PREHARVEST FOOD SAFETY
PREHARVEST FOOD SAFETY

Edited by

Siddhartha Thakur
College of Veterinary Medicine
North Carolina State University
Raleigh, North Carolina

and

Kalmia E. Kniel
Department of Animal and Food Sciences
University of Delaware
Newark, Delaware

ASM PRESS
Washington, DC
Contents

Contributors vii
Preface xiii
About the Editors xv

I. OVERVIEW OF THE PREHARVEST FOOD SAFETY PROBLEM

1 Introduction to Preharvest Food Safety 3
   Mary E. Torrence

2 Preharvest Farming Practices Impacting Fresh Produce Safety 19
   Eduardo Gutierrez-Rodriguez and Achyut Adhikari

3 Preharvest Food Safety Challenges in Beef and Dairy Production 47
   David R. Smith

4 Preharvest Food Safety in Broiler Chicken Production 69
   Walid Q. Alali and Charles L. Hofacre

5 Egg Safety in the Realm of Preharvest Food Safety 87
   Manpreet Singh and Jagpinder Brar

6 Nuts and Grains: Microbiology and Preharvest Contamination Risks 105
   Pardeepinder K. Brar and Michelle D. Danyluk

7 Risks Associated with Fish and Seafood 123
   Sailaja Chintagari, Nicole Hazard, Genevieve Edwards, Ravi Jadeja, and Marlene Janes

8 Water for Agriculture: the Convergence of Sustainability and Safety 143
   Sarah M. Markland, David Ingram, Kalmia E. Kniel, and Manan Sharma

9 Importance of Soil Amendments: Survival of Bacterial Pathogens in Manure and Compost Used as Organic Fertilizers 159
   Manan Sharma and Russell Reynnells

II. EMERGING ISSUES IN PREHARVEST FOOD SAFETY

10 Reducing Foodborne Pathogen Persistence and Transmission in Animal Production Environments: Challenges and Opportunities 179
   Elaine D. Berry and James E. Wells
CONTENTS

11 Emerging Foodborne and Agriculture-Related Viruses 205
David H. Kingsley

12 Toxoplasma gondii as a Parasite in Food: Analysis and Control 227
Dolores E. Hill and Jitender P. Dubey

13 Local Food Systems Food Safety Concerns 249
Benjamin Chapman and Chris Gunter

14 Preharvest Food Safety Under the Influence of a Changing Climate 261
Kalmia E. Kniel and Patrick Spanninger

15 Potential for Meta-Analysis in the Realm of Preharvest Food Safety 273
Jan M. Sargeant and Annette M. O'Connor

III. EMERGING SOLUTIONS TO PREHARVEST FOOD SAFETY

16 Phage Therapy Approaches to Reducing Pathogen Persistence and Transmission in Animal Production Environments: Opportunities and Challenges 291
Anna Colavecchio and Lawrence D. Goodridge

17 Regulatory Issues Associated with Preharvest Food Safety: United States Perspective 309
Shirley A. Micallef and Robert L. Buchanan

18 Regulatory Issues Associated with Preharvest Food Safety: European Union Perspective 325
Lis Alban

19 Current Status of the Preharvest Application of Pro- and Prebiotics to Farm Animals to Enhance the Microbial Safety of Animal Products 349
Rolf D. Joerger and Arpeeta Ganguly

20 Molecular Tools to Study Preharvest Food Safety Challenges 361
Deepak Kumar and Siddhartha Thakur

21 Mathematical Modeling Tools to Study Preharvest Food Safety 383
Cristina Lanzas and Shi Chen

22 Understanding the Complexities of Food Safety Using a “One Health” Approach 401
Kalmia E. Kniel, Deepak Kumar, and Siddhartha Thakur

Index 413
Contributors

Achyut Adhikari
School of Nutrition and Food Sciences
Louisiana State University
Baton Rouge, Louisiana

Walid Q. Alali
College of Public Health
Hamad bin Khalifa University
Doha, Qatar

Lis Alban
Danish Agriculture and Food Council
Copenhagen, Denmark

Elaine D. Berry
USDA, Agricultural Research Service
U.S. Meat Animal Research Center
Clay Center, Nebraska

Jagpinder Brar
Department of Food Science
Purdue University
West Lafayette, Indiana

Pardeepinder K. Brar
Department of Food Science and Human Nutrition
Citrus Research and Education Center
Institute of Food and Agriculture Sciences
University of Florida
Lake Alfred, Florida

Robert L. Buchanan
Center for Food Safety and Security Systems
Department of Nutrition and Food Science
University of Maryland
College Park, Maryland
Benjamin Chapman  
Department of Agricultural and Human Sciences  
NC State University  
Raleigh, North Carolina

Shi Chen  
Department of Population Health and Pathobiology  
College of Veterinary Medicine  
North Carolina State University  
Raleigh, North Carolina

Sailaja Chintagari  
Department of Food Science and Technology  
University of Georgia  
Griffin, Georgia

Anna Colavecchio  
Department of Food Science and Agricultural Chemistry  
Food Safety and Quality Program  
McGill University  
Ste Anne de Bellevue, Quebec  
Canada

Michelle D. Danyluk  
Department of Food Science and Human Nutrition  
Citrus Research and Education Center  
Institute of Food and Agriculture Sciences  
University of Florida  
Lake Alfred, Florida

Jitender P. Dubey  
U.S. Department of Agriculture  
Agricultural Research Service, Northeast Area  
Animal Parasitic Diseases Laboratory  
Beltsville Agricultural Research Center-East  
Beltsville, Maryland

Genevieve Edwards  
School of Nutrition and Food Sciences  
Louisiana State University  
Baton Rouge, Louisiana

Arpeeta Ganguly  
Department of Animal and Food Sciences  
University of Delaware  
Newark, Delaware

Lawrence D. Goodridge  
Department of Food Science and Agricultural Chemistry  
Food Safety and Quality Program  
McGill University
Ste Anne de Bellevue, Quebec
Canada

**Chris Gunter**
Department of Horticulture Sciences
NC State University
Raleigh, North Carolina

**Eduardo Gutierrez-Rodriguez**
Department of Food, Bioprocessing, and Nutrition Sciences
North Carolina State University
Raleigh, North Carolina

**Nicole Hazard**
School of Nutrition and Food Sciences
Louisiana State University
Baton Rouge, Louisiana

**Dolores E. Hill**
U.S. Department of Agriculture
Agricultural Research Service, Northeast Area
Animal Parasitic Diseases Laboratory
Beltsville Agricultural Research Center-East
Beltsville, Maryland

**Charles L. Hofacre**
Department of Population Health
Poultry Diagnostic and Research Center
University of Georgia
Athens, Georgia

**David Ingram**
Food and Drug Administration
Center for Food Safety and Applied Nutrition
College Park, Maryland

**Ravi Jadeja**
Department of Animal Science
Oklahoma State University
Stillwater, Oklahoma

**Marlene Janes**
Department of Animal Science
Oklahoma State University
Stillwater, Oklahoma

**Rolf D. Joerger**
Department of Animal and Food Sciences
University of Delaware
Newark, Delaware

**David H. Kingsley**
U.S. Department of Agriculture
Agricultural Research Service
Food Safety and Interventions Research Unit
Delaware State University
Dover, Delaware

Kalmia E. Kniel
Department of Animal and Food Sciences
University of Delaware
Newark, Delaware

Deepak Kumar
Department of Veterinary Public Health & Epidemiology
College of Veterinary and Animal Sciences
Govind Ballabh Pant University of Agriculture & Technology
Pantnagar, Uttarakhand
India

Cristina Lanzas
Department of Population Health and Pathobiology
College of Veterinary Medicine
North Carolina State University
Raleigh, North Carolina

Sarah M. Markland
Department of Animal and Food Sciences
University of Delaware
Newark, Delaware

Shirley A. Micallef
Department of Plant Science and Landscape Architecture
Center for Food Safety and Security Systems
University of Maryland
College Park, Maryland

Annette M. O’Connor
Department of Veterinary Diagnostic and Production Animal Medicine
Iowa State University College of Veterinary Medicine
Ames, Iowa

Russell Reynnells
University of Maryland Eastern Shore
Department of Agriculture, Food, and Resource Science
Princess Anne, Maryland

Jan M. Sargeant
Center for Public Health and Zoonoses and Department of Population Medicine
Ontario Veterinary College
University of Guelph
Guelph, Ontario
Canada
Manan Sharma
U.S. Department of Agriculture
Agricultural Research Service
Beltsville Area Research Center
Environmental Microbial and Food Safety Laboratory
Beltsville, Maryland

Manpreet Singh
Department of Food Science
Purdue University
West Lafayette, Indiana

David R. Smith
Mississippi State University
College of Veterinary Medicine
Mississippi State, Mississippi

Patrick Spanninger
Department of Animal and Food Sciences
College of Agriculture and Natural Resources
University of Delaware
Newark, Delaware

Siddhartha Thakur
Department of Population Health and Pathobiology
College of Veterinary Medicine
North Carolina State University
Raleigh, North Carolina

Mary E. Torrence
Office of Applied Research and Safety Assessment
Center for Food Safety and Applied Nutrition
U.S. Food and Drug Administration
Laurel, Maryland

James E. Wells
USDA, Agricultural Research Service
U.S. Meat Animal Research Center
Clay Center, Nebraska
Preface

Assuring the safety of the world’s food supply continues to be a priority, a necessity, and a challenge. The challenges are created by increasing globalization, reductions in trade barriers, and an ever-growing human population that has developed a craving for fresh, diverse foods. Foodborne pathogens may enter the food supply at the preharvest or harvest phases of the farm-to-fork continuum. However, classic control measures and regulations are instituted primarily at the postharvest phase. High-profile outbreaks still occur, from *E. coli* O157:H7 in ground beef and spinach and *Listeria* in cantaloupes to *Salmonella* in tomatoes, affecting morbidity and mortality. The economic impact of foodborne outbreaks is vast, with significant impact on humans, industry, and our society as a whole.

We turned our attention to the work being done to prevent food contamination in the preharvest phase, which has been increasingly recognized as an important step in the food continuum. Preharvest food safety encompasses the measures that are taken to ensure that food products are produced in a safe and wholesome manner on the farm, thereby ensuring an optimally safe commodity all the way to slaughter, packing, and/or processing. Because many enteric pathogens enter the food chain during production, and some can even proliferate during this phase, it is crucial to understand their preharvest ecology and epidemiology in order to identify and evaluate appropriate intervention strategies. Preharvest control measures have expanded and improved, so it is timely to summarize the recent developments and consider the needs and opportunities for the future in the preharvest food realm.

Our goal in creating this book is to provide the scientific community and stakeholders in the food industry with a knowledgeable resource that discusses the developments and challenges of preharvest food safety, focusing on a variety of microbiological hazards in a variety of foods. The chapters in this book address the current state of knowledge and practice, emerging issues, and emerging solutions, with a focus on both research and control measures. A key aspect of the book is the inclusion of multiple food commodities e.g., food animals, produce, grains, and seafood, and the relevant pathogens for each commodity. In so doing, this book will serve as a comprehensive volume that can be used by food safety scientists in general, as well as those focused on a particular commodity. An important objective of this work is to facilitate understanding of the importance of complex
microbial ecology dynamics to preharvest food safety. In the past, little effort was made to undertake an ecological or systems-based approach to understand the broad issues relating to food safety with specific examples, and this book aims to remedy that. Indeed, it is obvious that many of the emerging food safety pathogens or the manifested outbreaks are directly (or indirectly) related to changes in the agri-food systems themselves over the past several decades.

The first section of this book examines the issues associated with preharvest food safety in broad agriculture sectors. We identify major foodborne pathogens of concern for specific products; what is known about the source, prevalence, and transmission of these pathogens in the candidate products; discuss multiple control measures; and identify critical data gaps for the development of future targeted controls. There is information about a vast array of pathogens, including bacteria, viruses, fungi, and protozoa, that are relevant to each of the major commodity types.

In the middle section, we address the emerging issues that impact the preharvest food safety area. We discuss the use of antimicrobials as growth promotants in the food animal industry and its implications. The critical role of the environment, including the potential impact of global climate anomalies on the emergence and transmission of foodborne pathogens, is also highlighted. Finally, we address the growth and challenges of the organic production system. State-of-the-art information on risk assessment, risk management, and emerging preharvest food safety issues in both developed and developing countries is included.

The third and final section aims to provide information on emerging solutions and novel intervention methods that can be employed at the preharvest level to reduce the burden of foodborne pathogens and other potential hazards. We focus not only on the challenges in preharvest food safety, but also on intervention and pathogen reduction strategies, e.g., Good Agricultural Systems, testing, HACCP. We take a holistic approach that treats production agriculture as a system with complex interactions between the environment, the microbe, and the food that are largely driven by ecological considerations and the actions of humans and animals.

This collection will be of use to scientists whose research includes foodborne pathogens, those working in the food industry seeking the latest verified research on food safety, and those interested in our food supply and its environmental impact.

This work required a deep well of knowledge, so sought out and we recruited the very best experts in preharvest food safety to contribute. We are deeply indebted to our many colleagues who worked diligently to write their reviews in spite of their busy schedules. This book would not have been possible without their invaluable input and participation. We also thank ASM Press for being patient with us during this process.

Siddhartha “Sid” Thakur
Kalmia “Kali” Kniel
About the Editors

Siddhartha “Sid” Thakur is a Professor in the College of Veterinary Medicine at North Carolina State University. He is also the Associate Director at the Comparative Medicine Institute where he leads the Emerging and Infectious Diseases Research program. He received his Bachelor of Veterinary Science and Animal Husbandry degree from Govind Ballabh Pant University of Agriculture and Technology (Udham Singh Nagar, India) and his Master’s of Veterinary Science in Veterinary Public Health at the Indian Veterinary Research Institute (Izatnagar, India). He earned his Ph.D. in Population Medicine at the College of Veterinary Medicine, NC State University. Prior to joining the faculty at NC State University, Dr. Thakur was an Oak Ridge Research Fellow at Center for Veterinary Medicine, FDA, Maryland. He espouses the concepts of “One Health” and seeks to understand how antimicrobial resistance develops in “superbugs” that affect animal and human health. He has won numerous awards including the Larry Beuchat Young Researcher Award by the International Association for Food and the International Global Engagement award by NC State. He is currently a NC State Chancellor faculty scholar. Dr. Thakur has authored or co-authored 45 peer-reviewed publications and runs a well-funded extramural research program.
Kalmia “Kali” E. Kniel is Professor of Microbial Food Safety in the Department of Animal and Food Sciences at the University of Delaware. She received her Ph.D. from Virginia Tech in Food Science and Technology with a focus on Food Microbiology. Her doctoral work focused on protozoan parasites. Prior to joining the faculty at the University of Delaware, she was a postdoctoral microbiologist at the USDA Agricultural Research Service’s Animal Parasitic Diseases Laboratory where she worked in the area of food safety and animal health. She is now nationally recognized as a leading expert in transmission of viruses, protozoa, and bacteria in the preharvest environment. Dr. Kniel has been active in researching the mechanisms behind the survival and inactivation of norovirus, hepatitis A virus, and other enteric viruses prevalent in our water and foods. She is an active advocate for teaching food safety at all levels and has been involved with elementary and secondary education. At the University of Delaware, she teaches courses on foodborne outbreak investigations and the basics of food science and food safety to hundreds of students each year.
Accredited Third-Party Certification, 313
Acid electrolyzed water
  pathogen reduction from shell eggs, 95
  shell eggs, 98–99
Acquired immunodeficiency syndrome (AIDS), 238, 240
Adenoviruses, 212, 217
Advisory Group on Integrated Surveillance of Antimicrobial Resistance (AGISAR), 402
Aflatoxin, nuts, 108
Agricultural chemical use, nuts and grains, 115
Agricultural land management, nuts and grains, 115
Agricultural Research Service (ARS), 11
Agricultural water, 143–145, 154
  irrigation and contamination, 144
  livestock water and contamination, 144–145
  regulation of, 317–318
  reuse, 148–150
Agriculture
  influenza viruses, 213
  poxviruses, 213–214
  virus threats potential in, 212–214
Aichi virus, 211, 217, 218
Almonds, 105
  handling contamination, 110
  production, 106
Alternaria
  associated with grains, 113
  nuts, 107
American Academy of Microbiology, 5, 13
American Medical Association, 403
Amplified fragment length polymorphism
  (AFLP-PCR), 371–372
Anellovirus, 212
Animal and Plant Health Inspection Service, USDA, 152, 181
Animal production
  advances in meat and poultry safety research, 180–182
  antimicrobial use in food animals, 404–405
  good animal management practices, 182
  livestock vaccines, 181
  pathogen persistence in, 184–186
  persistence and transmission of zoonotic pathogens, 191
  preharvest measures, 179–180
  preharvest pathogen reduction, 189–190
  preharvest research and development, 190–192
  reducing water and produce contamination, 189–190
  selecting resistant animals, 186–188
Animals
  contamination of nuts, 109
  produce contamination, 29, 258
  reservoirs of viruses, 214–218
Antibiotic use
  beef production, 51–52
  poultry farms, 78–79
  reduction and elimination in agriculture, 292
Antimicrobial resistance (AMR), 11–12, 292, 402
  emergence of, 362
  environmental AMR, 405–406
  surveillance of, 402–404
  transfer of, 28
WHO Advisory Group on Integrated Surveillance of Antimicrobial Resistance (AGISAR), 402
see also One Health
Antimicrobials
  genetically modified phages as, 295–297
  phages as, 305–306
  regulatory approval of phage-based, 299–300
  risk of development of resistant bacteria, 339–340
  use in food animals, 404–405
  use in humans, 404
Aquaculture production, risks with fish and seafood, 131–132
Arabidopsis thaliana, 408
Arenaviridae, 215
Arenaviruses, 208
Aristotle, 49
Arizona Leafy Greens Products Shipper Marketing Agreement, 312
Aspergillus spp.
  associated with grains, 113
  nuts, 107–108
Astroviruses, 211–212, 217
Avian flu, influenza, 213
Bacillus spp.
direct-fed microbials, 352, 353, 354
nuts, 108
Bacillus cereus, 53
associated with grains, 114
DNA microarray, 367
nuts, 108, 113–114
Bacillus subtilis
associated with grains, 113
bacteriophages against, 298
Bacterial insensitive mutants (BIMs), phage therapy, 304–305
Bacterial pathogens
in surface waters, 152–153
survival in manure-amended soils, 160–169
see also Biological soil amendments (BSAs)
Bacteriophage therapy
bacteriophages, 8
discovery of, 292
intrinsic and extrinsic characteristics of, 293
see also Phage therapy
Bacteroidetes, 188
Bats, viruses of, 215
Battery cage housing system, laying hens, 92
Bdellovibrio bacteriovorus, 189
Beef and dairy farms
cattle production systems, 48–49
food security in, 47–48
Beef and dairy products
biological hazards, 53–61
Campylobacter spp., 59
chemical hazards, 50–53
Coxiella burnetii, 53, 60–61
Listeria monocytogenes, 59–60
physical hazards, 53
regulatory and voluntary programs, 61
Salmonella spp., 58–59
STEC (Shiga-toxin-producing E. coli), 54–58
Bellevue Community Kitchen, 254
Bifidobacteriaceae
Bifidobacterium animalis, 352, 353
Bifidobacterium spp., 298, 352
Bifidobacterium longum, 352, 355
Bifidobacterium thermophilum, 352, 353
Bioinformatics, 10–11
Biological soil amendments
microbial contamination route, 26–29
organic fertilization of soil, 318–319
term, 318
Biological soil amendments (BSAs)
antibiotic-resistant genes in manure-amended soils, 168
benefits of, 159–160
detection of EHEC E. coli in manure, 169
E. coli survival in manure-amended soils, 163–164
E. coli and Salmonella survival in manure dust, 167–168
guidance and proposed rules, 161
pathogen survival in biosolids-amended soils, 165–166
soil type and pathogen survival in manure-amended soils, 162–163
see also Compost
Biosecurity, at poultry farm, 77–78
Biotechnology Information, NIH, 10
Birds
avian flu, 213
produce contamination, 252
Bivalve shellfish, viruses in, 217
Bocavirus, 211
Botryodiplodia theobromae, nuts, 108
Bovine
bovine leukemia virus, 208
respiratory disease, 278–279
tuberculosis, 49–50
viruses of, 216
Bovine Alliance on Management and Nutrition, 351
Bovine spongiform encephalopathy (BSE), European Union, 327, 334–335
Brassica (rape, mustard, forage radish), 37
Buckwheat, 37–38
Buffer strips, sustainable practices, 35–36
Buffer zones, sustainable practices, 34–35
Bunyavirus, 214
Burkholderia cepacia, 408
California Cantaloupe Marketing Order, 312
California Leafy Green Products Handler and Marketing Agreements, 168
guidance for biological soil amendments, 161
California Leafy Greens Marketing Agreement (LGMA), 312, 314, 317
Campylobacter spp., 11
antimicrobial resistance, 335
contaminated poultry products, 69–70
Denmark Action Plan, 337
in eggs, 87–88
in European Union, 336–337, 343
foodborne illnesses, 54
hazard in beef and dairy, 59
MALDI-TOF MS, 369
in manure, 160
meat safety assurance programs, 340
new standards for broilers, 71–72
persistence in animal production, 184–186
poultry, 181
poultry industry, 7, 74–79
RAPD (random amplification of polymorphic DNA), 370–371
real-time PCR, 364–365
systematic review, 276
vaccines for, 8, 74
waterborne disease, 265
### INDEX

**Campylobacter coli**, CDC report, 291

**Campylobacter jejuni**
- CDC report, 291
- DNA microarray, 366
- hazard in beef and dairy products, 53, 59
- loop-mediated isothermal amplification (LAMP) assay, 367–368
- outbreak linked to peas, 319
- probiotics, 350
- short-term cover cropping, 37

**Cattle**
- bacteria in gastrointestinal ecosystem, 188–189
- *Escherichia coli* and, 6–7

**Center for Veterinary Medicine, FDA’s**, 7, 11, 14, 300

**Centers for Disease Control and Prevention (CDC)**, 10, 11, 20, 69, 401

**Campylobacter jejuni**, 291

**Food Safety Report (2015)**, 266

**greenhouses**, 33

**human and animal domain interface**, 407

**PulseNet molecular subtyping network**, 373

**Salmonella** and human-animal domain interface, 407

**Salmonella contamination**, 406–407

**Chemical disinfectants**
- pathogen reduction from shell eggs, 95
- shell eggs, 95–96

**Chemicals, strategies for agricultural water**, 145–146

**Chickens**
- battery cage housing system for laying hens, 92
- free-range housing system for laying hens, 93
- housing system, 91–93
- vaccination, 90–91
- *see also* Shell eggs

**Chlorine, washing produce**, 252–253

**Cladosporium spp.**
- associated with grains, 113
- nuts, 107

**Climate change**, 13
- fruit and vegetable production, 266–268
- global developments, 261–262, 264, 269
- global seasonal rainfall anomalies, 263
- mycotoxins, 268
- seafood, 265–266
- waterborne disease, 264–265

**Clinton, Bill**, 4

**Clostridia spp.,** 53

**Clostridium botulinum**
- associated with grains, 113–114
- bacterial risk in seafood, 128
- DNA microarray, 367
- nuts, 108

**Clostridium difficile**, RAPD (random amplification of polymorphic DNA), 371

**Clostridium perfringens**, 354, 357

**Cobacillus**, 188

**Corrobacillus**, 188

**Coxiella burnetii**, hazard in beef and dairy products, 53, 60–61

**Coxsackievirus A16**, 210

**Crassostrea virginica**, norovirus in, 130

**CRISPR (clustered, regularly interspaced, short palindromic repeat)-Cas system**, 296–297

**Cronobacter**
- associated with grains, 114
- nuts, 108

**Crop protection sprays, produce safety**, 26

**Crotalaria juncea** *(sunn hemp)*, 38

**Cryptosporidium spp.,** 227, 228
- clinical signs in humans, 238
- diagnosis and treatment, 240
- foodborne transmission, 238
- host tissues invaded by, 235
- oocyst characteristics, 236
- prevention, 241
- produce-related oocysts, 250

**Cryptosporidium parvum**
- in manure, 160, 162
- waterborne disease, 264, 264–265

**Cunninghamella spp.,** nuts, 107

**Cyclospora outbreaks**, 20

**Cyclospora cayetanensis**, 227, 228

**Cystosporidium**, 227, 228

**DNA microarray**, 366

**Chickens**
- hazard in beef and dairy products, 53, 59
- foodborne illnesses, 54
- nuts, 108

**Codex Alimentarius, 24**

**Community supported agriculture (CSA), produce contamination, 254–255**

**Compartmental models, foodborne pathogens, 388–393**

**Compost**, 169–172
- guidance for applying biological soil amendments (BSAs), 161
- microbial competition inhibiting pathogen growth, 171–172
- produce contamination, 257–258
- resuscitation/regrowth of pathogens in, 170–171
- survival and resuscitation of pathogens in, 170

**Compost and agricultural teas (CTs), guidance for applying biological soil amendments (BSAs), 161**

**Control programs, preharvest food safety, 7–9**

**Conventional farming systems, production practices and safety, 32**

**Cooperative Extension System, 132**

**Copper-silver ionization, strategies for agricultural water, 146–147**

**Cosavirus**, 211

**Cosavirus**, 211

**Coxiella burnetii**, hazard in beef and dairy products, 53, 60–61

**Coxsackievirus A16**, 210

**Crosisaea virginica**, norovirus in, 130

**CRISPR (clustered, regularly interspaced, short palindromic repeat)-Cas system**, 296–297

**Cronobacter**
- associated with grains, 114
- nuts, 108

**Crop protection sprays, produce safety, 26**

**Crotalaria juncea** *(sunn hemp)*, 38

**Cryptosporidium spp.,** 227, 228
- clinical signs in humans, 238
- diagnosis and treatment, 240
- foodborne transmission, 238
- host tissues invaded by, 235
- oocyst characteristics, 236
- prevention, 241
- produce-related oocysts, 250

**Cryptosporidium parvum**
- in manure, 160, 162
- waterborne disease, 264, 264–265

**Cunninghamella spp.,** nuts, 107

**Cyclospora outbreaks**, 20

**Cyclospora cayetanensis**, 227, 228

**Cystosporidium**, 227, 228

**DNA microarray**, 366

**Chickens**
- hazard in beef and dairy products, 53, 59
- foodborne illnesses, 54
- nuts, 108

**Codex Alimentarius, 24**

**Community supported agriculture (CSA), produce contamination, 254–255**

**Compartmental models, foodborne pathogens, 388–393**

**Compost**, 169–172
- guidance for applying biological soil amendments (BSAs), 161
- microbial competition inhibiting pathogen growth, 171–172
- produce contamination, 257–258
- resuscitation/regrowth of pathogens in, 170–171
- survival and resuscitation of pathogens in, 170

**Compost and agricultural teas (CTs), guidance for applying biological soil amendments (BSAs), 161**

**Control programs, preharvest food safety, 7–9**

**Conventional farming systems, production practices and safety, 32**

**Cooperative Extension System, 132**

**Copper-silver ionization, strategies for agricultural water, 146–147**

**Cosavirus**, 211

**Coxiella burnetii**, hazard in beef and dairy products, 53, 60–61

**Coxsackievirus A16**, 210

**Crosisaea virginica**, norovirus in, 130

**CRISPR (clustered, regularly interspaced, short palindromic repeat)-Cas system**, 296–297

**Cronobacter**
- associated with grains, 114
- nuts, 108

**Crop protection sprays, produce safety, 26**

**Crotalaria juncea** *(sunn hemp)*, 38

**Cryptosporidium spp.,** 227, 228
- clinical signs in humans, 238
- diagnosis and treatment, 240
- foodborne transmission, 238
- host tissues invaded by, 235
- oocyst characteristics, 236
- prevention, 241
- produce-related oocysts, 250

**Cryptosporidium parvum**
- in manure, 160, 162
- waterborne disease, 264, 264–265

**Cunninghamella spp.,** nuts, 107

**Cyclospora outbreaks**, 20

**Cyclospora cayetanensis**, 227, 228

**Cystosporidium**, 227, 228
Cyclospora cayetanensis (continued)

- diagnosis and treatment, 240
- foodborne transmission, 237
- host tissues invaded by, 235
- oocyst characteristics, 236
- outbreak traced to cilantro, 319
- prevention, 241

Cyclovirus, 212

Dairy farms. See Beef and dairy farms

Dairy products. See Beef and dairy products

DANISH Product Standard, 342–343

Danish Veterinary and Food Administration, 329, 340

DBatVir database, 215

Decombination technologies for shell eggs, 95
- acidic electrolyzed water, 98–99
- chemical disinfectants, 95–96
- formaldehyde fumigation, 100
- nonthermal gas plasma treatment, 98
- ozone treatment, 97–98
- pasteurization of eggs, 96
- thermoultrasonication, 96–97
- UV irradiation, 99–100

Denmark Action Plan, Campylobacter in, 337

Direct-fed microbials (DFMs), 351
- composition of, 353–355
- microorganisms approved for use, 352

DNA microarray, detection technique, 366–367

Documentation and record keeping, nuts and grains, 116

Domestic animals, produce contamination, 29

Ebola virus, 208, 215

Egg Rule, 7

Egg safety, 87–88
- contamination of shell eggs, 88–94
- FDA rule on shell eggs, 100–101
- prevention controls for, 94
- see also Shell eggs

Electrolyzed oxidized water (EOW), shell eggs, 98–99

Enterobacteriaceae, abundance in produce, 33

Enterobacter sakazakii, real-time PCR, 365

Enterococcus spp.
- associated with grains, 113
- nuts, 108

Enterococcus faecalis, competition in compost, 171

Enterococcus faecium, direct-fed microbials, 352, 353, 355

Enterohemorrhagic E. coli (EHEC)
- detection in manure, 169
- in surface and harvested rainwater, 153–154

Enteroviruses, 210, 217

Environment. See Climate change

Environmental Protection Agency (EPA), 23, 51, 115, 309

compost, 169

Guidelines for Water Reuse (2012), 148–150

irrigation water, 144

see also Regulation in United States

Enzyme-linked immunosorbent assay (ELISA), Toxoplasma infection, 236–237, 240

Equipment, produce contamination, 29–31

Escherichia coli, 5, 11
- application and location for survival in manure-amended soils, 165, 166
- bacteriophage-based products, 300
- bacteriophages against, 298
- cattle and, 6–7
- cattle super-shedding of, 183–184
- development of bacterial insensitive mutants (BIMs), 304–305
- environmental transmission of, 390
- food and vegetable production, 266–267
- foodborne outbreaks by contaminated water, 150–152
- lettuce exposure to manure runoff, 160
- manure application, 115
- meta-analysis, 274
- multiplex PCR, 364
- nuts, 108
- persistence in animal production, 184–186
- postharvest washing, 26
- prevalence on cattle hides, 179
- produce-related outbreaks, 249–250
- production water, 252
- real-time PCR, 364–365
- recalls and outbreaks associated with, 112
- regulating water, 145
- resuscitation/regrowth in compost, 170–171
- shedding of, 8
- shell eggs, 100
- shrimp aquaculture, 125
- soil microbial community, 27
- storage of nuts, 111
- stress response genes in, survival in manure-amended soils, 164–165
- in surface waters, 153
- survival and resuscitation in compost, 170
- survival in biosolids-amended soils, 165–166
- survival in manure-amended soils in greenhouse, 163–164
- survival in manure dust, 167–168
- vegetative filter strips for eliminating, 36
- viable but nonculturable (VBNC) state, 23

water safety, 24

within-host models, 397

see also Shiga-toxin-producing E. coli (STEC)

European Center for Disease Prevention and Control (ECDC), 326

European Food Safety Authority (EFSA), 10, 131, 325, 335

Biohazard Panel, 299
meat safety assurance programs, 340–341
microorganisms with QPS status by, 352
zoonotic hazards, 326–327
European Livestock and Meat Trading Union
(UECBV), 326, 339
European Medicine Agency, 336
European Poultry Industry (AVEC), 326
European Surveillance of Veterinary Antimicrobial
Consumption, 336
European Union
Escherichia coli in, 6
food safety in, 325–327
human cases of zoonoses, 326
meat safety assurance programs, 340–341
microorganisms approved in direct-fed microbials, 352
Salmonella in, 5, 7
see also Regulatory framework in European
Union
Exotic pets, viruses in, 217–218
Fabaceae (sunn hemp), 37
Fagopyrum esculentum (buckwheat), 38
Farmers’ markets, produce contamination, 254
Farming systems, production practices and safety, 32
Fecal coliforms, vegetative filter strips for eliminating, 36
Federal Food, Drug, and Cosmetic Act, 61, 318
Federal Insecticide, Fungicide, and Rodenticide Act, 61
Feed components and additives, chickens, 89–90
Felidae, 231, 232
“Fight Bac” campaign, 19
Filberts, 106. See also Nuts
Firmicutes, 188
Fish and seafood
aquaculture production risks associated with, 131–132
bacterial risks associated with, 124–128
causes of seafood risks, 132–133, 137
Clostridium botulinum, 128
consumption, 23, 123
foodborne diseases and outbreaks, 123–124
fully cooked, 133, 137
hepatitis A, 130
Listeria monocytogenes, 124, 126–127
norovirus, 129–130
parasitic risks associated with, 130–131
raw or minimally processed, 132
ready-to-eat, 132–133
risks associated with, 123–124, 137–138
Salmonella, 124, 125–126
thermal resistance of bacteria in shrimp, 134, 135, 136
Vibrio cholerae, 124, 127
Vibrio para-haemolyticus, 127–128
Vibrio vulnificus, 128
viral risks associated with, 129
Florida Department of Agriculture and Consumer Services, 312
Flukes, fish and seafood risks, 131
Food and Agricultural Organization of the United Nations, 292
Food and Drug Administration (FDA), 9, 20, 88, 309
antimicrobial resistance, 11–12
Center for Veterinary Medicine, 7, 11, 14, 300
Food Safety Action Plan, 312
food safety at preharvest stage, 310
GenomeTrakr Network, 406
genomic sequencing, 10
rule on shell egg safety, 100–101
rules for growing produce, 158
see also Regulation in United States
Food animals. See Animal production
Foodborne illnesses/outbreaks, 3, 54
fruits/vegetables contact with surface or irrigation water, 150–152
preharvest contamination, 409
Foodborne pathogens
basic reproduction number, 391–392
compartmental models for, 388–393
deterministic compartmental infectious disease model, 390
evaluation of control strategies, 392–393
flow charts for epidemiological models, 389
metapopulation models, 393
network models, 393–395
transmission of, 390–391
within-host models, 395–397
see also Mathematical modeling
Food business operators (FBOs), 330
general rules on hygiene for, 331
specific rules on hygiene for, 331–332
Food hubs, produce contamination, 254–255
Food Quality Protection Act, 61
Food safety, 3–4
E. coli super-shedding by cattle, 183–184
microbiota manipulations and, 350–351
One Health concept, 401–402
organic and free-range production, 9
preharvest issues, 4–6
quality checks, 361–363
see also One Health
Food Safety and Inspection Service (FSIS)
beef and dairy products, 54, 55
pasteurization of eggs, 96
poultry products, 70, 180
USDA’s, 5, 6, 7, 299, 311
Food Safety and Produce Initiatives, 4
Food Safety Initiative (1998), 6
Food Safety Modernization Act (FSMA), 4, 9, 14, 19, 22, 23–24, 30, 311
Final Rule on Produce Safety, 311, 312, 313, 316, 319
Food Safety Modernization Act (FSMA) (continued)
  fresh produce industry, 251
  regulating water, 145
Food Safety Report (2015), 266
Food security, 23, 47, 61, 268, 291–292
Foods safety, future of, 13–14
Food Stamp Nutrition Education Program,
  University of California Cooperative
  Extension, 132
Foreign Supplier Verification Program, 313
Formaldehyde fumigation
  pathogen reduction from shell eggs, 95
  shell eggs, 100
Francis (Pope), 261
Free-range production, food safety, 9
Frost protection, produce safety, 25–26
Fruits and vegetables
  climate change and production, 266–268
  cycle of pathogens in production of, 250
  foodborne outbreaks by water contact, 150–152
  see also Produce
Fungi, associated with grains, 113
  *Fusarium* spp.
    associated with grains, 113
    nuts, 108
Gastrointestinal tract (GIT)
  phage survival in, 301
  stability of phages in, 303–304
General Food Law
  European Union, 327–328
  precautionary principle, 330–331
Genome Trakr Network, 10, 406
Genomic sequencing, 10–11
*Giardia* spp., 227, 228
  clinical signs in humans, 238
  diagnosis and treatment, 240
  foodborne transmission, 238
  host tissues invaded by, 235
  oocyst characteristics, 236
  prevention, 241
  produce-related cysts, 250
*Giardia intestinalis*, in manure, 162
Global Aquaculture Alliance, 313
Global developments, climate change, 261–262, 264, 269
Global Food Safety Initiative, 313
Global Genomic Initiative, 10
Global Microbial Identifier (GMI), 10
Global Precipitation Climatology Project, 267
Global Red Meat Standard, 313
Good agricultural practices (GAPs), 5, 13
  assessing the benefits of, 316
  National Organic Program (NOP) vs., 255–256
  nuts and grains, 114–116
  produce contamination, 255
  recommendations, 312
Good management practices, animal production, 182
Good Manufacturing Practices (GMPs), fully
  cooked fish and seafood, 133
Grains
  agricultural chemical use, 115
  agricultural land management, 115
  bacteria associated with, 113–114
  cereal production, 105–106
  documentation and record keeping, 116
  fungi associated with, 113
  good agricultural practices for, 114–116
  harvesting of, 115–116
  manure application, 115
  microbiology and contamination sources, 112–114
  plant cleaning and sanitation, 116
  water source, 114–115
  worker hygiene, 115
  see also Nuts
Greenhouses
  *E. coli* survival in manure-amended soils, 163–164
  production practices and safety, 33
Guide to Minimize Microbial Food Safety Hazards
  for Fruits and Vegetables (GMMFSH), 19
Guide to Tomato Good Agricultural Practices
  (T-GAPS), guidance for biological soil
  amendments, 161
HACCP. See Hazard Analysis and Critical Control
  Point (HACCP)
Hantaviruses, 208, 215
Harvesting
  contamination of nuts, 109–110
  nuts and grains, 115–116
  see also Preharvest food safety
Hatcheries
  antibiotic use, 78–79
  biosecurity, 77–78
  farm and environment, 75–79
  feed withdrawal, 76–77
  litter, 75–76
  poultry production, 74–79
  prebiotics and probiotics, 79
Hazard Analysis and Critical Control Point
  (HACCP), 4, 5, 12, 13, 50, 125, 133, 180, 331
Hazelnuts, 106. See also Nuts
*Helminthosporium*, associated with grains, 113
Hendra virus, 208, 214, 217
Hepatitis A, 54
Hepatitis A virus (HAV), 130, 206, 217
Hepatitis E virus (HEV), 208, 209–210, 215, 217
Herpes B virus, 207
Highly active antiretroviral therapy (HAART), 240
Hippocrates, 402
Housing system, chickens for egg safety, 91–93
Human Aichi virus, 211
Human bocavirus (HuBoV), 211
Human immunodeficiency virus (HIV)–like strains, 208, 215
Human noroviruses (HuNoV), 206, 217
Hydrogen peroxide, washing produce, 253
Immune system
   phage clearance by, 301–302
   phage-mediated modulation of, 297–299
Immunosorbent agglutination assay test (IAAT), 240
Indirect fluorescent antibody assay (IFA), 240
Individual-based models, foodborne pathogens, 395
Influenza viruses, 207, 208, 213, 217, 218
Innate immunity, 301–302
Institute of Medicine (IOM), 5, 12, 13
Intergovernmental Panel on Climate Change (IPCC), 262, 267
Internalization of pathogens, in produce, 253
International Food Information Council Foundation, 132
International trade, 3–4
Interventions, preharvest food safety, 7–9
Irrigation water contamination and, 144
   see also Water
Johne’s disease, 185
King, Lonnie, 402
Klasseviruses, 211
Klebsiella pneumoniae, 303
Koch, Robert, 49
Lactobacillus spp.
   direct-fed microbials, 352, 353
   poultry industry, 76
Lactobacillus acidophilus
   bacteriophages against, 298
   direct-fed microbials, 353, 355
   strains in cattle, 57
Leafy Greens Marketing Agreement (LGMA), 312
Leptospira spp., 53, 265
Lethal agent delivery systems (LADS), phages, 295–296
Liaison Center for the Meat Processing Industry (CLITRAVI), 326
Listeria spp., 10
   fully cooked fish and seafood, 133, 137
   in manure, 160, 162
   real-time PCR, 364–365
Listeria innocua, thermal resistance in shrimp, 136
Listeria monocytogenes, 53, 408
   amplified fragment length polymorphism (AFLP–PCR), 371
   bacterial risk in seafood, 124, 126–127
   bacteriophage-based products, 300
   competition in compost, 171
   crabs and boiling of, 137
   crabs and steaming of, 138
   DNA microarray, 367
   hazard in beef and dairy products, 59–60
   loop-mediated isothermal amplification (LAMP) assay, 368
   in milk, 339
   multiplex PCR, 364
   nuts, 108
   outbreaks, 20, 21
   packinghouse contamination, 30
   persistence in animal production, 185, 186
   produce-related outbreaks, 249–250
   RAPD (random amplification of polymorphic DNA), 370
   ready-to-eat fish and seafood, 133
   recalls and outbreaks associated with, 112
   sanitizing produce, 253
   shell eggs, 98–99
   soil amendments, 319
   soil microbial community, 27–28
   storage of nuts, 111
   in surface waters, 153
   thermal resistance in shrimp, 136
   viable but nonculturable (VBNC) state, 23
Listeria welshimeri, thermal resistance in shrimp, 136
Livestock water contamination and, 144–145
   see also Water
Loop-mediated isothermal amplification (LAMP) assay, detection technique, 367–368
Macadamias, 106. See also Nuts
Macrophomina phaseolina, nuts, 108
MALDI-TOF MS (matrix-assisted laser desorption ionization–time of flight mass spectrometry), detection technique, 368–369
Mallon, Mary (Typhoid Mary), 185
Manure
   E. coli and Salmonella survival in manure dust, 167–168
   guidance for applying biological soil amendments (BSAs), 161
   microbial contamination route, 26–29
   nuts and grains, 115
   preharvest food safety, 9–10
   produce contamination, 257–258
Manure-amended soils
   application and location and E. coli survival in, 165, 166
   pathogen survival in, 160–169
   role of stress response genes in E. coli, 164–165
   survival of E. coli in, of greenhouse trials, 163–164
   see also Biological soil amendments (BSAs)
Maryland Department of Agriculture, 315

INDEX 419
Mastitis, dairy cattle, 187–188
Mathematical modeling
compartmental models for foodborne pathogens, 388–393
computational statistics, 385
individual-based models, 395
metapopulation models, 393
model classifications, 385–387
modeling cycle, 384
modeling steps, 384–385
network models, 393–395
preharvest food safety, 383–384, 387–388, 397
principles of, 384–387
time series of infection prevalence, 386
within-host models, 395–397
Meat. See Animal production
Meat Inspection Act of 1906, 180
Meat safety assurance programs, European Union, 340–341
Meta-analysis
advantages of, 274
calculating a summary effect, 280–281
challenges, 284
evaluating heterogeneity, 281–282
exploring causes of heterogeneity, 282–283
limitations of, 283–284
meta-regression and subgroup analysis, 282–283
process of, 278–284
reporting the results of, 284
risk of bias tools, 276–277, 278
statistical pooling of data, 273–274, 284–285
systematic reviews, 274–277
visualizing results from individual studies, 278–280
Metagenomics
definition, 218
viruses, 209, 218–219
Metapopulation models, foodborne pathogens, 393
Metchnikoff, Elie, 349–350
Methicillin-resistant Staphylococcus aureus (MRSA), 5, 405
Microbial contamination
fruits and vegetables in U.S., 20–22
packaging equipment and tools, 29–31
potential routes of, 22–31
soils, manure and biological soil amendments, 26–29
water, 23–26
wildlife and domestic animals, 29
Microbiota, manipulation, and food safety, 350–351
Micrococcus, nuts, 108
Middle East respiratory syndrome (MERS) virus, 208, 214, 215, 217
Migratory waterfowl, viruses in, 217
Models
classifications, 385–387
see also Mathematical modeling
Molecular detection techniques
DNA microarray, 366–367
endpoint PCRs, 363–364
LAMP (loop-mediated isothermal amplification) assay, 367–368
MALDI-TOF MS, 368–369
multiplex PCR, 363–364
real-time PCR, 364–366
simplex PCR, 363
Molecular typing techniques, 369–375
amplified fragment length polymorphism (AFLP–PCR), 371–372
MLST (multilocus sequence typing), 372
PCR-RFLP (restriction fragment length polymorphism), 369–370
PFPE (pulsed-field gel electrophoresis), 372–373
RAPD (random amplification of polymorphic DNA), 370–371
whole-genome sequencing (WGS), 374–375
Macor, associated with grains, 113
Multilocus sequence typing (MLST), 372
Mustard greens, 37–38
Mycobacterium bovis, 49–50
Mycothixins, climate change and, 268
Myoviridae, phage, 301
National Academy of Sciences, 180
National Advisory Committee on Microbiological Criteria for Foods, 124
National Antimicrobial Resistance Monitoring System, 11, 70, 131
National Center for Emerging and Zoonotic Infectious Diseases, 407
National Conference on Interstate Milk Shipments (NCIMS), 52–53, 61
National Institute of Environmental Health Sciences, 264
National Institute of Food and Agriculture, USDA, 6, 154
National Marine Fisheries, 124
National Organic Program NOP (good agricultural practices (GAPs) vs., 255–256
USDA, 34, 161, 169, 319
National Poultry Improvement Plan, 12, 101
National Residue Program (NRP), 51–52
National Safety Council, 48
National Water Quality Inventory, 144
Network models, foodborne pathogens, 393–395
Next-generation sequencing (NGS), 374
Nipah virus, 208, 214, 217
Nonthermal gas plasma treatment
pathogen reduction from shell eggs, 95
shell eggs, 98
Norovirus
foodborne illnesses, 54
seafood outbreaks, 129–130
waterborne disease, 265
North Carolina Layer Performance and Management Program, 92
Nurmi concept, 350
Nuts, 105–106
agricultural land management, 115
animals contaminating, 109
bacterial pathogens on, 108
contamination in handling of, 110–111
documentation and record keeping, 116
good agricultural practices for, 114–116
harvesting of, 115–116
harvesting process contaminating, 109–110
natural microflora on, 107–108
pathogen prevalence and concentration in, 111–112
plant cleaning and sanitation, 116
preharvest contamination sources for, 108–111
production, 106–107
recalls and outbreaks, 112
soil contaminating, 108–109
storage contaminating, 111
water source, 114–115
worker hygiene, 115
see also Grains
Obama, Barack, 4
One Health
antimicrobial resistance (AMR) surveillance, 402–404
antimicrobial use in food animals, 404–405
antimicrobial use in humans, 404
approach, 401–402, 409
concept, 401–402
environmental AMR, 405–406
environmental domain interface, 407–409
human and animal domain interface, 407
preharvest food safety, 406–407
Salmonella, 406–407
term, 401
Organic farming systems, production practices and safety, 32
Organic fertilizers. See Biological soil amendments (BSAs)
Organic production, food safety, 9
Organization for Economic Cooperation and Development, 143
Overhead cooling, produce safety, 26
Ozone
agricultural water, 146
pathogen reduction from shell eggs, 95
shell eggs, 97–98
Packinghouse, produce contamination, 29–31
Parasites, fish and seafood risks, 130–131
Pasteurization
pathogen reduction from shell eggs, 95
shell eggs, 96
Pasteurized Milk Ordinance (PMO), 52, 61
Pathogenesis, Toxoplasma gondii, 238–240
Pathogen persistence
in animal production, 184–186
gastrointestinal ecosystem, 188–189
Pathogens
cycle in fruit and vegetable production, 250
factors of produce contamination, 251–258
produce-related outbreaks, 249–251
see also Produce contamination
PCR (polymerase chain reaction)
amplified fragment length polymorphism (AFLP-PCR), 371–372
DNA microarray, 366–367
endpoint PCRs, 363–364
MLST (multilocus sequence typing), 372
PCR-RFLP (restriction fragment length polymorphism), 369–370
RAPD (random amplification of polymorphic DNA), 370–371
real-time PCR, 364–366
WGS (whole-genome sequencing), 374–375
see also Molecular detection techniques; Molecular typing techniques
Peanuts, 107. See also Nuts
Pecans, 106, 110. See also Nuts
Pediococcus acidilactici, chicken feed, 90
Penicillium spp., 107–108, 113
Performance metrics, food safety, 12–13
Pets, viruses in, 217–218
Phage therapy
bacteriophage-based products for reducing foodborne pathogen and spoilage bacteria, 300
challenges, 301–305
development of bacterial insensitive mutants (BIMs), 304–305
genetically modified phages as antimicrobials, 295–297
moving away from antibiotic use, 292, 305–306
opportunities for, 292–300
phage clearance by immune system, 301–302
phage-mediated modulation of immune system, 297–299
regulatory approval of phage-based antimicrobials, 299–300
release of endotoxin, 305
simultaneous control of multiple pathogens, 292–295
stability of phages in gastrointestinal tract (GIT), 303–304
Phascolarctobacterium, 188
Picobirnaviridae, 212
Picobirnavirus, 212
Pistachios production, 106–107. See also Nuts
Plant cleaning and sanitation, nuts and grains, 116
Poaceae, 112. See also Grains
Podoviridae, phage, 301

Polygonaceae (buckwheat), 37

Poultry
- bacteria in gastrointestinal ecosystem, 189
- viruses of, 216–217
- see also Animal production

Poultry production
- antibiotic use, 78–79
- battery cage housing system for laying hens, 92
- biosecurity at poultry farm, 77–78
- farm and farm environment, 75–79
- feed withdrawal, 76–77
- free-range housing system for laying hens, 93
- hatchery, 74–79
- litter in broiler chicken house, 75–76
- prebiotics and probiotics, 79

Poultry products
- breeder flocks, 73–74
- control of foodborne pathogens in broiler production, 72–79
- feed contamination and recontamination, 72–73
- integrated production system in U.S., 71
- new Campylobacter standards for broilers, 71–72
- new Salmonella standards for broilers, 71
- overview of infections in humans, 69–70
- USDA-FSIS standards, 71–72

Poxviruses, 208, 213–214

Prebiotics, 355–356
- definition, 350, 356
- future prospects, 356–357
- poultry farms, 79
- regulation of, 351

Precautionary principle, European Union, 330–331, 343

Preharvest
- antimicrobial resistance, 11–12
- Campylobacter, 7
- E. coli and cattle, 6–7
- evidence-based directions and performance metrics, 12–13
- general issues, 4–6
- genomics, sequencing and bioinformatics, 10–11
- interventions, prevention and control programs, 7–9
- nontraditional areas, 9–13
- organic and free-range production, 9
- pathogen reduction in animal production, 189–190
- poultry industry, 7
- Salmonella, 7
- traditional areas of focus, 6–9
- water, manure and produce, 9–10

Preharvest food safety
- beef and dairy products, 61
- historical perspective of, 49–50
- mathematical modeling in, 383–384, 387–388
- multistate outbreaks, 409

One Health and Salmonella, 406–407
- overview of, 19–22
- packinghouse, equipment and tools, 29–31
- potential routes of microbial contamination, 22–31
- regulation in United States, 311–312
- screening, 361–363
- soils, manure and biological soil amendments, 26–29
- water, 23–26
- wildlife and domestic animals, 29

Presidential Food Safety Working Group, 4

Prevention programs, preharvest food safety, 7–9

Prevotella, 188

PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), 284

Probiotics
- definition, 350
- future prospects, 356–357
- poultry farms, 79
- regulation of, 351

Produce
- disease outbreaks, 249–251
- irrigation and surface runoff waters, 252
- preharvest food safety, 9–10
- production practices impacting safety, 31–33
- sources of pathogenic microorganisms, 251

Produce contamination
- animals, 258
- audit expenses, 257
- birds, 252
- data collection identifying barriers, 257–258
- documentation/time, 257
- equipment and facilities, 258
- farmers’ markets, 254
- GAPs (good agricultural practices) and GAP audits, 255
- GAPs vs. National Organic Program, 255–256
- internalization of pathogens, 253
- investigating audit barriers and compliance, 256–257
- irrigation and surface runoff waters, 252
- local foods and community supported agriculture, 254–255
- traceability, 258
- use of compost and manure, 257–258
- variation in buyer needs, 257
- washing produce, 252–253
- water source, treatment and testing, 258

Produce Safety Rule, 9, 19, 23, 26, 30, 145

Production practices
- conventional vs. organic farming systems, 32
- greenhouses, 33
- impacting fresh produce safety, 31–33
- sustainable farming systems, 32–33

The Prolongation of Life (Metchnikoff), 349
**Proteus vulgaris**, DNA microarray, 367

*Pseudomonas*, nuts, 108

*Pseudomonas aeruginosa*, 305, 408

*Pseudomonas syringae*, bacteriophage-based products, 300

Pulsed light technology
- pathogen reduction from shell eggs, 95
- shell eggs, 99

Pulse-field gel electrophoresis (PFGE), 184, 185, 186, 372–373

PulseNet, molecular subtyping network, 373

Quality checks
- food safety, 361–363
- see also Molecular detection techniques; Molecular typing techniques

Rainfall
- global seasonal anomalies, 263
- water quality, 25

Random amplification of polymorphic DNA (RAPD), 363, 370–371

Regulation in United States, 309–311, 320
- agricultural water, 317–318
- assessing benefits of good agricultural practices (GAPs), 316
- best practices, certifications and FSMA compliance, 312–313
- current issues and future directions, 316–320
- economies of scale, 314–315
- market channels, 315
- one-size-fits-all approach in educational programs, 315–316
- organic fertilization of soil, 318–319
- preharvest food safety in, 311–312
- preventative approach, 314–316
- third-party audits and government verification, 313–314
- workers, wildlife, equipment and environmental impacts, 319–320

Regulatory framework in European Union
- actions in pipeline in, 336–343
- antimicrobials and risk of development of resistant bacteria, 339–340
- antimicrobial use and resistant bacteria, 335–336
- bovine spongiform encephalopathy (BSE), 327, 334–335
- *Campylobacter*, 336–337
- control of *Salmonella*, 328–330
- food business operators (FBOs), 330, 331
- General Food Law, 327–328
- general rules on hygiene, 331
- graphical description of, 328
- meat safety assurance programs, 340–341
- microbiological criteria and *Salmonella*, 332–333
- precautionary principle, 330–331, 343
- private industry standards, 342–343
- requirements for FBOs, 334
- *Salmonella*, 336
- specific rules on hygiene for FBOs, 331–332
- zoonotic hazards, 338–339
- zoonotic parasites, 337–338

Reoviruses, 207, 212

Resistance, term, 131

*Rhizopus*
- associated with grains, 113
- nuts, 107–108

Risk assessment, 48

Risk of bias tools, meta-analyses, 276–277, 278, 281

RNA viruses, 207, 208, 212, 213

Rodents, viruses of, 215–216

Rotavirus, 212

Round worms fish and seafood risks, 130

*Ruminococcaceae* family, 188–189

*Saccharomyces boulardii*, chicken feed, 90

*Saccharomyces cerevisiae*
- bacteriophages against, 298
- chicken feed, 90

*Saffold virus*, 210–211

*Saliviruses*, 211

*Salmonella*, 5, 10, 11
- antimicrobial resistance, 335
- bacterial risk in seafood, 125–126
- in bovine lymph nodes, 294
- CDC report, 291
- contaminated poultry products, 69–70
- contamination of fish and seafood, 131
- contamination of melons and tomatoes, 10
- contamination of nuts, 108, 110, 112
- control programs, 182
- eggs, 87–88
- epidemiological models of, in animal host, 389
- European Union regulation, 328–330
- European Union strategy for, 336, 343
- foodborne illnesses, 54, 339
- heterogeneity evaluation, 282
- infection in poultry, 187
- manure application, 115
- mathematical models, 387, 396
- meat safety assurance programs, 340–341
- meta-analysis, 274
- microbiological criteria and, 332–333
- new standards for broilers, 71
- One Health and preharvest food safety, 406–407
- persistence in animal production, 184–186
- postharvest washing, 26
- poultry industry and, 7, 74–79
- prevalence and concentration on nuts, 111–112
- ready-to-eat fish and seafood, 133
- real-time PCR, 364–366
- recalls and outbreaks associated with, 112
- specific phage, 302, 303
**Salmonella (continued)**

- Storage of nuts, 111
- Swine, 181
- Systematic review, 275–276
- Vaccine, 74
- Viable but nonculturable (VBNC) state, 23
- Wildlife contamination, 29

**Salmonella spp.**

- Bacteriophage-based products, 8, 298, 300
- Basic reproduction number, 391–392
- DNA microarray, 366–367
- Environmental domain interface, 407–409
- Foodborne outbreaks by contaminated water, 151–152
- Fully cooked fish and seafood, 133, 137
- Hazard in beef and dairy products, 53, 58–59
- In manure, 160
- Produce-related outbreaks, 249–250
- Production water, 252
- RAPD (random amplification of polymorphic DNA), 370
- Resuscitation/regrowth in compost, 170–171
- Short-term cover cropping, 37
- Surface waters, 152–153
- Survival and resuscitation in compost, 170
- Survival in biosolids-amended soils, 165–166
- Survival in manure dust, 167–168
- Thermal resistance in shrimp, 135

**Salmonella enterica** serotypes, 7, 70

- In cattle, 58–59
- Enteritidis, 7, 88, 96, 97, 108–109, 253, 364
- Heidelberg, 70, 355, 373
- Infantis, 70, 88, 135, 171, 189, 330, 369, 408, 409
- Johannesburg, 70
- Kentucky, 70, 74, 408, 409
- Montevideo, 59, 70
- Newport, 31, 58, 70, 125, 133, 151–152, 318, 373, 408, 409
- Senftenberg, 96–97

**Sand filtration, strategies for agricultural water**, 147

**Sanitizers**, fruit contamination, 31

**Santa Barbara Organic Soup Kitchen**, 254

**Sarcocystis** spp., 227, 228

- Clinical signs in humans, 238
- Diagnosis and treatment, 240
- Host tissues invaded by, 235
- Oocyst characteristics of, 236
- Prevention, 241

**Schwabe, Calvin**, 402

**Seafood**

- Climate change and, 265–266
- See also Fish and seafood

**Severe acute respiratory syndrome (SARS) virus**, 208, 214, 215, 217

**Severe fever thrombocytopenia syndrome virus**

- (SFTS), 214

**Shell eggs**

- Acidic electrolyzed water, 98–99
- Chemical disinfectants, 95–96
- Contamination of, 88–94
- Decontamination processes, 95
- Decontamination technologies for, 94–100
- FDA rule on safety, 100–101
- Feed components and additives, 89–90
- Formaldehyde fumigation, 100
- Housing system for chickens, 91–93
- Nonthermal gas plasma treatment, 98
- Ozone treatment, 97–98
- Pasteurization of eggs, 96
- Preharvest factors, 93–94
- Pulsed light technology, 99
- Thermoultrasonication, 96–97
- UV irradiation, 99–100
- Vaccination of chickens, 90–91
- See also Egg safety

**Shiga-toxin-producing** *E. coli* (STEC), 48, 54

- Beef products, 180
- Hazard in beef and dairy products, 54–58
- In manure-amended soil, 169
- In surface waters, 153

**Shigella flexneri**, multiplex PCR, 364

**Shigella** spp.

- Foodborne illnesses, 54
- Produce-related outbreaks, 249–250
- Production water, 252
- Real-time PCR, 365
- Short-term cover cropping, 37
- Short-term cover cropping, sustainable practices, 37–38

**Siphoviridae**, phage, 301

**Soils**

- Microbial contamination route, 26–29
- Organic fertilization of, 318–319
- Sustainable practices, 36–37
- See also Biological soil amendments (BSAs); Compost

**Spanish flu pandemic**, 213

**Standards for the Growing, Harvesting, Packing and Holding of Produce for Human Consumption** (FDA Supplemental Proposed Rule), 159, 161

**Staphylococcus** spp.

- Foodborne illnesses, 54
- Produce-related outbreaks, 249–250
- Production water, 252
- Real-time PCR, 365
- Short-term cover cropping, 37
- Short-term cover cropping, sustainable practices, 37–38

**Siphoviridae**, phage, 301

- Foodborne illnesses, 54
- Nuts, 108

**Staphylococcus aureus**, 53

- Associated with grains, 113
- Bacteriophages against, 298
- Methicillin-resistant, 5, 405
- Multiplex PCR, 364
- Nuts, 108
shell eggs, 98, 100
STEC. See Shiga-toxin-producing E. coli (STEC)
Streptococcus
nuts, 108
vegetative filter strips for eliminating, 36
Stress conditions, fresh produce safety, 23
Stress response genes, E. coli survival in
manure-amended soils, 164–165
Sunn hemp, 37–38
Superinfection immunity, concept of, 295
Sustainable practices
buffer zones, 34–35
farming production practices and safety, 32–33
short-term cover cropping, 37–38
soil solarization, 36–37
vegetable filter strips, 35–36
Swine
gastrointestinal ecosystem, 188
Trichinella surveillance in, 337
viruses in, 216
Systematic review methodology, 273–274
Systemic reviews, meta-analysis, 274–277
Taenia saginata/Cysticercus bovis, surveillance in
beef, 337–338, 343
Tape worms, fish and seafood risks, 131
Taqman probes, real-time PCR, 364–366
Thermoultrasonication
pathogen reduction from shell eggs, 95
shell eggs, 96–97
Tick-borne encephalitis, 208, 210
Time lag bias, 283
Title 21 Code of Federal Regulations, 61
Tomato-Good Agriculture Practices, 312, 317
Toxoplasma
meat safety assurance programs, 341
risk assessment in animals, 338
Toxoplasma gondii, 227, 228
diagnosis and treatment, 240–241
epidemiology, 232–234
foodborne transmission, 235–238
host tissues invaded by, 235
life cycle of, 229
morphology and structure, 228–232
oocyst characteristics of, 236
pathogenesis and clinical features, 238–240
prevention, 241
stages in in vitro and in vivo preparations, 233
stages of, 231
tachyzoites of, 230
tissue cysts of, 234
transmission electron micrograph of tachyzoite, 232
transmission electron micrograph of tissue cyst, 235
transmission paths, 391
Trichinella
European Union regulation, 333–334, 343
meat safety assurance programs, 341
surveillance in pigs, 337
Trichoderma spp., nuts, 107
Tuberculosis, in cattle, 49–50
Ultraviolet radiation, strategies for agricultural
water, 146
United Egg Producers Animal Husbandry
Guidelines, 312
United States
microorganisms approved in direct-fed
microbials, 352
see also Regulation in United States
University of California Cooperative Extension,
Food Stamp Nutrition Education Program, 132
University of Maryland, 315–316
U.S. Department of Agriculture (USDA), 51, 70, 94,
309
Animal Plant Health Inspection Service, 152
community supported agriculture (CSA), 254–255
Food Safety and Inspection Service (FSIS), 5, 6, 7,
299, 311
good agricultural practices (GAPs), 255–256
good agricultural practices (GAPs) and GAP
audits, 255
National Institute of Food and Agriculture, 154
National Organic Program, 34, 161, 169, 255–256
see also Regulation in United States
U.S. National Residue Program (NRP), 51–52
U.S. President’s Food Safety Initiative, 19
U.S. Public Health Service, 61
UV irradiation
pathogen reduction from shell eggs, 95
shell eggs, 99–100
Vaccinations, 8
chickens for egg safety, 90–91
time lag bias, 283
control strategies, 392–393
efficacy of, 282
livestock, 181
program for commercial layers, 91
Vegetative filter strips (VFSs)
examples for eliminating pollutants, 36
sustainable practices, 35–36
Verticillium spp., nuts, 107
Viable but nonculturable (VBNC) state, 23
Vibrio spp.
fish and seafood, 124, 132
fully cooked fish and seafood, 133, 137
Vibrio cholerae
bacterial risk in seafood, 124, 127
thermal resistance in shrimp, 134
Vibrio parahaemolyticus
bacterial risk in seafood, 125, 127–128
crabs and boiling of, 137
Vibrio parahaemolyticus (continued)
crabs and steaming of, 138
DNA microarray, 367
outbreaks in seafood, 265–266
real-time PCR, 365
thermal resistance in shrimp, 134

Vibrio vulnificus
bacterial risk in seafood, 128
real-time PCR, 365
thermal resistance in shrimp, 134
waterborne disease, 265

Viruses
adenoviruses, 212
Aichi virus, 211
anellovirus, 212
animal reservoirs of, 214–218
astroviruses, 211–212
bats, 215
bivalve shellfish, 217
bocavirus, 211
bovines, 216
coronaviruses, 214
cosavirus, 211
cyclovirus, 212
definition, 205
emerging pathogen, 205–209
enterovirus, 210
exotic and common pets, 217–218
Hendra virus, 214
hepatitis E virus (HEV), 209–210
influenza, 213
Klasseviruses, 211
metagenomics, 218–219
migratory waterfowl, 217
Nipah virus, 214
picoebirnavirus, 212
poultry, 216–217
poxviruses, 213–214
reovirus, 212
rodents, 215–216
rotavirus, 212
Saffold virus, 210–211
saliviruses, 211
spreading by contaminated food, 209–212
swine, 216
threats associated with agriculture, 212–214
tick-borne encephalitis, 210
wild bush meat, 215
VTEC/STEC, in ruminants, 338–339

Wallemma, associated with grains, 113
Walnuts, 107. See also Nuts
Washing, produce contamination, 252–253
Water
agricultural reuse, 148–150
for agriculture, 143–145, 154
bacterial pathogens in surface, 152–153
chemicals for agricultural, 145–146
copper and silver ionization of, 146–147
crop protection sprays, 26
frost protection, 25–26
illustrated cases, 150–154
irrigation, 252
irrigation and contamination, 144
livestock, and contamination, 144–145
microbial contamination route, 23–26
mitigation strategies for agricultural, 145–147
overhead cooling, 26
ozone in, 146
preharvest food safety, 9–10
produce contamination, 252, 258
reducing contamination in animal production, 189–190
regulating, 145
regulation of agricultural, 317–318
reuse, 147–150
reuse terminology, 148, 149
sand filtration, 147
source for nuts and grains, 114–115
surface runoff, 252
ultraviolet radiation (UV) for disinfection, 146
zero-valent iron (ZVI) filtration, 147
Waterborne disease, climate change and, 264–265
White House National Action Plan for Combating Antibiotic Resistant Bacteria, 403
Whole-genome sequencing (WGS), 374–375
Wild bush meat, viruses of, 215
Wildlife, produce contamination, 29
Within-host models, foodborne pathogens, 395–397
Worker hygiene, nuts and grains, 115
World Food Summit, 47
World Health Organization (WHO), 24, 253, 291, 292
Advisory Group on Integrated Surveillance of Antimicrobial Resistance (AGISAR), 402
water guidelines, 149, 150
World Health Organization and Agriculture Organization (WHO/FAO) of United Nations, 5

Xanthomonas, nuts, 108
Xanthomonas campestris, bacteriophage-based products, 300

Yellow Card scheme, 340
Yersinia
meat safety assurance programs, 340–341
zoonotic hazards, 338, 343

Zero-valent iron (ZVI) filtration, strategies for agricultural water, 147
Zoonosis, definition of, 207
Zoonosis Directive, 7, 328
Zoonosis Regulation, 328
Zoonotic infections, European Union, 326–327