Food Engineering Series
Series Editor: Gustavo V. Barbosa-Cánovas

Anubhav Pratap-Singh
Ferruh Erdogdu
Shaojin Wang
Hosahalli S. Ramaswamy *Editors*

Microwave Processing of Foods: Challenges, Advances and Prospects

Microwaves and Food

Springer

Food Engineering Series

Springer's *Food Engineering Series* is essential to the Food Engineering profession, providing exceptional texts in areas that are necessary for the understanding and development of this constantly evolving discipline. The titles are primarily reference-oriented, targeted to a wide audience including food, mechanical, chemical, and electrical engineers, as well as food scientists and technologists working in the food industry, academia, regulatory industry, or in the design of food manufacturing plants or specialized equipment.

Anubhav Pratap-Singh • Ferruh Erdogdu
Shaojin Wang • Hosahalli S. Ramaswamy
Editors

Microwave Processing of Foods: Challenges, Advances and Prospects

Microwaves and Food

Springer

Editors
Anubhav Pratap-Singh
Food and Beverage Innovation Centre
Faculty of Land and Food Systems
The University of British Columbia
Vancouver, BC, Canada

Ferruh Erdogdu
Professor of Food Process Engineering
Department of Food Engineering
Ankara University
Golbası-Ankara, Türkiye

Shaojin Wang
College of Mechanical and Electronic Engineering
Northwest A&F University
Yangling, Shaanxi, China

Hosahalli S. Ramaswamy
Department of Food Science and Agricultural Chemistry
McGill University
Ste-Anne-de-Bellevue, QC, Canada

ISSN 1571-0297 ISSN 2628-8095 (electronic)
Food Engineering Series
ISBN 978-3-031-51612-2 ISBN 978-3-031-51613-9 (eBook)
https://doi.org/10.1007/978-3-031-51613-9

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Microwaves are everywhere. The cosmic microwave background radiation (CMB), a faint glow of microwaves permeating the universe, is all around us and serves as a reminder of the big bang. Akin to the CMB, microwaves have permeated our modern lives and have become an essential part of our culinary practices. While food processing has been practiced since prehistoric times, modern food processing started in the early eighteenth century when Nicholas Appert invented the canning process (also known as Appertization or Thermal Processing) to provide food for the arduous military expeditions led by the French Emperor Napoleon Bonaparte. Appert's process relied on the principle of utilizing heat to kill disease and spoilage causing microorganisms, rendering the food safe for extended periods of time. The microorganisms themselves were discovered only in the late eighteenth century by Louis Pasteur, in whose honor the process of pasteurization is named. In the early nineteenth century, Percy Spencer, an engineer at Raytheon Corporation working on radar systems during World War II, noticed the melting of a chocolate bar in his pocket due to the energy emitted by magnetrons used in the radar systems. This discovery led to the launch of Radarange, the first commercial oven. As microwave technology advanced, so did its applications in food processing. Researchers and food scientists began exploring the potential of microwaves beyond reheating and defrosting. In the following decades, research efforts intensified, leading to a deeper understanding of microwave interactions with food components and the development of specialized microwave processing techniques. The potential benefits of using microwaves in food processing became evident, including reduced processing times, improved product quality, and enhanced nutrient retention. The unique heating properties of microwaves, such as rapid and volumetric heating, made it particularly appealing for various food processing applications.

Propelled by rapidly changing lifestyles and rapid urbanization, the global microwaveable food industry has grown to US$ 148 billion in 2023, and is expected to continue its rapid growth to reach US$ 230 billion by 2033. Microwavable foods like shelf-stable, chilled and frozen meals (beef, pork, poultry, seafood, vegetarian meals, and frozen and chilled pizza), and soups offer convenient solutions that require minimal preparation time. The frozen food industry is also switching to microwaveable products due to the ease of microwave thawing and cooking. At the same time, technology has caught up, producing microwave solutions for not only heating of food, but also to support other operations like dehydration, frying, concentration, thawing, freezing, tempering, extraction, etc. As microwave technology continues to evolve, it has found its place in various aspects of food processing, ranging from drying, pasteurization, and thawing to baking, cooking, and extrusion. Concurrent developments in packaging technologies also played an important role in the success of microwaveable food products. Specially designed microwave-safe packaging, which has the ability to evenly heat different kinds of foods in different ways, has become an integral aspect of the microwave food industry offering convenience of quick, ready-to-eat meals. Most importantly, the microwave industry plays a vital role in ensuring food safety. Microwave pasteurization and sterilization techniques offer valuable alternatives to traditional thermal processing methods for effectively eliminating harmful microorganisms to extend the shelf-life while preserving their nutritional values. One of the key aspects that ensure the success of microwave processing, for food safety and other applications, is understanding the heat distribution within the food. With advancements in process modeling and simulation techniques, researchers have gained valuable insights into predicting and optimizing microwave processing parameters for specific food products, further enhancing the industry's capabilities. By simulating microwave interactions with food components, scientists and engineers can now design more efficient and precise microwave processing systems.

This book, *Microwave Processing of Foods: Advances and Prospects*, represents a comprehensive compilation of the current state of knowledge in microwave processing of food. Each chapter serves as a critical review, incorporating the authors' personal experiences and the latest published research to shed light on various aspects of microwave food processing. From the fundamentals of microwave heating to exploring the effects of microwaves on food composition and safety, and from traditional applications to cutting-edge innovations, this volume showcases the remarkable journey of microwave processing and its far-reaching implications for the food industry. This volume is divided into following seven parts:

Part I. Microwave Heating—Principles, Applications, and Overview This introductory section provides an overview of microwave processing by introducing the readers to microwave ovens, discussing the important principles related to heating in microwave ovens, introduces the temperature measuring techniques that can be used in microwave ovens, and summarizes the effect of microwaves on microorganisms and overall food quality. First, Chapter 1 introduces the microwave technology from a historical context and outlines attempts to implement microwave heating in the food industry, as well as attempts to dispel some myths associated with microwave processing. The chapter suggests that successful niche microwave businesses cater to other businesses, while abandoned processes may have created products intended for direct sale to consumers. Chapter 2 introduces the readers to various types of domestic and industrial microwave ovens widely used for heating, drying, and thawing processes in the food industry, offering energy efficiency and improved processing quality. Challenges related to non-uniform heating, dominated by electric field distribution, exist hindering better industrialization of microwave thermal processing. Chapter 3 discusses the significant influence of dielectric properties on microwave thermal processing success. Precise modulation of microwave process parameters with changing dielectric properties can optimize energy transfer and heating control within food materials. Understanding the dielectric and thermal properties of food is crucial for optimizing microwave processing technique. Chapter 4 delves into temperature-sensing techniques in microwave-assisted food processing. Non-homogeneous temperature distribution can lead to hot and cold spots, affecting food safety and quality. Various temperature sensing methods, such as thermometers, thermocouples, and infrared thermometers, are discussed that help ensure consistent heating and optimized temperature distribution during microwave processing. Chapter 5 focuses on the factors influencing the activity of microorganisms during microwave pasteurization and sterilization of foods. Microwaves can destroy microorganisms at lower temperatures than conventional heating methods, while preserving food components from thermal effects. This chapter reviews important factors for accurately assessing non-thermal effects and microwave treatment for food safety. Chapter 6 highlights the advantages and changes in food quality during microwave heating. Microwave technology provides energy-efficient and convenient cooking methods, benefiting individuals with restricted movement. The chapter aims to explore changes in food quality during microwave heating to develop cooking methods that maximize nutritional values while minimizing hazards.

Part II. Microwave—Effect on Food Composition This section delves into the effects of microwaves on food constituents, viz. proteins, enzymes, carbohydrates, starches, and lipids. By investigating how microwaves affect different food components, a deeper understanding of how to preserve food quality and safety during processing can be obtained. Chapter 7 discusses the impact of microwave heating on proteins in food. Microwave heating can alter the kinetics of how peptides and proteins fold, potentially affecting the nutritional value of food. The chapter emphasizes the need for thorough investigation of the effects of microwave heating on protein structures, considering different power levels, exposure times, and meal compositions. Chapter 8 discusses the effects of microwave irradiation on enzymes, their structure, and their activity during different processes like blanching and germination and also enhancing the rates of enzymatic reactions with microwave radiation. Electromagnetic energy can change the structure of enzymes and the rate of reaction through both thermal and non-thermal effects; however, this field requires deeper exploration to disambiguate the issues. Chapter 9 explores the multifaceted role of microwaves in altering the functional properties and structural characteristics of carbohydrates in food. Microwaves, despite their primary interaction with water, exhibit a secondary influence on carbohydrate structures, leading to changes in functional attributes, chemical composition, and intermolecular dynamics. The chapter also discusses how microwaves facilitate more efficient extraction and modification of carbohydrates, offering faster processing times and minimized impact on their chemical structures. Chapter 10 explores the modification of starch using microwave radiation. Microwaves can effectively supply energy to starch, and the outcome of the treatment depends on factors like water content, power-to-mass ratio, and processing time. The chapter reviews various applications of microwave radiation in starch processing, discussing both physical and chemical modifications, as well as their potential and limitations. Chapter 11 delves into the impact of microwaves on food lipids. The generation of free radicals during microwaving can lead to oxidative damage and lipid oxidation. However, despite some studies suggesting harmful effects on dietary lipids, microwave-assisted extraction has become a cutting-edge technique for removing lipids from various sources, including plants and animals. Overall, this section provides readers with valuable insights into the effects of microwave heating on essential food components, as well as a better understanding of how microwave processing can be optimized to enhance food quality and nutritional values. Chapter 12 discusses the various factors that influence microwave drying, including their impact on the thermophysical properties, color, nutritional values, and dielectric properties. Some applications of microwaves as an alternative heat source in different fields are also reviewed along with a description of effects of various factors on microwave drying.

Part III. Microwave—Traditional Applications This section explores the wide array of applications for microwaves in food processing such as drying, thawing, tempering, cooking, baking, roasting, frying, extrusion, disinfection of agricultural produce, and thermal sterilization and pasteurization. These applications highlight the versatility and efficiency of microwaves in food preparation. Chapter 13 explores microwave thawing/tempering as a rapid and effective defrosting technology for food. The chapter discusses the advantages of microwave thawing over conventional methods and highlights strategies to improve heating uniformity and scaling up the technique for industrial applications. Chapter 14 discusses microwave heating's use as a cooking technique, discussing its impact on the physical quality, composition, and sensory attributes of food during cooking. The advantages of microwave cooking, such as quick heating, nutrient preservation, and ease of control, open opportunities for the creation of novel foods. Chapter 15 focuses on microwave baking, which offers time and energy-saving advantages. However, non-uniform heating and quality defects can occur in microwaved-bakery products. The chapter discusses formulation and technology-based approaches to address these challenges and optimize microwave baking for quality and staling of bakery products. Chapter 16 discusses the advantages of microwave roasting in terms of shorter processing time, energy efficiency, and preservation of color components and nutritional quality. The chapter highlights the need for optimization studies and adapting microwave roasting on an industrial scale. Chapter 17 introduces microwave frying as an alternative cooking method. The chapter discusses the advantages of microwave frying, such as shorter frying times, lower oil content, enhanced product texture and color, and reduced acrylamide concentrations, offering insights into this innovative and economical method. Chapter 18 explores microwave extrusion technology, which offers high potential for upscaling applications while maintaining homogeneous temperature distribution throughout the product. The chapter discusses various expansion mechanisms and case studies on the development of value-added processes and products using microwave extrusion. Chapter 19 discusses the use of microwaves for disinfestation of postharvest agricultural products, emphasizing the use of microwave technology for controlling insect pests to improve safety and quality without chemical residues. Chapter 20 discusses microwave-assisted thermal sterilization and pasteurization as efficient alternatives to conventional thermal processing methods. Microwave heating offers high energy efficiency and reduced CO_2 emissions, making it a promising technology for producing microbiologically safe foods with extended shelf life. Thus, this section acquaints the readers with the diverse applications of microwave heating in various food processing techniques, emphasizing its efficiency and potential to improve food quality and safety.

Part IV. Microwave—Novel Applications This section presents cutting-edge research on novel microwave applications, including microwave vacuum dehydration, osmotic drying, flavor generation, and 3-D printing. Chapter 21 discusses microwave vacuum drying, which offers a faster and more efficient drying process compared to hot-air drying. The chapter highlights the retention of food product quality characteristics and nutritional values under microwave vacuum drying conditions. Chapter 22 discusses the applications of microwave processing for osmotic drying. The chapter highlights the increase in drying efficiency of combination for osmotic drying with microwaves or microwave-vacuum application in the context of finished dried product quality. Chapter 23 explores the impact of microwave processing on food flavor. While microwave processing offers advantages like reduced processing times and maintenance of nutritional values, it can also cause non-uniform temperature distribution and chemical changes that affect food flavor and texture. Chapter 24 focuses on microwave 3D printing technology, which helps solidify materials during the extrusion process, improving the quality of printed food products. The chapter explores the development process of microwave 3D printing technology and its potential applications. The innovative approaches showcase in this section highlight the potential of microwaves in revolutionizing food processing and product development.

Part V. Microwave—Product and Packaging Applications Microwaves find specialized applications in various food industries, such as dairy, poultry, and meat processing. Moreover, food packaging material choices and package designs play an important role in optimizing microwave processing. This section explores various applications of microwave technology in food processing, focusing on dairy products, poultry and egg products, meat processing, and microwave packaging materials. Chapter 25 discusses the use of microwave technology in pasteurization and sterilization of dairy products. This chapter also highlights the importance of understanding food dielectric properties for designing efficient heating equipment and achieving uniform energy absorption during microwave processing. Chapter 26 provides an overview of microwave applications in the meat industry, covering cooking, pasteurization, sterilization, and defrosting. Concerns about meat quality during microwave processing and discussing the advantages and challenges of using microwave technology are also addressed. Chapter 27 examines the applications of microwave technology in cooking, pasteurization, and defrosting of chicken, poultry, and egg products. The benefits of microwave technology in providing rapid and even heating, improving cooking yields, and preserving nutritional contents are highlighted for specific applications. Chapter 28 discusses various microwave gadgets and the widespread application of microwave energy in the food industry, from domestic to commercial and industrial microwave ovens. The chapter highlights the benefits of quick and efficient food preparation and energy-saving. Chapter 29 discusses the significance of microwave packaging materials for microwavable food products. This chapter explores effects of microwaves on packaging material properties and food/packaging interactions, emphasizing the importance of proper packaging design for efficient microwave treatment, food safety, and shelf life. Chapter 30 focuses on the advancement of polymeric packaging for microwave thermal processing technologies. This chapter explores the interactions between food and packaging materials under microwave heating and highlights the impact of packaging performance on the quality, safety, and shelf life of food products during microwave processing. Additionally, microwaveable active packaging systems are discussed. In a nutshell, this section apprises readers about microwave product and packaging applications in the food industry.

Part VI. Microwave—Food Safety Safety is a paramount concern in food processing. This section explores the non-thermal effects of microwave processing on food, microbial safety concerns, and the regulatory aspects related to microwave-based thermal processes. Chapter 31 provides an overview of the Food Safety Modernization Act of 2011, which has raised regulatory authorities for the U.S. Food and Drug Administration (FDA). The chapter emphasizes the importance of compliance with regulations when developing microwave-based thermal processes for food to ensure safe food products. It also discusses the FDA Food Code and its relevance to microwave energy usage in various food processes. Chapter 32 focuses on microbial safety concerns associated with microwave processing. This chapter addresses the non-uniform heat distribution that can create hot and cold spots in food and discuss the challenges and performance of microwave processing in achieving food safety. Chapter 33 discusses the non-thermal effects of microwave processing, which can impact the composition of food nutrition through chemical and biochemical reactions. There is a need for further research to understand the mechanisms of these effects and ensure the chemical safety of microwave-processed food. Additionally, the chapter highlights the importance of microwave packaging in preventing chemical migration and ensuring food safety. Chapter 34 explores the application of microwave decontamination in medicine, food, and personal protective equipment. The chapter covers the use of microwave technology to decontaminate N95 masks and degrade harmful substances like aflatoxin in food, providing insights into safe decontamination processes. The microbial and chemical safety challenges associated with microwave processing, as well as the regulatory outlook highlighted in this section, inform important food safety considerations during microwave processing.

Part VII. Microwave—Process Modeling Process modelling plays a vital role in optimizing microwave food processing. This section explores power-modulated microwave processing, batch, and continuous flow systems, and the latest advances in simulation techniques to enhance process efficiency and sustainability. Chapter 35 discusses microwave power modulation techniques that aim to improve heating uniformity in microwave processing. By adjusting the power supply during heating, these techniques mitigate non-uniform heating issues, particularly during thawing. The chapter explores different power modulation techniques, their effectiveness, and optimization strategies for better power modulation. Chapter 36 focuses on batch and continuous-flow microwave processing systems, each with distinct characteristics and applications. The chapter emphasizes the importance of efficient and uniform heating in microwave systems and discusses modeling studies to enhance microwave technology and develop new resonators. It covers interventions to improve efficiency and uniformity, as well as challenges and trends in modeling studies related to microwave processing. Chapter 37 addresses the issue of unevenly distributed microwave fields during food heating, often requiring motion (e.g., rotation and translation) of the heated food to improve heating uniformity. The chapter introduces multiphysics algorithms used to simulate food being heated with microwaves under complex motion conditions. Overall, this section explores breakthrough directions for future developments and their potential applications in modelling and simulation of microwave applications in the food industry.

Vancouver, BC, Canada — Anubhav Pratap-Singh
Golbası-Ankara, Türkiye — Ferruh Erdogdu
Yangling, Shaanxi, China — Shaojin Wang
Ste-Anne-de-Bellevue, QC, Canada — Hosahalli S. Ramaswamy

Contents

Part I
Microwave Heating–Principles, Applications, and Overview

Chapter 1
Microwave Heating: General Concerns, Myths, and Realities

Gregory J. Fleischman

1 Introduction

In 1988, the National Center for Food Safety and Technology (now the Institute for Food Safety and Health) was opened. This consortium of United States government (Food and Drug Administration—FDA), academia (Illinois Tech, Chicago, Illinois, USA) and food industry (member food companies) created an accessible avenue of open dialog on regulatory issues, research projects, and industry interest in existing and emerging food processing technologies from a food safety point-of-view. It came through this consortium in the early 1990s that the food industry was becoming interested in microwave-based thermal sterilization. The intended products would inevitably include at least some low acid foods (LACFs) and therefore it was anticipated that there would be process filings, as required by LACF regulations (see Chap. 34). I came to the FDA in 1991 in part to address these. The first filing would not appear for 16 years.

The increasing interest in microwave implementation in the early '90 s was reflected in the establishment of dedicated microwave groups in food companies and the growth of microwave equipment manufacturers in the United States and Europe. By the end of the '90 s, the companies had disbanded their microwave groups, and equipment manufacturers either turned to conventional food processing equipment or to non-food microwave applications. At that time, I was unaware that such surge and ebb of microwave interest by the food industry was a periodic occurrence.

G. J. Fleischman (✉)
United States Food and Drug Administration, Bedford, IL, USA
e-mail: gregory.fleischman@fda.hhs.gov

A. Pratap-Singh et al. (eds.), *Microwave Processing of Foods: Challenges, Advances and Prospects*, Food Engineering Series, https://doi.org/10.1007/978-3-031-51613-9_1

2 Industrial Microwave Heating in the Twentieth Century: A Selective History

In 1947, microwave heated foods came to consumers in the form of hotdogs delivered steamy on a warm bun in only 20 seconds from Speedy Weeny vending machines (Fig. 1.1). Only 2 years earlier, engineers at the Raytheon Corporation, who had been devoting their efforts to microwave-based communication, created the first applicator to heat foods with microwave energy. The applicator was a culmination of experience with accidental (and maybe some purposeful) exposure to microwave energy that warmed the food that the engineers had with them, as well as the engineers themselves.

The microwave ovens that Raytheon developed over the next several years were sold to food service establishments and vendors like Speedy Weeny. Though their cost was high, the ovens' performance justified their purchase. For example, the recommended cooking time of a roast at 190 °C is 20 min per pound in a conventional oven. In an early 1.6 kW microwave oven, it was 3 min per pound [1]. And let us not forget the 20 second steamy hot dog on a warm bun from Speedy Weeny machines. Such gains in microwave heating rate over conventional heating were not

Fig. 1.1 The Speedy Weeny offered steaming hot dogs cooked in 20 seconds and delivered on a warm bun. All references to this vending machine refer to microwave energy as a heating source. Permission N/A

lost on the microwave equipment manufacturers and the food industry. An example of the anticipation of the role that microwaves could play in the food industry is a 1950 patent that describes a microwave cooking apparatus that is "especially suitable for carrying out the cooking necessary in the canning [sterilization] of foodstuffs, such as fruits, vegetables, etc." [2]. Despite the questionable feasibility of the apparatus (it operated at ambient pressure instead of the 2 atm generally needed in sterilization, and it required a non-existent microwave transparent food container), the patent was an indication of the belief that a microwave-based process could challenge even a well-established conventional process; at that time steam/water sterilization had already 150 years of successful and continuous application and study. Indeed, pundits in the 1950s and 60s forecast a rosy future for microwave heating in food industries, and a not so rosy future for microwave heating in the home [3]. These forecasts could not have been more wrong, as the domestic microwave oven became a huge commercial success in the latter twentieth century and beyond, while the majority of implementations of microwave heating in the food industry usually started with much anticipation followed by quiet shutdowns.

The early pundits can't be blamed for their forecasts. On one hand, the early ovens targeted for home use in the 1950s were very expensive— over $14,000 in 2023 USD. No improvement in home meal preparation could justify that expenditure for practically all families. With nothing to indicate that ovens would decrease astoundingly in price (for example, a modern microwave countertop oven costing $150 now would cost just less than $14 in 1955!), no one would predict that a home microwave oven market would ever materialize. On the other hand, though ovens targeted for food service facilities were also expensive, about $80,000 in 2023 USD, their cost was justified by their performance and frequency of use. It was natural to assume that these justifications would remain in place at the scale of industrial processing. Factoring in that microwaves had an "aura of magic" for the food industry [4] industrial microwave food processing seemed to have a bright future.

The appearance in 1967 of the moderately affordable countertop microwave oven, the Amana Radarange, began the pivot of microwave usage toward the home. Shortly after that, microwave processes in the food industry were facing unexpected realities. Though niche applications such as bacon pre-cooking, frozen food tempering and pasta drying were developed and continue to this day, the anticipated general displacement of conventional thermal processes by microwave-based ones never materialized. The August 1973 issue of *The Journal of Microwave Power* (now the *Journal of Microwave Power and Electromagnetic Energy*) ran a series of articles on microwave use in the food industry. They were downbeat about the then present state of microwave food processing with one even titled "Why Did They Fail?" [5] and another introduced with "While many of the leading commercial applications of microwave power. . .are no longer operative. . ." [6]. But the articles were at the same time upbeat about the future with the lessons that were learned up to that point. Each article posited a possible explanation for the struggle of microwave processing in the food industry. Bedrosian [4] wrote that in the food industry, microwaves were mistakenly perceived as a simple magical solution to problems with conventional energy sources, and that the microwave equipment industry was ready to oblige that belief with no critical review of the actual potential for success. Schiffmann [6] cited inaccurate economic projections. Meisel [7], in a survey of microwave food processing systems in Europe, believed that despite 20 years of interest by the European food industry, insufficient funding of research and development was the reason for the lack of widespread use of microwaves. Freedman [8] saw microwave applications in the food industry as "the use of high technology products in low technology industries" calling it a "peculiar mismatch" that undermined microwave implementation. He thought with time, the newness of the technology would wane, making it more welcome, but cautioned that the economics required that any microwave processing be applied to foods where higher prices were the norm. In other words, an increased price due to the use of microwave technology of already higher priced food would be more acceptable to consumers than even a small increase in a much lower cost basic staple.

Twelve years later, little had changed. Mudgett [9] blamed the lack of microwave industrial development at that time on two main factors. The first was the empirical, or "black box", approach to process development (later called the cook-and-look approach). Results from these were unpredictable and frequently disappointing. A more deterministic approach was recommended. First, food would be characterized by its dielectric properties in addition to its thermal properties. Then the dielectric properties would be used to determine heating patterns within the food for a particular microwave oven through a mathematical analysis of the heat transfer coupled with internal heat generated by microwaves. But computational power of the time was very limited and only simplified applications of microwave heating could be examined.

The second factor was the cost and reliability of microwave equipment relative to conventional equipment. Mudgett saw hope in the improved design, increased reliability, and decreasing cost of electronic equipment. Interestingly, Mudgett also saw the changing energy dynamics of the time as propitious for microwave food processing. At the time, the growing concern over the depletion of fossil fuels and the reliance on foreign sources of them was causing a swing away from oil and gas to nuclear, renewables, and coal. Mudgett argued, rather confusingly, that reliance on coal and nuclear fuels will grow in the United States on the one hand, but on the other these will not be used extensively owing to government regulations and potential environmental damage. Regardless, the apparent take-away message was that energy costs were increasing. Though how this was advantageous for microwave processing was not explained. Only if microwave heating were more economical than conventional heating could increasing energy costs be favorable to it. But an accompanying economic analysis, conducted by Mudgett, pitting microwave energy against conventional energy as the heat supply for pressurized sterilization equipment clearly favored conventional over microwave energy..

In 1993, the book *Microwave Cooking and Processing: Engineering Fundamentals for the Food Scientist* [10] appeared. The chapter, Microwave Processing of Foods, starts with two pages that again recount failed processing attempts, though written 8 years after Mudgett.

In two chapters in the *Handbook of Microwave Technology for Food Applications* [11], Edgar and Osepchuck [12] and Schiffman [3] discussed the continuing struggle for microwave energy to go further than niche processes. Edgar and Osepchuk discussed the revival of potato chip processing, specifically citing Louise's no-fat potato chip that became a market failure. Schiffman extensively discussed the various microwave processes up to that time: cooking, tempering, baking, drying, pasteurization, and sterilization. Aside from the niche processes, the rest saw either limited industrial application or none at all. Notably, Schiffman also wrote that studies by several major U.S. food manufacturers were unable to support the oft-claimed benefit of microwave sterilization as providing greater product quality than conventional sterilization because of the shorter come-up and processing times when microwave energy was used.

While there were many anticipated industrial applications that never materialized, some that did demonstrated that early success did not translate to continued success. The "They" in "Why Did They Fail?" [5] were microwave finish fryers of potato chips that dominated industrial microwave processing in the 1960s. Finish frying allowed the use of potatoes that gave low visual quality chips when entirely deep-fried. By partially deep frying and finishing with microwave frying, even these potatoes gave quality chips. However, for a variety of reasons this first example of a microwave-assisted process was abandoned. They were diverse: reliability issues with the equipment, the economics of the potato harvest, the economics of the potato chip companies themselves, improved designs of conventional fryers, emerging competing processes, the unfavorable physics of microwave heating of low moisture chips (as they were after the deep-frying step), and others.

Schiffman [3] describes a successful microwave sausage patty pre-cooker that replaced a process using gas-fired heated grill plates. The gas-fired process rendered much fat, which led to frequent fires. Clean-up took two persons the duration of a whole shift. The patties were distorted, and yield was low. The microwave process increased yield by at least 80%, maintained patty shape, increased its tenderness, eliminated fires, and reduced cleanup to 1 h by 1 person. Even this huge improvement over conventional cooking that ran for 10 trouble-free years was replaced with a steam and gas grill system. No reason was given, though economics was probably the main factor.

Schiffman [13] discusses the Microwave Doughnut Frying System developed and sold by DCA Food Industries, Inc. in the 1970s, citing the advantages it had over a purely conventional fryer. Despite larger and more uniformly fried doughnuts, longer shelf-lives, and lower oil absorption, the technology was abandoned. No economic reasons were given. But the fryer itself required extensive manipulation just for the regular changing of frying oil, and no conventional doughnut mix would work with it. This latter problem was solved by the development of proprietary mixes that only DCA could provide to bakers, which may have eventually worked against the technology. Schiffman wrote that the doughnut fryer was an innovation that was far ahead of its time. Yet, it has been almost 50 years since the last such fryer operated and no other fryers, for doughnuts or other deep-fried products, have appeared.

Lastly, though research in the 1970s at the U.S. Army's Natick Laboratories showed that microwave sterilization could not achieve the required level of microbiological safety that conventional sterilization could, European companies Alfa-Laval, OMAC and Berstorff developed industrial microwave sterilizers starting as early as the 1970s; all ceased operations after several years of use.

So, by the end of the twentieth century, microwave food processing remained established only in the niche applications of bacon cooking, meat tempering and pasta drying.

3 Industrial Microwave Food Processing in the Twenty-First Century

The realization that microwave energy could heat food from within led to the early anticipation that it could entirely supplant conventional energy sources in a variety of food applications. But even where microwave energy only assisted conventional processing, it could not hold on. The twenty-first century is seeing a resurgence in interest in industrial microwave food processes, supported by research and the computational power now at hand to conduct sophisticated multiphysics analyses of whatever process is conceived. The research effort of the last 20 years, modeling and experimental, has struck a hopeful note about what could happen. While industrial food processing involving vacuum drying and pasteurization appear to be growing applications of microwave energy, baking, frying, blanching, freeze drying, and sterilization, though also having received much research effort, continue to elude serious industrial implementation.

With respect to baking, Yolacaner et al. [14] covered the research on microwave-assisted hot air and microwave-assisted infrared baking of bread but made no mention of commercialization. They did describe a commercialized baking process exclusively microwave-based for crustless bread. A French company, MO2, used microwave baking to create a line of crustless breads. However, a recent online search indicates it is not currently in operation. Crustless bread is still available, but it appears microwave processing was upended yet again by several different conventional approaches: baking at lower temperatures, applying moisture to the bread surface during baking, and enclosing all surfaces of the bread during baking. One odd, yet conventional, approach to crustless bread was used by Sara Lee in 2002 [15]. A patented apparatus [16] was employed to slice off the crusts from the loaves at the bakery. It is telling that a company would invest in a custom device to de-crust bread but not to develop a process to make the bread without the crust to begin with! Nevertheless, even this technology, though much less complicated than microwave technology, faltered. Despite the most expensive product launch of the Sara Lee baked goods division at that time and high early sales [15], the bread eventually and quietly disappeared. No announcement was made, or reason given, though most likely it was the 30% increase in price over the same bread but with crusts intact. For strong advocates of microwave thermal processing, it may be comforting to see another technology having the same problem in industrial food processing as microwaves.

Microwave frying, assisted or otherwise, still appears to be a no-show. Edgar and Osepchuck [12], after discussing Louise's no-fat potato chip, mentioned two other companies that continued in this manner but in an online review of existing low and reduced-fat potato chips on the market, none appears to use microwaves to achieve the lower fat content. Instead, two conventional methods used are air frying and baking. Another uses a thicker potato slice to start with, which produces a chip that had the same amount of oil per chip, but a lower percentage owing to the greater potato mass.

Blanching is a mild thermal process that inactivates spoilage enzymes in foods that undergo further processing for long term storage. Blanching is most associated with frozen foods, mainly vegetables and fruits. Despite the low temperatures of storage, spoilage enzymes can still be active, thus the need for pre-freezing inactivation. But any thermal treatment will change food attributes in general. Minimizing these changes while still accomplishing enzyme inactivation is where microwave-assisted blanching could be more effective than an exclusively conventional approach. Research has borne this out under laboratory conditions and patents have been secured for the process in the United States, Europe, and China. However, even a mild thermal treatment needs to be a complete thermal treatment, and the usual problem of non-uniform heating has prevented microwave-assisted blanching from going beyond the research stage [17].

If there were an award for the most enduring and researched process that never had a presence in the food industry, it would go to freeze-drying. When dried at ambient pressure, food shrinks and deforms because of the dynamics of water evaporation. In freeze-drying, the food is first frozen then dried under sufficiently low pressure that ice sublimates instead of melts when warmed, usually by contact with a warm surface, allowing the food to retain its shape. The processing time can be as great as 12 h. It's easy to see that the penetrability of microwave energy would reduce processing time significantly. The first studies on microwave freeze-drying took place in the 1950s and that work took up a significant portion of books by Copson [18, 19]. Despite the various problems besetting the process, a microwave-based freeze-drying process was too alluring to abandon and work continued on it. Yet, Metaxas [20] reported that "Freeze drying…using microwave energy has been singularly unsuccessful despite the enormous research and development effort." Note the use of the word "enormous" in describing the research and development effort, which has persisted into the twenty-first century. Nevertheless, in 2012 it was reported that microwave-assisted freeze drying remained of academic interest only [21]. Although Ozcelik and Püschner [22] mentioned an operating freeze dryer unit (*μWaveVac12120fd*, Püschner Microwave Power Systems, Schwanewede, Germany, www.pueschner.com) and though the company currently mentions freeze-drying on their website, their present offerings appear to be exclusively microwave vacuum dryers.

Table 1.1 A comparison between snacks that could compete with crunchy cheese. (The use of the American ounce as a basis for comparison was purposely chosen to give easily comparable numbers.)

Snack	Requires microwave?	Perceived as healthy	Specific content (g/ounce)			Specific cost midpoint (/ounce)
			Fat	Protein	Calcium	
Crunchy cheese	Yes	Yes	14	10	0.35	\$2.08
String cheese	No	Yes	6	7	0.20	\$0.41
Common chips	No	No	10	2	0.007	\$0.60

Vacuum drying appears to have an increasing industrial presence. Companies such as Ferrite Microwave Technologies (Nashua, New Hampshire, USA, www.ferriteinc.com), Industrial Microwave Systems (Morrisville, North Carolina, USA, www.industrialmicrowave.com) and, again, Püschner Microwave Power Systems, show equipment and applications to food, though it is not known to what extent these systems are actually applied to food versus other materials mentioned on their respective webpages. However, another company, EnWave (Vancouver, British Columbia, Canada, www.enwave.net), has focused on drying organic materials with its patented REV™ (Radiant Energy Vacuum) systems that can tumble dry hardy materials or tray dry delicate ones. Recently, Ceyhun [23] discussed the favorable retention of nutritional compounds using the REV™ system as compared to air-drying and freeze-drying. However, Ceyhun also comments that the REV™ process has yet to gain widespread use and therefore is relatively costly.

At this point it is of interest to digress and examine a particular product of the REV™ process. In the past microwave processes have lost out to conventional processes where the same product was produced by both, and, for similar though not identical products, other factors such as cost favored conventional production. One of the purported success stories on EnWave's website is crunchy (dried) cheese. Currently two such products[1] are known to use EnWave's REV™ process; Moon Cheese (Nutradried Food Company, LLC, Ferndale, Washington State, USA) and Käze Cheese Bites (Pearl & Rose Premium Foods LLC, Newark, New Jersey, USA, www.pearlandrose.net and www.kazecheese.com). And it appears that the REV™ process is the only way to manufacturer it. Table 1.1 compares crunchy cheese to two potential competitors; string cheese because both products are pure cheese, and common chips because both are dry, crunchy snacks.

Both Moon Cheese and Käze Cheese Bites are recognized as healthy: low-carb, high protein and calcium, and gluten-free. But string cheese can make the same claim, at roughly a fifth of the cost. What's gained by crunchy cheese is convenience,

[1]Umland's Crunchy Cheese (Umland LLC, Marengo, Illinois, USA, www.umlandscrunchycheese.com) is also available but how it is produced is unknown. From the website "We have found a machine that is able to take the water out while retaining all the flavor and nutrition of the cheese." It sells directly from the website for \$2.89/ounce.

which includes shelf stability, but does it justify a premium price? The only advantage common chips have over crunchy cheese is cost (though specialized chips such as vegetable chips can be almost as expensive, but also have a healthy snack appeal). It will be interesting to see if the advantages of convenience, nutrition and uniqueness support a continued market presence for crunchy cheese, or if the high price compared to other snack choices causes its disappearance. It seems difficult to believe, though, that consumers would tolerate cheese without water at a 500% increase in cost when they could not tolerate bread without crust at a 30% increase in cost.

Industrial sterilization processes in the United States have been revived with two processes, one being the microwave-assisted thermal sterilization (MATS) system developed at Washington State University for single serving foods or single portion meals and the other a continuous flow puree sterilization system developed at North Carolina State University. The MATS system is currently being licensed by 915 Labs (Denver, Colorado, USA, www.915labs.com) that have units in India and the United States. However, it is not known the degree to which the system is being used.

Yamco LLC (Snow Hill, North Carolina, USA, www.yamco.net) has been using the puree sterilization system, developed in the 2000s, since 2007. In fact, it was the FDA low-acid canned food filing of sweet potato puree sterilized by this process that ended the 16-year wait for such a microwave-based filing, alluded to at the beginning of this chapter. It's growth to encompass several other purees and its continuous presence since its debut, qualifies it as a fourth established niche process, along with the previously mentioned processes of frozen food tempering, bacon pre-cooking and pasta drying.

Food sterilization in Europe was also revived in the early 2000s after the several previous implementations had ended. According to their website, Top's Foods (Lammerdries, Belgium, EU, www.topsfoods.com) has been consistently producing shelf-stable single portion meals sterilized using proprietary microwave technology backed by world-wide patents since 2002. The website singles out inflight, healthcare and retail markets for their single portion meals.

Industrial interest in microwave pasteurization has grown as well, and more so than sterilization. The refrigerated products of pasteurization require a milder and more easily implementable process than what is required for sterilization. One clear advantage is processing at ambient pressure since temperatures needed for pasteurization are below 100 °C obviating the need for a pressure vessel as would be required in sterilization. Thus, to create single portion pasteurized meals, various systems have been recently developed such as those by Sairem Microwave and Radio Frequency (Décines-Charpieu, France, EU) and Micvac AB (Mölndal, Sweden, EU, www.micvac.com). The MATS sterilization system has also been modified to operate as a microwave-assisted pasteurization system (MAPS).

The landscape of twenty-first century food processing appears dotted with various microwave applications. Some are full-fledged and others still developing. It will be interesting to see how they fare in the long run.

4 Observations

4.1 B2B Versus B2C

Four niche applications of microwave heating in the food industry have withstood the test of time: frozen meat tempering, bacon pre-cooking, pasta drying, and puree sterilization. These four have a common factor that appears to have been overlooked in previous reviews of industrial microwave food processing. They sell to other businesses that incorporate their product into other products for general sale to the public or still other businesses. For example, pre-cooked bacon goes to food service establishments for their morning bacon offerings. Business-to-business (B2B) commerce is the term for this and distinguishes it from business-to-consumer (B2C) commerce. Most or all the microwave B2C production of the twentieth century either ended or were upended by conventional heat sources. The myriad reasons of why they did not prevail seem secondary to the consistency that they all made products for direct sales to consumers. This is not to say that a B2B microwave venture is guaranteed success, but it seems at least necessary. One possible explanation is a general economy of scale in B2B versus B2C. In selling to other businesses large bulk product is sold simplifying packaging and shipping, the savings of which could offset, and perhaps more than offset, the added cost of microwave processing. In selling to consumers, small portions are packaged and sold. Even if the *packaged* product is sold in bulk (in cases or lots), the expense of packaging of small individual portions and careful shipping may not offset the added cost of using microwave energy.

Another explanation of the success of the B2B approach could be the separation of the microwave technology from the company using the product of that technology. A good example of this is the previously discussed Yamco process to produce sterilized purees. The company purchasing the puree does not need to purchase, operate, or understand the technology of its production and focuses only on the puree quality and how to use it in a final product. Meanwhile, Yamco focuses on the technology and production of the puree without the need to determine how it will be used in a final product.

4.2 High Technology Product in a Low Technology Industry

I believe this statement, written by Freedman [8], provides an overarching reason for the difficulties of applying high value microwave technology in low value food processing. Reasons such as economics, familiarity, acceptance, even the B2B versus B2C discussion above, can be subsumed by this reason. High technology usually implies high costs that may be easier to recoup in high technology industries because of greater profit margins, but more difficult to recoup in low profit margin industries such as food processing. High technology requires a deeper understanding than low technology which would impact both familiarity and acceptance in a low technology industry. B2B commerce with respect to microwave heating appears to get around this by separating the high technology product from the low technology industry, as demonstrated by Yamco, discussed above.

4.3 Pulsed Electric Field Processing and Microwave Processing

Potato chip finish frying was one of the earliest applications of microwave heating in the food industry. As noted previously, for a variety of reasons, it was abandoned. Pulsed electric field (PEF) processing is another high technology process. It uses high voltage electric fields applied in very short duration pulses to biological cells for the purpose of creating pores in the cell wall. This ability has many applications, but it is now a standard pretreatment of potatoes for chipping and french fries owing to multiple distinct and conspicuous advantages for both the manufacturer and consumer [24]. Its inclusion in the manufacturing process adds cost to the whole chip and fry production, but it appears that it also generates savings for manufacturers that offset that cost. The consumer gets higher quality chips and fries, yet they are not paying higher prices for them. It is therefore of no wonder that PEF preprocessing rose from initial application to a standard pre-processing step in only 10 years. Microwave finish frying initially worked in this regard because it allowed manufacturers to use usually discarded low quality potatoes. However, other factors, as discussed previously, prevailed returning the industry to conventional frying. What makes PEF different is that it does not actually create the finished products, but instead prepares the potato to yield improved results with conventional frying. Perhaps future applications of microwave energy can do something similar.

4.4 Nutrition

An indirect challenge to microwave thermal processing is the study of Miller and Knudson [25]. They performed a comparative nutritional study on 8 vegetables and 10 fruits, each packaged as canned, frozen, and fresh (from a grocer’s shelf), that challenges the almost dogmatic opinion that processing, and particularly canning, always lowers the quality of food. Vegetables showed similar nutrient content across all three packaging options. While fruits showed variation, all three packaging options were nevertheless considered nutritious options. An equalizing factor was that “fresh” foods are picked unripe, so their full nutrition is not fully developed, while processed foods are done so at the peak of their ripeness. Nevertheless, between unprocessed fresh foods, mildly processed frozen foods and extensively processed canned foods there doesn’t appear to be much room for improvement that microwave processing could provide.

4.5 Plastics

Microwave processing of food depends on plastics. Whether it is for industrial processing or heating of products in home microwaves, plastics are heavily used. The recent awareness of microplastics and their presence from the tops of mountains to ocean depths may eventually develop into a public backlash against plastics and a pivot back to highly recyclable materials like aluminum and glass that do not pose environmental hazards. Aluminum is very recyclable but blocks the passage of microwaves. Glass is also recyclable and though microwave transparent, it would be difficult and perhaps expensive to use in any microwave process.

4.6 Microwave Disinformation

Although disinformation about microwaves has been floating around the internet for many years, it does not appear to have affected microwave home use. But it is interesting to note that food products that have been made using microwave energy do not announce themselves as such. The crunchy cheese products do not mention microwave processing, for example. Examining the packaged products of European pasteurizers online, it also appears that microwaves are not mentioned. For B2B commerce, it is probably immaterial that microwave is mentioned. But for B2C commerce, it appears that the mention of microwave processing is avoided.

5 Summary

Microwave heating has not lived up to the anticipation that it would permeate throughout the food industry wherever thermal processing is used. The assumption that the improvement of food quality by switching from conventional to microwave heating would be sufficient for commercial success has not been borne out. Though laboratory work has quantified incremental increases in food quality owing to microwave use, the degree of the increases appears to be insufficient to justify the added expense of deploying microwave energy. Moreover, processing conventionally has been shown to create products that have a high degree of nutritional quality; even a severe process such as sterilization has been shown to have similar nutrient content of frozen and of grocery fresh foods as well.

Of all the evaluations and re-evaluations of the reasons why, Freedman's [8] appraisal that the fundamental mismatch between a high technology product, microwave heating, with a low technology industry, food processing, provides an overarching explanation for this. The success of niche applications of bacon cooking, pasta drying, tempering and puree sterilization can also be explained in this way. Their B2B (business-to-business) approach keeps microwave technology in the hands of the technology companies, with only the product of that technology, and not the technology itself, benefitting food companies. This means that microwave heating will most likely remain confined to niche processes. However, once established, they appear to be enduring.

Disclaimer: The opinions of the author are his alone and do not represent or reflect those of the FDA.

References

1. Copson, D. A. (Feb. 1956). Session IV-general session on biologic effects microwave energy in food procedures. *IRE Transactions on Electronics, PGME-4*, 27–35. https://doi.org/10.1109/IRET-ME.1956.5008557
2. Marshall, L. K. (1950). *High-Frequency Electromagnetic Cooking Apparatus*. U.S.Patent 2,495,415. US
3. Schiffman, R. F. (2001). Microwave processes for the food industry. In A. K. Datta & R. C. Anantheswaran (Eds.), *Handbook of microwave technology for food applications* (pp. 299–337). Marcel Dekker, Inc.
4. Bedrosian, K. (1973). The necessary ingredients for successful microwave applications in the food industry. *The Journal of Microwave Power, 8*(2), 173–178.
5. O'Meara, J. P. (1973). Why did they fail? *The Journal of Microwave Power, 8*(2), 167–172.
6. Schiffman, R. F. (1973). The applications of microwave power in the food industry in the United States. *The Journal of Microwave Power, 8*(2), 137–142.
7. Meisel, N. (1973). Microwave applications to food processing and food Systems in Europe. *The Journal of Microwave Power, 8*(2), 143–148.
8. Freedman, G. (1973). The future of microwave heating equipment in the food industries. *The Journal of Microwave Power, 8*(2), 161–166.
9. Mudgett, R. E. (1985). Direction in microwave food processing. In P. M. Cheremisinoff, O. G. Farah, & R. P. Oullette (Eds.), *Radio frequency/radiation and plasm processing: industrial applications & advances* (pp. 43–55). Technomic Publishing Company, Inc..
10. Buffler, C. R. (1985). *Microwave cooking and processing: engineering fundamentals for the food scientist* (p. 128). John Wiley & Sons AVI (an imprint of Van Nostrand Reinhold).
11. Datta, A. K., & Anantheswaran, R. C. (2001). *Handbook of microwave technology for food applications*. Marcel Dekker, Inc.
12. Edgar, R. H., & Osepchuk, J. M. (2001). Consumer, commercial and industrial microwave ovens and heating systems. In A. K. Datta & R. C. Anantheswaran (Eds.), *Handbook of microwave technology for food applications* (pp. 215–278). Marcel Dekker, Inc.
13. Schiffman, R. F. (2017). Microwave-assisted frying. In M. Regier, K. Knoerzer, & H. Schubert (Eds.), *The microwave processing of foods* (2nd ed., pp. 142–151). Woodhead Publishing.
14. Turabi Yolacaner, E., Sumnu, G., & Sahin, S. (2017). *Microwave-assisted baking*. In M. Regier, K. Knoerzer, & H. Schubert (Eds.), *The Microwave Processing Of Foods* (2nd ed., pp. 117–141). Woodhead Publishing.
15. Anonymous. (2002). Sara lee to offer bread without a crust. *The Los Angeles Times Archives*. Available online at: https://www.latimes.com/archives/la-xpm-2002-may-04-fi-rup4.6-story.html
16. Berger, R. A., Buell, C. M., Wilson, K. I., Hickman, R. D., Plassa, J. M. A., Nadal, J. L., & Janeway, B. (2007). *Method and apparatus for making loaves crustless, sliced bread*. U.-S. Patent 7,223,429. Sara Lee Bakery Group Inc.