pathogen inactivation. COMSOL Multiphysics overcomes these limitations by allowing simultaneous, physics-based simulations of heat transfer, fluid flow, electromagnetic fields, and microbial kinetics in actual food matrices.

Thermal processing

Thermal technologies such as MW and ohmic heating are widely used for microbial inactivation, but they suffer from energy distribution heterogeneity, which can result in safety risks. MW heating has proven effective in eliminating pathogens in food products; however, a limited understanding of bacterial cell interactions with electromagnetic fields, coupled with temperature inconsistencies within processed foods stemming from uneven electromagnetic field distribution, presents a challenge (Muñoz et al., 2023; Patel et al., 2023). COMSOL allows coupled solutions of Maxwell's equations and heat transfer equations, enabling visualization of electromagnetic wave propagation, energy absorption, and subsequent heating within food matrices and containers. As a result, researchers can identify, analyze, and visualize temperature inconsistency issues by simulating the electromagnetic field distribution within a virtual model of food and its container, given that the resultant heat generation and temperature profile can be accurately predicted. Furthermore, bacterial cells can be modeled as dielectric particles within a host medium, and localized electric field enhancement or dielectric heating can be simulated, thus offering insights into potential non-thermal inactivation mechanisms. This phenomenon is highly dependent on the sample shape and can be numerically solved (Bhattacharya & Basak, 2023).

Its application extends beyond MWs to ohmic microbial inactivation, another advanced thermal technology. Kim et al. (2020) and Choi et al. (2020) employed COMSOL to simulate the electric field distribution, natural convection, and microbial kinetics associated with the ohmic heating of tomato and orange juices. Their findings identified critical control points and confirmed the accuracy of the simulations in predicting heating uniformity and microbial inactivation. Similarly, Wang et al. (2024a) developed a novel 3D model that integrates electric fields, heat transfer, and fluid dynamics to simulate the effects of agitation (10–20 rpm) on the temperature uniformity and pasteurization efficiency. This study computed both the pasteurization value (P -value) and

the protein non-denaturation ratio and concluded that agitation substantially decreased the processing time and enhanced the temperature uniformity. From a system design and optimization perspective, this 3D model serves as a valuable tool because it combines ohmic heating with agitation to improve process efficiency and quality retention.

The application of COMSOL in the thermal inactivation of microorganism modeling was further evident in a study by Badin et al. (2023), who modeled natural convection during raspberry pulp pasteurization. The model integrated degradation kinetics, which is overlooked by most studies, for quality attributes such as anthocyanin and ascorbic acid. The results of the model successfully predicted transient temperature profiles, fluid flow patterns, and migration in the slowest heating zone, providing a critical assessment of microbial safety and nutrition.

Nonthermal processing

Nonthermal techniques, including plasma, ultrasound, and pulsed electric field (PEF) methods, have attracted considerable research attention for their potential to maintain food quality while simultaneously achieving microbial inactivation (King et al., 2026; Lim et al., 2025). Numerous investigations have demonstrated the efficacy of COMSOL as a valuable instrument for modeling, analyzing, and optimizing these advanced methods. In a study focused on the design of a batch ultrasonic reactor for the rapid pasteurization of juices, COMSOL was used to simulate coupled ultrasound and fluid flow. The results from the simulation revealed areas with both low-pressure amplitudes and low fluid velocities, which the authors referred to as passive zones. These zones limit the efficiency of microbial inactivation in traditional ultrasonic reactors (Baboli et al., 2020). Although the model development has some limitations, such as the assumption of ideal boundary conditions (i.e., perfect energy transfer at the probes) and the neglect of real-time changes in liquid properties like viscosity, the geometry developed in this study eliminated passive zones and drastically reduced the 5-log reduction time for *E. coli* to 0.38 min. This is also the first study to achieve a 5-log reduction for *S. aureus* in 0.55 min via ultrasound.

Further research by Hashemi et al. (2024) combined thermodynamics, kinetics, and CFD modeling to capture *E. coli* inactivation under sonication. The results showed that microbial resistance was strain-dependent, and that higher temperatures accelerated the rate of inactivation by reducing the time required to reach maximum lethality. These findings suggest that COMSOL-based models can inform temperature-ultrasound synergies for improved efficacy. Similarly, Moya et al. (2022) developed

a PEF-ohmic model for agar-based systems, simulating the electric field distribution, temperature uniformity, and microbial inactivation of *Salmonella Typhimurium* 878. Their model confirmed that COMSOL can effectively identify cold spots, optimize electrode configurations, and predict microbial lethality. This hybrid modeling approach demonstrated how combining electric and thermal mechanisms enhances microbial safety in solid foods.

Bao et al. (2021) modeled yeast inactivation in apple juice, and the results revealed that microbial inactivation strongly depended on the cell concentration and soluble solids. Arserim et al. (2021) extended this to dielectric barrier discharge systems, simulating distributions of reactive oxygen and nitrogen species. Although the model agreed with the experimental results with approximately 1-log reduction, deviations highlighted the need to include UV effects and local electric field influences in future plasma models.

Despite the limitations noted above, including the narrow validation scope in most studies and simplified microbial kinetics that overlook strain-specific resistance and sublethal injury, these COMSOL-based models still offer practical value for identifying optimal processing parameters to maximize microbial inactivation efficiency. Table 6 summarizes key processing methods, modeled food systems, and major outcomes from representative COMSOL applications in this domain.

COMSOL multiphysics in modeling chemical reactions

Chemical reactions are fundamental to food quality throughout harvesting, processing, storage, and distribution. The kinetics of these reactions, which frequently occur in parallel or sequentially, present a challenge for quantification, yet they are crucial for effective quality control (Giannakourou et al., 2021). Mathematical modeling offers a mechanistic understanding of these

Table 6 COMSOL Multiphysics in microbial growth inactivation modeling

Product treated	Microbial inactivation method	Variables used	Study objectives	Reference
Tomato juice	Ohmic heating	-Acid and nonacid adapted pathogens	- Predict temperature distribution of tomato juice - Inactivation trend of acid and nonacid adapted food-borne pathogens	(Kim et al., 2020)
Liquid foods	PEF	-Applied voltage -Treatment time -and electrode radius	- Microbial inactivation and specific energy optimization	(Araujo et al., 2019)
Orange juice	Ohmic heating	-Geometry	- Simulate the temperature distribution and inactivation of <i>Escherichia coli</i> O157:H7	(Choi et al., 2020)
Water samples	Cold plasma	-Cold plasma frequencies	- Simulate the amount and the distribution of reactive species	(Arserim et al., 2021)
Apple juice	Atmospheric cold plasma	-Initial cell concentration and soluble solids	- Develop model correlating the cell concentration and soluble solids with inactivation rates	(Bao et al., 2021)
Fruit juice	PEF	-Chamber geometry -Chamber size	- Simulate electric field distribution for effective inactivation	(Mohan et al., 2024)
Carrot juice	High pressure processing (HPP)	-Pressure - Carrier	-To predict the flow and temperature fields inside the vessel, and variations of sterility	(Rivera et al., 2024)
Carrot slice	MW pasteurization	- Exposure time	-To develop mathematical model for MW pasteurization -To simulate temperature distribution within the product	(Roohi & Hashemi, 2020)
Ground beef	Thawing	- Heating rate	- To predict heat transfer rate and temperature distribution -To develop model for microbial inactivation and estimate kinetic parameters of inactivation	(de Albuquerque et al., 2019)

Table 7 COMSOL multiphysics modeling in chemical reactions in food processing

Food product/device name	Reaction simulated	Major objectives of the study	Reference
Frozen products	-Thermal degradation of vitamin C	- Develop FEM based coupled Multiphysics kinetic model - Compare heating performance of inverter and cycled MW based on average temperature, heating nonuniformity, and nutritional value change	(Yang et al., 2021)
Beer	- Biomass fermentation	- Determining temperature profile during fermentation, simulate growth of microorganisms, protein consumption, and formations of aromatic compounds - Validate the proposed model experimentally	(Li et al., 2025)
Sonobioreactor	- Biological system during microbial growth	- Develop a well-defined reactor by simulating the pressure distribution of a sonobioreactor - Assess the performance by growing 2 biologically interesting microorganisms	(Najjarzadeh et al., 2020)
French Fries	-Maillard reaction	- Develop mathematical model of Maillard reaction, heat and mass transfer for predicting acrylamide formation, temperature, and water content in French fries	(Chan, 2020)
Plasma-chemical reactor	- Decomposition and destruction of waste	- Develop a mathematical model of plasma-chemical reactor for the thermophysical calculation of the reactor	(Obratsov et al., 2018)
Poly hydroxybutyrate (PHB)	- Bacterial production of poly- β -hydroxybutyrate	- Simulation of bacterial production of poly- β -hydroxybutyrate from methane in vertical loop fermenter - Experimental validation of the proposed model	(Mofradnia et al., 2022)
Reaction chamber	- Vinegar storage time	- Design of reaction chamber - Simulation of velocity field and particle distribution of flow field in the reaction chamber	(Lin et al., 2021)
Yeast	- Kinetics of yeast glycolysis	- Develop a kinetic model for yeast glycolysis	(Lao-Martil et al., 2023)
Celery juice	- Kinetics of <i>Escherichia coli</i> and <i>Salmonella Typhi</i>	- Mathematical, thermodynamic, and CFD process modeling and pathogen inactivation	(Hashemi et al., 2024)
Liquid food	- Kinetics of enzyme inactivation	- Develop model based on FEM to predict the feasibility and effectiveness of polyphenol oxidase inactivation in non-Newtonian characteristic liquid food	(Wang et al., 2024b)
Berry puree	- Degradation kinetics of Anthocyanins	- Develop a 3D model of berry puree to analyze the heat transfer process of the berry puree	(Zhang et al., 2025)
Milk	- Vitamin degradation kinetics	- Modeling of free convection and vitamin degradation - Extensive comparisons of the proposed model and experimental analysis	(Lalwani et al., 2021)

processes, facilitating accurate predictions of product characteristics, shelf-life assessments, and effective process design (Van Boekel, 2021). COMSOL Multiphysics has proven particularly effective for simulating food-related chemical reactions by coupling transport phenomena with kinetic models, enhancing the predictive power of reaction engineering in food systems (Staszak, 2023). A summary of recent applications of COMSOL Multiphysics in chemical reaction modeling is provided in Table 7, and the major chemical reaction engineering simulation steps are illustrated in Fig. 4.

Nutrient degradation and quality deterioration

Several studies have used COMSOL to model the degradation of vitamins, polyphenols, and pigments under different thermal and nonthermal treatments. Lalwani et al. (2021) developed a kinetic model considering spatial temperature gradients caused by free convection. Their simulations showed that the rate of degradation varied depending on where the sample was taken, suggesting that placing the thermocouple in the middle of the tube provided more accurate kinetic data. Yang et al.

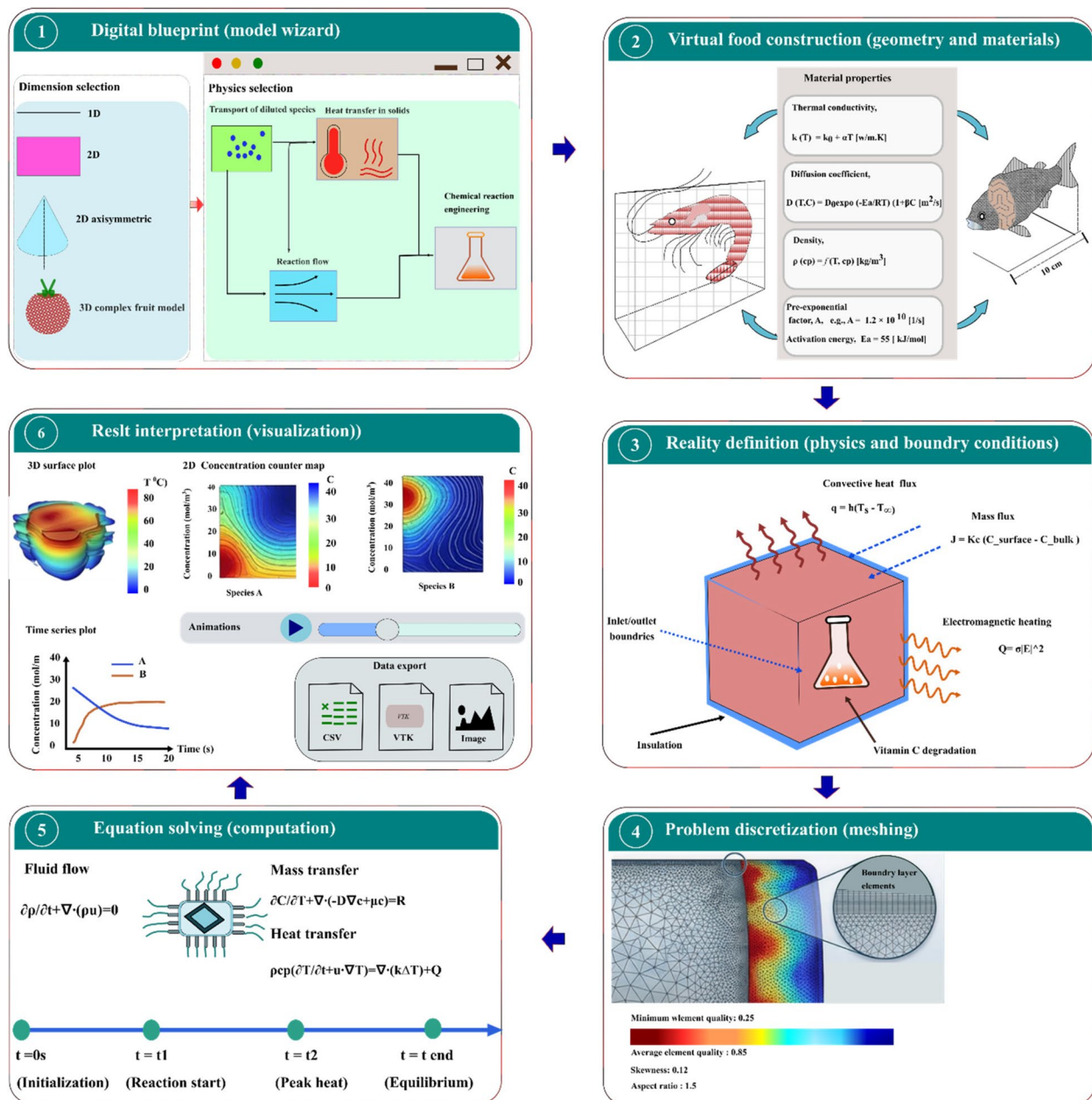


Fig. 4 Typical COMSOL multiphysics workflow for simulating chemical reactions in food processing. The workflow progresses through six main stages: (1) model setup, including dimension and study type selection; (2) system definition, including geometry and material properties (thermal, diffusion, kinetic parameters A , E_a); (3) physics and boundary conditions, including heat transfer, species transport, and reaction interfaces; (4) discretization, including mesh generation with boundary layer refinement; (5) computation, including solver configuration and execution; and (6) results, including visualization of concentration and temperature profiles with data extraction

(2021) compared inverter and cyclic MW heating modes, and reported only minor differences in heating uniformity and vitamin retention. Smaller food geometries favored uniform heating, and inverter systems slightly reduced vitamin C losses. Zhang et al. (2025) simulated anthocyanin release and breakdown, demonstrating that

compared with conduction or conventional heating, MW heating induced greater losses. Wang et al., (2024a, 2024b) modeled polyphenol oxidase inactivation during RF treatment, identifying optimal flow rates and holding times for enzyme control. Gargari et al. (2025) used COMSOL to predict how potato drying affects color,

linking reaction kinetics to microbial safety. These studies show how kinetic modeling can help preserve nutrients and clarify how reactions change with temperature.

Flavor formation and Maillard reaction

Flavor development and nonenzymatic browning are complex processes in which multiple reaction pathways coexist. Lee et al. (2023) modelled coupled heat transfer and Maillard reaction kinetics, showing how melanoidins emerge as major end products. A follow-up study expanded this work to aroma compound kinetics, identifying key intermediates that could serve as process-based quality markers (Lee et al., 2024). Li et al. (2025) integrated temperature profiling with simulations of microbial growth, protein consumption, and aroma compound formation. The findings revealed that elevated coolant flow rates and reduced operating temperatures were sustained throughout prolonged fermentation, delaying thermal accumulation. The simulated data predicted protein depletion after 210, 110, and 90 h at 12.5, 18, and 20 °C, respectively. Furthermore, the findings indicated that a reduction in the colorant flow rate accelerated the temperature increase throughout fermentation, leading to the early production of ester-based flavor-active compounds under the defined parameters. These outcomes closely align with experimental observations in beer fermentation, confirming the ability of the model to capture key biochemical and physicochemical dynamics (Gargalo et al., 2021). Their COMSOL simulations linked fermentation temperature profiles to protein consumption rates and ester production, validating experimental brewing outcomes. These models collectively highlight the ability of COMSOL to capture the interplay of thermal conditions, reaction kinetics, and metabolite formation, offering quantitative tools for process control and flavor optimization.

Fermentation and bioreaction engineering

COMSOL has also been applied to simulate chemical and biochemical reactions in engineered food systems. Najjarzadeh et al. (2020) developed a pressure-distribution model for a sonobioreactor, which they then validated using experiments involving microbial inoculation. The model accurately predicted vibration and flow patterns, showing its potential for optimizing enzymatic processes. Lao-Martil et al. (2023) developed a kinetic metabolic model of yeast glycolysis during steady-state growth. This model facilitated the rational metabolic engineering of *S. cerevisiae*, leading to enhanced fermentation efficiency and the production of specific metabolites. These studies highlight capacity of COMSOL to extend beyond

classical degradation or browning reactions into bioreactor design and microbial metabolic modeling.

Challenges and limitations of applying COMSOL multiphysics to food processing

Although COMSOL Multiphysics is increasingly utilized in food engineering research, its wider application in industrial-scale processing is still limited by several challenges. These include the inherent variability of food properties, difficulties in validating models, constraints in physics coupling, and the lack of food-specific modeling templates. Overcoming these obstacles is essential for ensuring reliable predictions and enabling the transfer of laboratory-scale simulations to industrial practice.

Variability in food properties

Food materials are intrinsically heterogeneous, and their thermo-physical and dielectric properties frequently undergo dynamic changes during processing. For example, Bi et al. (2023) reported that the thermal conductivity and diffusivity of potatoes initially decreased before subsequently increasing with increasing MW power, whereas the specific heat exhibited an inverse pattern. Similarly, significant decreases in thermal conductivity and specific heat were observed during plum drying (Muñoz-López et al., 2018); conversely, Kamble et al. (2024) observed that MW treatment increased the thermal conductivity and decreased the density of pineapple juice. Assuming constant properties in COMSOL models risks oversimplification and misrepresentation of critical phenomena such as crust formation. To reduce errors, researchers may rely on food property databases (Heldman et al., 2018), integrate physicochemical predictions with machine learning (Cavalcanti et al., 2024), or experimentally determine food-specific properties.

Validation difficulties

Following successful simulations of unit operations in food processing, validation is mandatory to check the reliability of the predicted models and their fitness with respect to the actual phenomena. In the absence of sufficient experimental validation, the application of COMSOL predictions to scale-up processes could lead to flawed process optimizations, safety hazards, and the inefficient use of resources. Common sources of mismatch between simulated and experimental data include boundary condition assumptions, property variability, and measurement limitations. While COMSOL often assumes uniform properties for simplicity, food matrices exhibit heterogeneous density, porosity, and moisture profiles. Techniques such

as arbitrary ALE formulations can help capture geometrical changes such as shrinkage during drying (Reddy et al., 2020). Nevertheless, comprehensive experimental validation remains indispensable for ensuring the transferability of modeling results to industrial practice.

Physics coupling limitations

Although COMSOL Multiphysics is effective in simulating coupled physics (heat, mass, and reaction), it has limitations when applied to specific food unit operations. For example, its predictions for air-particle interactions in fluidized bed drying are less accurate than those obtained using ANSYS Fluent (Benavides-Morán et al., 2021). Similarly, non-Newtonian fluids, which are common in sauces and pastes, require custom PDEs in COMSOL, demanding a high level of user expertise. These challenges increase both the complexity and time requirements for developing robust simulations.

Lack of dedicated food-specific templates

COMSOL is designed primarily for general engineering applications; and currently lacks dedicated food-specific modules. This absence forces food engineers to customize PDEs, define boundary conditions manually, and adapt templates from other disciplines. While some researchers have shared custom models (e.g., Kim et al., 2020, for the ohmic heating of tomato juice), the model setup remains time-consuming and error-prone for less experienced users. In addition, some simulations have been reported to require extremely long runtimes (Kubo et al., 2019), reflecting the inefficiency of custom-built frameworks. Although shared libraries provide interim support, the development of standardized food-specific templates with detailed property databases would significantly accelerate adoption in both academia and industry. These limitations highlight the pressing need for integrating food-specific material libraries, improving Multiphysics coupling strategies, and strengthening validation protocols. Collaborative efforts between COMSOL developers and food engineers will be essential to bridge laboratory-scale modeling with industrial-scale applications, a theme further elaborated in the Future Perspectives section.

Meshing challenges and computational cost

For approximating computer-aided design (CAD) geometry and solving complex differential equations through discretization, meshing is a crucial process in COMSOL. However, improper meshing can cause inaccurate results, particularly when simulating irregular food geometries such as shrimp, fish, and whole fruit, and their arrangement with processing equipment, for example in a MW

heating setup for fruit or shrimp drying. Therefore, accurate modeling depends on an appropriate mesh design and rigorous sensitivity analysis.

Several studies have identified approaches for assessing mesh sensitivity. Among these, Wang et al. (2024b) established a systematic methodology for their agitated ohmic heating model, evaluating 4 levels of physics-controlled mesh refinement, from coarse to fine. They quantitatively assessed the total heat source applied to the egg material across these refinement levels, ultimately selecting the coarsest mesh that produced statistically indistinguishable results from the finer meshes ($p > 0.05$). Importantly, the coarsest mesh level did not achieve full convergence, thereby defining a practical lower limit for refinement. Badin et al. (2023) employed a hybrid unstructured grid and declared mesh independence when further refinement was produced, and no significant effect on the numerical results was observed, though specific convergence metrics were not detailed. Araujo et al. (2019) verified their model by aligning it with analytical solutions, while the puree sterilization study did not explicitly document mesh sensitivity testing beyond model validation against experimental temperature data. These investigations underscored boundary layer meshing at critical interfaces, including electrode-food surfaces, container walls, and tube walls, as significant challenges for food geometries.

Despite these techniques, some limitations remain. For example, most studies relied on visual inspection or unstated "negligible change" statements, and there was limited documentation of mesh quality metrics such as the aspect ratio and skewness. Additionally, modeling coupled transient Multiphysics with 3D geometry could lead to significant computational costs (Shah & Takhar, 2025). To ensure reliability and reduce computational cost, future work should adopt multi-metric convergence testing, systematic refinement protocols, symmetry exploitation, and cost benefit analysis. Furthermore, for COMSOL modeling studies in food processing to be used by future researchers and to serve as a baseline for future meshing strategies, the meshing stage should be reported in detail. The report should include the mesh type; element size and distribution; mesh independence or sensitivity analysis; mesh quality metrics; geometry-specific challenges and mitigation strategies; and computational resources such as time, random access memory (RAM), processor, and cores which go beyond just reporting the element type.

Future directions and short guidance for users

As previously discussed, COMSOL Multiphysics has shown considerable promise in simulating various food processing operations; however, its broader adoption

requires clear guidance for new users and exploration of emerging trends. This section therefore provides (i) practical resources and a step-by-step approach to help beginners develop fundamental modeling proficiencies, and (ii) a prospective analysis of research frontiers, including the integration of AI and IoT, interdisciplinary applications, and multistage simulations that could define the next generation of food process modeling.

Resources for beginners

Food engineering students, researchers, and experts who are interested in using COMSOL Multiphysics to model various unit operations in food processing are expected to have strong foundations in mathematics, thermodynamics, heat transfer, mass transfer, reaction engineering, AutoCAD, and a deep understanding of the engineering properties of food materials for efficient modeling and simulations. All the aforementioned subjects are delivered at various levels (undergraduate and postgraduate classes), and continuous revision, practice, memorization, and reference are necessary when COMSOL is used, as the quality of the inputs, i.e., the parameters used for simulations, the mechanisms and boundary conditions, and the assumptions, directly affects the results.

Simulations using COMSOL Multiphysics involve defining the geometry (1D, 2D, or 3D, or importing CAD drawings), selecting physics (heat transfer, fluid flow, reaction kinetics, etc.), specifying physics (stationary or time dependent), assigning material properties, and setting boundary conditions. These steps are followed by meshing, configuring the solver, executing the simulation, and finally performing post-processing for visualization, analysis, and discussion. The general COMSOL Multiphysics workflow for chemical reaction simulations in food processing is presented in Sect. 5, Fig. 4. This workflow applies similarly to other unit operations involving thermal treatment, mass transfer, and microbial inactivation.

Students, researchers, and industry professionals should adopt a dual approach: practical experience gained through guided tutorials and a solid theoretical foundation. Starting with simple simulations builds confidence in creating geometries, selecting physics settings, and meshing, which then prepares them for more complex food-related scenarios. Quick references such as software guides and mechanics (Multiphysics & Module, 2025), unit operations (Singh & Heldman, 2014), and textbooks focusing on physics (Theodore et al., 2011) are leveraged to contextualize simulations within food-specific phenomena (e.g., non-Newtonian fluids, shrinkage). Furthermore, Supplementary File S1 offers three practical examples, complete with

screenshots, verification procedures, and references, to assist beginners in navigating the initial stages of the learning process. Although many resources exist, effective modelling in food processing starts with understanding the underlying concepts and phenomena due to the inherent complexity of food systems. Table 8 lists selected quick references and learning resources for COMSOL users in food engineering.

Emerging trends

Emerging applications of COMSOL in food processing can be grouped into three categories; the integration of AI, IOT, and COMSOL for real-time smart processing, interdisciplinary applications in food processing, and multistage simulations.

Integration of AI, IoT, and COMSOL for real-time smart processing

AI- and machine learning-assisted optimization can enhance COMSOL simulations by identifying optimal combinations of processing parameters (e.g., temperature, pressure, pH, and time) for unit operations such as fermentation, drying, and pasteurization. This integration has the potential to enhance product quality while improving cost-effectiveness. Dynamic simulations of food processing operations can be achieved by coupling COMSOL with IoT sensors, thereby enabling real-time monitoring. While IoT-enabled sensors have been reported in applications such as packaging (Sobhan et al., 2025) and quality control (Shaik et al., 2024), their integration with COMSOL in food processing remains largely unexplored, representing a promising avenue for future research. As an illustration, real-time moisture content data acquired from IoT sensors could be directly integrated into COMSOL models, allowing for dynamic adjustments to heating parameters during MW processes, which would promote uniform heating and mitigate both over- and under-processing (Lee and Ma, 2025).

In addition to AI- and IoT-based integration, digital twin technology offers another transformative pathway. Digital twins function as virtual replicas of processes, equipment, or products, allowing testing and optimization without costly physical prototypes. To fully leverage this potential, future research should extend digital twin applications across diverse unit operations and food systems. For example, virtual experiments can simulate rheological property variations under different process parameters, supporting the design of food processes, equipment configurations, and quality control strategies. Additionally, coupled Multiphysics simulations (e.g., heat and mass transfer) could be incorporated into digital twins to estimate heat transfer coefficients from

Table 8 Quick references for mastering COMSOL multiphysics for food engineering

Reference name	Type	Material's role for users	Reference
COMSOL Multiphysics user's guide	Textbook	- A well-structured user's guide with several features; including techniques how to create a mesh, how to create parameters and variables, how to add the physics and material properties, and how to solve and display the results	(COMSOL, 2025)
Computational Fluid Dynamics and COMSOL Multiphysics: A Step-by-Step Approach for Chemical Engineers	Textbook	- It guides users by providing a step-by-step approach to solve typical problems in chemical engineering, with snapshots to improve clarity and ease of understanding	(Chaurasia, 2021)
Multiphysics modeling using COMSOL: a first principles approach	Textbook	- Presented brief techniques for using COMSOL Multiphysics, step-by-step approaches for building geometries with snapshots, simulation examples, and debugging mechanisms for simulation errors	(Pryor, 2009)
COMSOL Multiphysics®	Website	- A COMSOL website with various teaching and learning materials - It provides various training videos, conferences, webinars, published papers from conferences, case studies, and continuously updated posts regarding recent advances in the application of COMSOL in the food industry	(COMSOL, 2026)
Food Process Engineering	Textbook	- Guide engineers and scientists by providing equations used in complex transformations of biological materials in the food industry and providing scenarios for efficient energy usage	(Heldman, 2012)
Introduction to Food Engineering	Textbook	- A comprehensive textbook mainly designed for undergraduate food science and food engineering students - Provide clear backgrounds and concepts for most of the unit operations involved in food processing, real-world food engineering solved problems, and what-if approaches to train students	(Singh & Heldman, 2014)
Fundamentals of Heat and Mass Transfer	Textbook	- A well-organized textbook with numerous heat and mass transfer topics, designed to help students to internalize terminologies and physical principles associated with heat transfer - Assist students in understanding heat transfer phenomena, computing heat transfer problems, and developing representative models of real processes and systems	(Theodore et al., 2011)
Mass Transfer Operations	Textbook	- Covers most mass transfer unit operations involved in food and chemical industries, provides concepts and step-by-step approaches for solving mass transfer problems, and details of mass transfer equipment design	(Treybal, 1980)
Transport Phenomena	Textbook	- A fundamental textbook, mainly designed for post-graduate classes, provides details of heat, mass, and momentum transfer and provides problem statements and approaches for solving them, which are a foundation for modeling and simulations of transport phenomena	(Bird, 2002)
Elements of Chemical Reaction Engineering	Textbook	- One of the major textbooks in chemical reaction engineering, designed for both graduate and undergraduate-level students - It starts with solving reaction engineering problems through reasoning; provide numerous practice problem statements to help students become familiar with chemical reaction engineering	(Fogler, 2016)

geometry, inlet/outlet temperatures, flow rates, and fluxes. However, such applications demand advanced expertise in both simulation and food engineering.

Interdisciplinary applications in food processing

COMSOL Multiphysics is a leading platform for simulating coupled phenomena, making it a powerful tool for understanding, designing, and optimizing

interdisciplinary food processing systems that span microbiology, biochemistry, and engineering. For example, coupling metabolic reaction kinetics with heat and mass transfer models during fermentation facilitates the design of optimized bioreactors. Coupled physics simulations, supported by mathematical formulations, provide mechanistic insights into the effects of fermentation process parameters (temperature, medium, and gas exchange) on microbial growth and yield maximization. Recently, Li et al. (2025) reported the effectiveness of COMSOL in simulating fermentation, indicating its potential for complex fermentation operations. However, their study employed MATLAB independently to simulate biochemical changes, without fully integrating Multiphysics coupling. Microbial growth models can be integrated with CFD in COMSOL to optimize precision fermentation production of alternative proteins.

A coupled Multiphysics model offers the potential to illustrate enzyme–substrate interactions with fluid flow in enzymatic hydrolysis processes, such as biomass conversion into biofuels. The mechanisms of cold plasma and PEFs in inactivating microorganisms can be mechanistically illustrated through simulations of plasma discharge and electric field effects, which are key aspects of food safety and quality. Furthermore, the use of ultrasound-assisted extraction and plasma-activated water preservation methods can help elucidate how acoustic cavitation improves oil extraction and the production of bioactive compounds and reactive species, as well as their antimicrobial effects.

Multistage simulations

Unlike single-unit simulations, multistage simulations account for interactions across sequential processing steps, enabling holistic optimization of food manufacturing chains. A recent study by Feyissa and Frosch (2023) reported successful COMSOL Multiphysics modeling of “Hamburgerryg” production involving drying, smoking, and multiple cooling steps (steam, water, and air), demonstrating its potential as a foundation for food digitalization, particularly in thermal processing chains. Moreover, this methodology can be adapted to hybrid nonthermal processing techniques, including the integration of ultrasound and PEF technologies, to achieve effective microbial inactivation and protein modifications.

These emerging applications demonstrate how COMSOL Multiphysics is evolving from a tool for simulations to a key platform for designing smart, interdisciplinary, and multi-step food processing systems. By integrating AI, the IoT, and digital twins and expanding its capabilities to include coupled biochemical and engineering systems, COMSOL can provide real-time, mechanistic, and scalable insights. These developments highlight its potential to

drive innovation, improve sustainability, and strengthen digitalization in the future of the food industry.

Conclusions

COMSOL Multiphysics has proven to be an indispensable tool for modeling complex Multiphysics phenomena in food processing, enabling virtual experimentation, process optimization, and mechanistic insights into heat transfer, mass transfer, microbial inactivation, and chemical reactions. Its ability to couple diverse physical processes and simulate irregular geometries provides unique advantages for identifying critical control points and enhancing food safety. Nevertheless, challenges such as variability in food properties, difficulties in experimental validation, and the lack of food-specific templates limit its broader adoption. Addressing these gaps will require collaborative efforts to integrate COMSOL with AI and IoT technologies, expand multidisciplinary coupling approaches (e.g., linking metabolic and transport models), and maintain rigorous experimental validation to ensure reliability. As computational modeling continues to advance, COMSOL is well positioned to drive innovation in food engineering; improve efficiency, sustainability, and product quality; and solidify its role as a cornerstone of modern food process simulation.

Supplementary Information

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Supplementary Material 1.

Authors' contributions

Shuai Wei: Conceptualization, Writing – original draft, Writing – review & editing, Funding acquisition, Supervision; Gebremichael Gebremedhin Hailu: Conceptualization, Formal analysis, Writing – original draft; Anand Kumar: Formal analysis, Methodology, Visualization; Eric Banan-Mwine Daliri: Formal analysis, Writing – review & editing; Deeban Arumugam: Formal analysis, Methodology, Visualization; Imran Khan: Methodology, Writing – review & editing; Sun-Il Choi: Formal analysis, Methodology, Writing – review & editing; Ok-Hwan Lee: Writing – review & editing; Deog-Hwan Oh: Writing – review & editing; Shucheng Liu: Resources, Writing – review & editing.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

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Competing interests

The authors declare no competing interests.

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