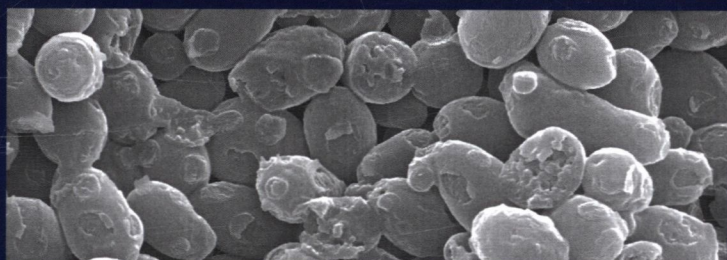
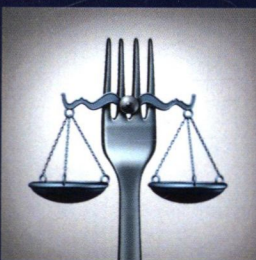
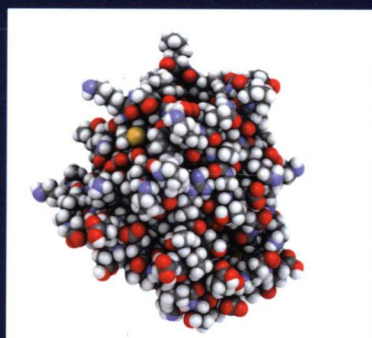
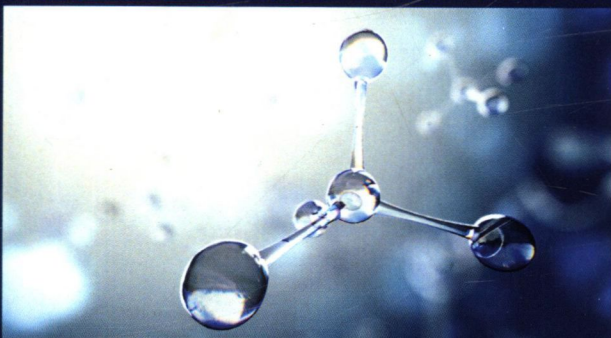


# ULTRASOUND

## ADVANCES IN FOOD PROCESSING AND PRESERVATION



EDITED BY **DANIELA BERMUDEZ-AGUIRRE**





# ULTRASOUND

## ADVANCES IN FOOD PROCESSING AND PRESERVATION

EDITED BY **DANIELA BERMUDEZ-AGUIRRE**

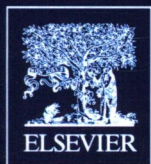
*The latest insight into the opportunities and challenges of this emerging technology*

This book is fully focused on the food industry, presenting the basic principles and most recent advances of ultrasound, in addition to the application of this technology in specific food products and unit operations. It also presents the current research needs and challenges of ultrasound to be transferred to industry settings in the near future.

This book is divided into three main areas. Chapters 1 to 5 focus on the basic principles of ultrasound and how the technology works on microbial cells, enzymes, and the chemistry behind the process. Chapters 6 to 15 cover the application of ultrasound in specific food products and processes, discussing changes on food quality and presenting some innovations in food ingredients and enhancement of unit operations. Finally, Chapters 16 to 20 present some topics about manufacture of ultrasound equipment and simulation of the process, the use of the technology to treat food industry wastewater, and an industry perspective. The laws and regulations concerning emerging technologies, such as ultrasound, are also discussed, including the new Food Safety Modernization Act.

### END USER KEY FEATURES

- Provides a clear and comprehensive panorama of ultrasound technology
- Contains updated research behind this technology
- Presents the majority of the current tested products and processes
- Explores potential future use within the food industry



**ACADEMIC PRESS**

An imprint of Elsevier  
[elsevier.com/books-and-journals](http://elsevier.com/books-and-journals)

ISBN 978-0-12-804581-7



9 780128 045817

# QUESTIONS

BERMUDEZ-AGUIRRE



ACADEMIC  
PRESS

# Ultrasound: Advances in Food Processing and Preservation

---

*Edited by*

Daniela Bermudez-Aguirre



**ACADEMIC PRESS**

An imprint of Elsevier

Academic Press is an imprint of Elsevier  
125 London Wall, London EC2Y 5AS, United Kingdom  
525 B Street, Suite 1800, San Diego, CA 92101-4495, United States  
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States  
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom

Copyright © 2017 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: [www.elsevier.com/permissions](http://www.elsevier.com/permissions).

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

### Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

### Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

### British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

ISBN: 978-0-12-804581-7

For information on all Academic Press publications visit our website at  
<https://www.elsevier.com/books-and-journals>



Working together  
to grow libraries in  
developing countries

[www.elsevier.com](http://www.elsevier.com) • [www.bookaid.org](http://www.bookaid.org)

*Publisher:* Andre Gerhard Wolff

*Acquisition Editor:* Nina Rosa Bandeira

*Editorial Project Manager:* Mariana Kühl Leme

*Production Project Manager:* Julie-Ann Stansfield

*Designer:* Matthew Limbert

Typeset by TNQ Books and Journals

# Ultrasound: Advances in Food Processing and Preservation

---



*To Maria Daniela and Emmanuel Andre*





# List of Contributors

- Ishfaq Ahmed**, Ocean University of China, Qingdao, P.R. China
- Monica Anese**, University of Udine, Udine, Italy
- Pedro E.D. Augusto**, University of São Paulo (USP), Piracicaba, Brazil
- Daniela Bermudez-Aguirre**, Independent Consultant, Pullman, WA, United States
- Francesca Bot**, University of Udine, Udine, Italy
- Mercedes G. Carrillo**, Buenos Aires University, Buenos Aires, Argentina; National Scientific and Technical Research Council, Buenos Aires, Argentina
- Clémentine M.G. Charoux**, Teagasc Food Research Centre, Dublin, Ireland; University College Dublin, Dublin, Ireland
- Hao Feng**, University of Illinois at Urbana-Champaign, Urbana, IL, United States
- Fabiano A.N. Fernandes**, Federal University of Ceará, Fortaleza, Brazil
- Mariana Ferrario**, Buenos Aires University, Buenos Aires, Argentina; National Scientific and Technical Research Council, Buenos Aires, Argentina
- Sandra N. Guerrero**, Buenos Aires University, Buenos Aires, Argentina; National Scientific and Technical Research Council, Buenos Aires, Argentina
- Ariel A.C. Toledo Hijo**, University of Campinas (UNICAMP), Campinas, Brazil
- Daniel A. Jacobo-Velázquez**, Tecnológico de Monterrey, Monterrey, Mexico
- Anet Režek Jambrak**, University of Zagreb, Zagreb, Croatia
- Sandra E. Kentish**, University of Melbourne, Parkville, VIC, Australia
- Zhenxing Li**, Ocean University of China, Qingdao, P.R. China
- Hong Lin**, Ocean University of China, Qingdao, P.R. China
- Haile Ma**, Jiangsu University, ZhenJiang, China
- Olga Martín-Belloso**, Tecnológico de Monterrey, Monterrey, Mexico; University of Lleida, Lleida, Spain
- Maria Angela A. Meireles**, University of Campinas (UNICAMP), Campinas, Brazil
- Alberto C. Miano**, University of São Paulo (USP), Piracicaba, Brazil
- Mariana Morales-de la Peña**, Tecnológico de Monterrey, Monterrey, Mexico
- Balunkeswar Nayak**, University of Maine, Orono, ME, United States
- Francesco Noci**, Galway-Mayo Institute of Technology, Galway, Ireland
- Colm P. O'Donnell**, University College Dublin, Dublin, Ireland

- Sindy Palma**, University of Illinois at Urbana-Champaign, Urbana, IL, United States  
**Alexey S. Peshkovsky**, Industrial Sonomechanics, LLC, New York, NY, United States  
**Stella Plazzotta**, University of Udine, Udine, Italy  
**Barbara Rasco**, University of Idaho, Moscow, ID, United States; Washington State University, Pullman, WA, United States  
**Sueli Rodrigues**, Federal University of Ceará, Fortaleza, Brazil  
**Meliza L. Rojas**, University of São Paulo (USP), Piracicaba, Brazil  
**Marcela Schenk**, Buenos Aires University, Buenos Aires, Argentina; National Scientific and Technical Research Council, Buenos Aires, Argentina  
**Eric Keven Silva**, University of Campinas (UNICAMP), Campinas, Brazil  
**Filipa V. Marques Silva**, University of Auckland, Auckland, New Zealand  
**Alifdalino Sulaiman**, Universiti Putra Malaysia, Selangor, Malaysia  
**Brijesh K. Tiwari**, Teagasc Food Research Centre, Dublin, Ireland  
**Francisco J. Trujillo**, The University of New South Wales, Sydney, NSW, Australia  
**Jorge Welte-Chanes**, Tecnológico de Monterrey, Monterrey, Mexico  
**Baoguo Xu**, Jiangsu University, ZhenJiang, China  
**Giovani L. Zabot**, Federal University of Santa Maria (UFSM), Cachoeira do Sul, Brazil  
**Min Zhang**, Jiangnan University, Wuxi, China  
**Bin Zhou**, USDA ARS, Beltsville, MD, United States

# Preface

Ultrasound is an emerging technology that has been widely explored in food science and technology since the late 1990s. First attempts were focused on microbial inactivation, but at the same time interesting discoveries in food properties, composition, and processes were observed that led to further research. Today it is well known that ultrasound can modify the physical properties of some foods, offering novel ingredients for innovative product development. Also, ultrasound can remove some undesirable compounds from foods such as allergens or change the chemical composition of the product (e.g., it can enhance the antioxidant activity). Ultrasound also can improve some basic unit operations such as drying, freezing, or extraction, reducing the use of solvents in the last. Ultrasound can improve the quality of the product after the process (better color, texture, nutritional content) under the right processing conditions. A lot of research has also been done regarding the manufacturing of ultrasound equipment compatible with the food industry, with important advances in the past five years. Additionally, regulatory agencies worldwide have paid attention to these emerging technologies and the several advantages they offer compared with traditional technologies, leading to changes in or creation of new regulations or even new definitions of processes, like the term pasteurization. Ultrasound is a technology with a promising future of use in the food industry in an extensive number of applications.

This book is fully focused on the applications of ultrasound in food science and food engineering, from basic principles of ultrasound, across food processing, to legislation and the industry perspective. The book is divided into three main sections: the first section is about how ultrasound works and its basic principles to understand the technology. Chapter 1 presents an excellent overview of the engineering principles of ultrasound; Chapters 2 and 3 are devoted to understanding the effects of ultrasound in microbial inactivation, showing in Chapter 2 the general mechanisms of cell inactivation and the advances in the use of this technology. Meanwhile, Chapter 3 presents detailed information on the use of hurdle technology for microbial inactivation, ultrasound being the main preservation factor. Chapter 4 provides an interesting perspective on the effects of ultrasound in some of the main enzymes studied in food science. Finally, Chapter 5 presents a brief introduction to sonochemistry of foods, a scarcely studied area with a huge potential for research. The second section of the book is about specific food products and processes: Chapter 6 is focused on the use of ultrasound to process and preserve dairy products, Chapter 7 presents a very

comprehensive review on the use of ultrasound to process fruit and vegetable juices, and Chapter 8 discusses the use of ultrasound to disinfect fresh produce. Chapter 9 presents an overview about how ultrasound affects the quality of some food products. Further, Chapter 10 shows how ultrasound can generate new ingredients by changing some physical properties during cavitation. In this second section, some food processes are also included: Chapter 11 presents novel information about how to remove allergens from food using ultrasound. Chapters 12–14 are focused on the enhancement of some unit operations by ultrasound, such as freezing, encapsulation, and emulsification, respectively. Chapter 15 includes other unit operations, focusing on mass transfer enhanced by ultrasound, drying being the focus of this chapter. The last section of the book is dedicated to the industry and regulations about ultrasound. Chapter 16 presents the use of ultrasound to treat food industry wastewater and Chapter 17 describes how some past drawbacks of ultrasound have been solved regarding equipment manufacturing. Chapter 18 presents the use of mathematical modeling to simulate the acoustic field during processing, very important information for transferring the technology to industry settings. Chapter 19 presents an industry point of view about the use of ultrasound. Last, but not least, Chapter 20 discusses laws and regulations that affect novel technologies such as ultrasound, especially with the new Food Safety Modernization Act.

The book is intended for undergraduate and graduate students studying food science or food engineering, young and experienced researchers working with emerging technologies, people from industry exploring novel technologies in R&D departments, and professionals working in research centers. Although the book is focused on food science and technology, anybody interested in the use of ultrasound can find valuable information.

I would like to acknowledge each of my colleagues that participated in this book for their excellent chapters, for their enthusiastic and professional collaboration, and for sharing their expertise. I am also very grateful to Elsevier, especially to Nina Bandeira, Mariana Kühl Leme, and Julie-Ann Stansfield for their help and hard work on this project from beginning to end.

Finally, this book is dedicated to novel and experienced researchers in ultrasound for their valuable contributions to this field, for making possible the advancement of the technology, and for being the inspiration of future researchers. I truly hope this book will contribute to the development of the technology and further transfer to the food industry.

**Daniela Bermudez-Aguirre**  
Editor



# Contents

List of Contributors	xvii
----------------------	------

Preface	xix
---------	-----

## 1. Engineering Principles of Ultrasound Technology

*Sandra E. Kentish*

1.1 Introduction	1
1.2 Acoustic Waves	1
1.2.1 Acoustic Transducers	1
1.2.2 Frequency and Power	2
1.2.3 Standing Waves	5
1.3 Acoustic Cavitation	5
1.4 Ultrasonic Atomization	10
1.5 Conclusions	11
References	11

## 2. Advances in Thermo- and Manothermosonication for Microbial Inactivation

*Daniela Bermudez-Aguirre*

2.1 Introduction	15
2.2 Microbial Inactivation by Ultrasound	16
2.2.1 Cavitation	16
2.2.2 Inactivation of Microorganisms by Ultrasound	17
2.3 Microbial Inactivation by Thermosonication	21
2.4 Microbial Inactivation by Manosonication and Manothermosonication	27
2.5 The Effects of Ultrasound on Other Agents	30
2.6 Conclusions	32
References	33

## 3. Hurdle Technology Using Ultrasound for Food Preservation

*Sandra N. Guerrero, Mariana Ferrario, Marcela Schenk, Mercedes G. Carrillo*

3.1 Introduction	39
3.1.1 The Hurdle Concept	41

3.2	<b>Most Commonly Used Hurdle Combinations Involving Ultrasound</b>	43
3.2.1	Use of Traditional Hurdles	44
3.2.2	Use of Ultrasound Combined With Novel Hurdles	68
3.2.3	Effects of Ultrasound-Based Combined Technologies on Food Quality Indicators	83
3.2.4	Drawbacks and Future Challenges	87
3.3	<b>Conclusions</b>	88
	<b>Acknowledgments</b>	89
	<b>References</b>	89
4.	<b>Advances in Thermosonication for the Inactivation of Endogenous Enzymes in Foods</b>	
	<i>Filipa V. Marques Silva, Alifdalino Sulaiman</i>	
4.1	<b>Introduction</b>	101
4.2	<b>Enzyme Fundamentals</b>	102
4.3	<b>Ultrasound Processing of Food</b>	104
4.3.1	Ultrasound Fundamentals	104
4.3.2	Ultrasound Effect on Enzymes	105
4.3.3	Models for Describing Enzyme Inactivation by Ultrasound Processing	106
4.4	<b>Effects of Thermosonication on Fruit and Vegetable Products Pectin Methylesterase (PME) and Polygalacturonase (PG)</b>	109
4.4.1	PME and PG Effects on Foods	109
4.4.2	Residual Activity After Manothermosonication, Thermosonication, and Ultrasound	109
4.4.3	Thermosonication Inactivation Kinetics and Parameters	112
4.5	<b>Effects of Thermosonication on Fruit and Vegetable Products Polyphenol Oxidase (PPO)</b>	112
4.5.1	PO Browning in Foods	112
4.5.2	Residual Activity After Thermosonication Treatment	116
4.5.3	First-Order Kinetic Parameters for Thermosonication Inactivation	116
4.6	<b>Effects of Thermosonication on Fruit and Vegetable Products Peroxidase (POD)</b>	121
4.6.1	POD Effects on Food and Blanching	121
4.6.2	Residual Activity and Modeling	121
4.7	<b>Effects of Milk Thermosonication on Endogenous Enzymes</b>	124
4.8	<b>Final Remarks</b>	126
	<b>References</b>	127
5.	<b>Sonochemistry of Foods</b>	
	<i>Daniela Bermudez-Aguirre</i>	
5.1	<b>Introduction</b>	131
5.2	<b>Sonochemistry and Cavitation</b>	132
5.2.1	Chemical Reactions	135

5.2.2	Cavitation in a Homogeneous Liquid System (Water)	136
5.2.3	Cavitation in Heterogeneous Systems	137
5.3	High-Frequency, Low-Power Ultrasound	141
5.4	Conclusions	141
	References	142

## 6. Dairy Products Processed With Ultrasound

*Francesco Noci*

6.1	Introduction	145
6.2	Analytical Applications of Low-Power Ultrasound	149
6.3	Effects of Ultrasound on Particle Size: Homogenization, Creaming, and Emulsions	149
6.3.1	Homogenization	149
6.3.2	Creaming	150
6.3.3	Emulsions	152
6.4	Ultrasound Processing and Foaming of Milk and Dairy Ingredients	152
6.5	Filtration Improvements by Ultrasound	153
6.6	Ultrasound and Fouling Removal	155
6.7	Use of Ultrasound for Microbial and Enzymatic Activity Reduction	155
6.7.1	Microbial Reduction by Sonication	155
6.7.2	Treatment of Sporeformers by Ultrasound	160
6.7.3	Effect of Ultrasound on Enzyme Activity	161
6.8	Ultrasound as an Aid for Crystallization	163
6.9	Ultrasound and Its Effects on Dairy Protein Functionality	165
6.10	Ultrasound for Modification of Properties in Dairy Products	171
6.11	Conclusions	173
	References	173

## 7. Ultrasound Processing of Fruit and Vegetable Juices

*Meliza L. Rojas, Alberto C. Miano, Pedro E.D. Augusto*

7.1	Processing Juices Using Ultrasound	181
7.2	Effects on Juice Structure and Physical and Technological Properties	182
7.2.1	Ultrasound and Juice Structure	182
7.2.2	Rheological Properties and Texture	184
7.2.3	Sedimentation Stability: Cloud Retention	186
7.2.4	Color	186
7.2.5	Effects on Microorganisms	187
7.3	Effects on Enzymes	188
7.4	Effects on Vegetable and Fruit Juice Constituents: Bioactive Compounds, Polysaccharides, and Proteins	190
7.4.1	Bioactive Compounds	190
7.4.2	Polysaccharides	191

7.4.3	Proteins	192
7.5	Industrial Perspectives and Commercial Use	193
7.6	Conclusions	194
	Acknowledgments	194
	References	194
<b>8.</b>	<b>Fresh Produce Treated by Power Ultrasound</b>	
	<i>Sindy Palma, Bin Zhou, Hao Feng</i>	
8.1	Introduction	201
8.2	Power Ultrasound Treatment Equipment	202
8.2.1	Principles of Ultrasonic Surface Cleaning	202
8.2.2	Power Ultrasound Produce Treatment Setup	203
8.3	Ultrasound Treatment to Enhance Produce Safety	206
8.3.1	Use of Probe Systems	206
8.3.2	Use of Tank and Large-Scale Units	207
8.4	Ultrasound Treatment and Produce Quality	208
8.4.1	Produce Quality After Ultrasound Treatment	208
8.4.2	Ultrasound Treatment to Enhance Produce Quality	210
8.5	Conclusion	211
	References	211
<b>9.</b>	<b>Ultrasound Processing and Food Quality</b>	
	<i>Clémentine M.G. Charoux, Colm P. O'Donnell, Brijesh K. Tiwari</i>	
9.1	Introduction	215
9.2	Effects on Food Quality	216
9.2.1	Liquid Foods	216
9.2.2	Solid Foods	222
9.3	Conclusions	230
	References	230
<b>10.</b>	<b>Physical Properties of Sonicated Products: A New Era for Novel Ingredients</b>	
	<i>Anet Režek Jambrak</i>	
10.1	Introduction	237
10.2	Influence of Ultrasound on the Physical Properties of Food	238
10.2.1	Proteins and Particle Size Reduction	239
10.2.2	Carbohydrates	245
10.2.3	Lipids	252
10.2.4	Extraction for Novel Ingredients	254
10.2.5	Improved Sonication Processes	258
10.3	Conclusion	261
	References	262