

Contents

Preface xv

1	Introduction to Nanotechnology-Enhanced Food Packaging Industry	1
	<i>Kunal Singha, Baburaj Regubalan, Pintu Pandit, Subhankar Maity, and Shakeel Ahmed</i>	
1.1	Introduction	1
1.2	Nanotechnology Applications in Food Processing	3
1.2.1	Nanotechnology Applications in Preserving Meat Density, Taste, and Presentation	3
1.2.2	Nanotechnology Applications for Maintaining the Food Nutrient Value	4
1.3	Nanotechnology Functions for Preserving or Shelf Life	4
1.4	Nanotechnology in Food Packaging	4
1.4.1	Usages of Nanosensors in Pathogen and Adulterant Detection in the Food Industry	6
1.4.2	Nanotechnology Applications in Food Safety Issues	7
1.4.3	Bio-Based Nano-packaging in Food Industry	8
1.5	Nanocoating Applications in Food Industry	8
1.6	Nanocoats Used in Food Manufacturing	9
1.7	Importance of Nanolamine in Food Business	10
1.8	Antimicrobial Films Used in Food Industry	10
1.9	Nano-scavenging Oxygen Film Used in Food or Eating Substances	11
1.10	UV-Proof Processing of Foods Using Nanometal Oxides	11
1.11	Nano-intelligent Food Labeling	12
1.12	Nanotechnology-Aided Freshness and Spoilage Indicators	12
1.13	Nanotechnology-Aided Oxygen Indicators in Food Industry	13
1.14	Application of Nanotechnology in Product Identification and Anti-counterfeiting	13
1.15	Usages of Nanotechnology in Traceability and Active Tags in Food and Drug Industry	13
1.16	Conclusions	14
	References	14

2	An Overview of Biopolymers in Food Packaging Systems	19
	<i>Jéssica de Matos Fonseca, Betina L. Koop, Thalles C. Trevisol, Cristiane Capello, Alcilene R. Monteiro, and Germán A. Valencia</i>	
2.1	Introduction	19
2.2	Main Polymers Isolated from Biomass	20
2.2.1	Casein and Whey	20
2.2.2	Cellulose and Derivatives	22
2.2.3	Chitin and Chitosan	23
2.2.4	Collagen and Gelatin	23
2.2.5	Soybean and Derivatives	29
2.2.5.1	Soy Protein	29
2.2.5.2	Soybean Soluble Polysaccharide	32
2.2.5.3	Soybean Fiber and Derivatives	32
2.2.6	Starch and Derivatives	35
2.3	Main Polymers Obtained by Microbial Production	35
2.4	Main Biodegradable Polymers Chemically Synthesized	40
2.5	Conclusions	41
	Conflicts of Interest	42
	Acknowledgments	42
	References	42
3	Nanostructures Based on Starch, Their Preparation, Processing, and Application in Packaging	55
	<i>Cristian C. Villa</i>	
3.1	Introduction	55
3.1.1	Starch Nanoparticles and Nanocrystals	55
3.1.2	Starch Nanomaterials in Food Packaging	57
3.1.3	Starch Nanomaterials as Carriers of Bioactive Molecules	58
3.1.4	Perspectives and Outlook	59
	References	60
4	Cellulose Nanostructures and Its Application as Effective Food Packaging Systems	67
	<i>Girilal M and Jyothi K. Nair</i>	
4.1	Introduction	67
4.2	Source of Cellulose	68
4.3	Cellulose Structure	68
4.4	Properties of Cellulose	70
4.5	Nanocellulose	70
4.5.1	Types of Nanocellulose	71
4.5.1.1	Cellulose Nanofibrils	71
4.5.1.2	Cellulose Nanofibers	72
4.5.1.3	Cellulose Nanowhiskers	72
4.5.1.4	Cellulose Nanoballs	72
4.5.1.5	Cellulose Nanocrystals	72

4.5.2	Properties of Nanocellulose	72
4.5.2.1	Mechanical Properties	73
4.5.2.2	Barrier Properties	73
4.5.2.3	Water Vapor Properties	73
4.5.2.4	Other Properties	73
4.5.3	Synthesis of Nanocellulose	74
4.5.3.1	Electrospinning	74
4.5.3.2	Extrusion	76
4.5.3.3	Casting	76
4.5.3.4	Paper Making Process Using Filtration	76
4.5.3.5	Coating Process	77
4.6	Nanocellulose as Packaging Material	77
4.7	Comparison of Nanocellulose and Cellulose	81
4.8	Disadvantages of Using Nanocellulose in Food Packaging	82
4.9	Conclusions	84
	References	84

5 Chitosan-Based Nanoparticles and Their Applications in Food Industry 87

Basant E. Elsaied and Ahmed A. Tayel

5.1	Introduction	87
5.2	Chitosan	88
5.2.1	Chitosan Precursor: Chitin Origins	88
5.2.1.1	Terrestrial Sources	88
5.2.1.2	Aquatic Sources	89
5.2.1.3	Microbiological Sources	89
5.2.2	Chemical Composition and Properties	90
5.2.2.1	Structural Properties	90
5.2.2.2	Physicochemical Properties	91
5.2.2.3	Diverse Properties	92
5.2.3	Preparation Methods and Manufacturing	92
5.2.4	Chitosan Modifications	93
5.2.5	Overview of Chitosan Applications	94
5.2.5.1	Food and Beverage Industry	94
5.2.5.2	Aquaculture	94
5.2.5.3	Pharmacy and Cosmetics	97
5.2.5.4	Dentistry	97
5.3	Nanoforms of Chitosan	97
5.3.1	Chitosan Nanocomposites	97
5.3.2	Chitosan Nanocarriers	97
5.3.3	Preparation Methods	98
5.3.3.1	Ionic Gelation Method	98
5.3.3.2	Reverse Micellar Method	98
5.3.3.3	Emulsion-Based Solvent Evaporation Method	98
5.3.3.4	Coprecipitation Method	98

5.3.4	Characterization Techniques	98
5.3.4.1	UV-Visible Spectroscopy (Spectroscopic Analysis)	98
5.3.4.2	Electron Microscopy (EM)	99
5.3.4.3	Dynamic Light Scattering (DLS)	99
5.3.4.4	Zeta Potential (ZP)	100
5.3.5	Overview of Applications	100
5.3.5.1	Tissue Engineering	100
5.3.5.2	Water Treatment	100
5.3.5.3	Agriculture	100
5.3.5.4	Drug Delivery	100
5.4	Chitosan-Based Nanoforms Applications in Food Industry	101
5.4.1	Opportunities in Food Processing	101
5.4.1.1	Chitosan-Based Nanoparticles: Enhancing Food Taste and Appearance	102
5.4.1.2	Chitosan-Based Nanoparticles: Maintaining Nutritional Value	103
5.4.2	Opportunities in Food Packaging	108
5.4.2.1	Chitosan Nanoforms Functionality as Food Packaging Materials	108
5.4.2.2	Chitosan-Based Nanoparticles Toxicity and Fate in Human Body	114
5.5	Updated Regulations in Application of Chitosan-Based Nanoparticles in Food	116
	References	117

6 Nutrients-Based Nanocarriers and Its Application in Packaging Systems 129

Leidy T. Sanchez, N. David Rodriguez-Marin, Magda I. Pinzon, and Cristian C. Villa

6.1	Lipid-Based Nanocarrier	129
6.1.1	Nanoemulsions	130
6.1.2	Nanoliposomes	130
6.1.3	Solid Lipid Nanoparticles (SLNps)	132
6.1.4	Nanostructured Lipid Carriers (NLCs)	132
6.2	Carbohydrate-Based Nanocarriers	132
6.2.1	Starch Nanoparticles (SNPs) and Nanocrystals (SNCs)	133
6.2.2	Chitosan Nanoparticles	133
6.2.3	Alginate Nanoparticles	133
6.3	Protein-Based Nanocarriers	134
6.4	Applications of Nanocarriers in Active and Bioactive Food Packaging	134
6.5	Outlooks and Perspectives	135
	References	136

7 Active Packaging Systems Based on Metal and Metal Oxide Nanoparticles 143

Lina F. Ballesteros, Hafsae Lamsaf, Sebastian Calderon V, Miguel A. Cerqueira, Lorenzo Pastrana, and José A. Teixeira

List of Abbreviations 143

7.1	Introduction	144
7.2	Metal and Metal Oxide Nanoparticles Used in Active Food Packaging	145
7.3	Methods of Production of Metal and Metal Oxide Nanoparticles	147
7.3.1	Physical Synthesis	147
7.3.2	Chemical Synthesis	148
7.3.3	Biological Synthesis	149
7.4	Incorporation of Metal and Metal Oxide Nanoparticles into Food Packaging Materials	149
7.4.1	Extrusion	150
7.4.2	Casting	150
7.4.3	Physical Vapor Deposition	151
7.4.4	Electrospinning	151
7.5	Effect of Metal and Metal Oxide Nanoparticles on Active Packaging Properties	152
7.5.1	Structure	152
7.5.2	Morphology	153
7.5.3	Mechanical Properties	155
7.5.4	Barrier Properties	156
7.5.5	Antimicrobial Activity	157
7.5.5.1	Silver Nanoparticles	157
7.5.5.2	Zinc Oxide Nanoparticles	159
7.5.5.3	Copper and Copper Oxide Nanoparticles	160
7.5.5.4	Titanium Dioxide Nanoparticles	160
7.5.5.5	Gold Nanoparticles	161
7.5.5.6	Other Nanoparticle Systems	161
7.5.6	Scavenger Properties	161
7.5.7	Photocatalytic Properties	162
7.5.8	Optical Properties	163
7.6	Migration of Nanoparticles	163
7.6.1	Food Safety and Regulations	164
7.6.2	Regulation	165
7.7	Environmental Impact of Active Food Packaging Materials	166
7.7.1	Biodegradability	166
7.7.2	Recyclability	167
7.7.3	Life Cycle Assessment	167
7.8	Conclusions and Future Trends	168
	Acknowledgments	168
	References	169
8	Fabrication of Intelligent Packaging Systems Using Nano-Indicators and Sensors	183
	<i>Xiuting Hu and Ming Miao</i>	
8.1	Introduction of Intelligent Packaging	183
8.2	Nanoparticle-Based Temperature Indicators	185
8.2.1	Silver Nanoparticle-Based TTI	185

8.2.2	Gold Nanoparticle-Based TTIs	187
8.2.3	Polydiacetylene/Silica Nanocomposite-Based TTI	188
8.2.4	Nanofiber-Based TTIs	189
8.3	Nanomaterial-Based Humidity Sensors	190
8.3.1	ZnO Nanoparticle-Based Humidity Sensors	190
8.3.2	Other Metallic Nanoparticle-Based Humidity Sensors	191
8.3.3	Polymeric Nanocomposite-Based Humidity Sensors	192
8.4	Nanomaterial-Based pH Indicators and Sensors	193
8.5	Nanoparticle-Based O ₂ Indicators	195
8.6	Nanomaterial-Based CO ₂ Sensors	197
8.7	Nanomaterial-Based Freshness Sensors	198
8.7.1	Freshness Sensors Based on Detection of Biogenic Amines	199
8.7.2	Freshness Sensors Based on Detection of Biogenic Sulfides	201
8.7.3	Freshness Sensors Based on Detection of ATP Degradation Products	202
8.8	Conclusions and Perspectives	205
	References	206

9 Nanostructure-Based Edible Coatings as a Function of Food Preservation 213

Anna Rafaela C. Braga, Josemar G. Oliveira Filho, Ailton C. Lemes, and Mariana B. Egea

9.1	Nanotechnology in Food Packaging: Principles and Applications	213
9.2	Edible Coatings	215
9.2.1	Chemical Characteristics of Edible Coatings	215
9.2.2	Methods to Apply Edible Coatings	216
9.2.3	Materials Used in the Edible Coatings	217
9.2.4	Incorporation of Nanomaterials in Edible Coatings	218
9.3	Safety of Nanocomposite for Application of Edible Coatings	223
9.4	Nanotechnology Regulation	225
9.5	Final Considerations and Outlook	227
	References	227

10 An Overview of Higher Barrier Packaging Using Nanoadditives 235

Johnsy George, Basheer Aaliya, Kappat V. Sunooj, and Ranganathan Kumar

10.1	Introduction	235
10.2	Gas and Moisture Permeability Through Polymer Packaging Materials	236
10.2.1	Permeability of Oxygen and Carbon Dioxide	237
10.2.2	Permeability of Moisture	238
10.3	Nanoadditives for Improving Barrier Properties	238
10.4	Methods to Prepare High Barrier Packaging Materials	239
10.4.1	Polymer Nanocomposites	239
10.4.2	Coating	240

10.4.3	Layer-by-Layer Assembly	240
10.5	Barrier Improvement by Reinforcement of Polymer Nanocomposites with Inorganic Nanoadditives	242
10.5.1	Metal and Metal Oxides Nanomaterials	243
10.5.1.1	Zinc	243
10.5.1.2	Magnesium	244
10.5.1.3	Silica	244
10.5.1.4	Titanium	245
10.5.1.5	Copper	246
10.5.1.6	Aluminum Oxide	246
10.5.2	Nanoclays	246
10.5.3	Carbon-Based Nanomaterials	248
10.6	Barrier Improvement of Biopolymers by Reinforcement with Organic Nanoadditives	249
10.6.1	Cellulose	250
10.6.2	Starch	252
10.6.3	Chitosan	253
10.6.4	Zein	253
10.6.5	Gelatin	254
10.6.6	Whey Protein Isolates	254
10.6.7	Soy Protein Isolates	255
10.7	Conclusion	255
	References	256
11	Nanostructure-Based Multilayer Food Packaging Films	265
	<i>Shiji Mathew</i>	
11.1	Introduction	265
11.2	Requirements of Food Packaging Systems	266
11.3	Multilayer Packaging Films	267
11.4	Structure and Functions of Multilayer Film Packaging	268
11.5	Nanotechnology-Based Multilayer Films	269
11.6	Preparation of Nano-Based Multilayer Films	269
11.6.1	Layer-by-Layer (LbL) Nanoassembly	270
11.6.2	Electrohydrodynamic Processing (EHDP)	271
11.6.3	Multilayer Coextrusion Technique	275
11.7	Practical Applications of Multilayer Films/Coatings for Packaging of Food	276
11.8	Conclusion and Future Outlook	276
	References	278
12	Characterization Techniques for Nanostructures in Food Packaging	285
	<i>Ashitha Jose, R. Aswani, and Radhakrishnan E. Krishnankutty</i>	
12.1	Introduction	285
12.2	Nanoparticles	286

12.3	Role of Nanoparticles in Packaging Applications	287
12.4	Nanocomposite in Food Packaging	288
12.5	Methods for the Development of Nanocomposites	288
12.6	Various Nanoparticles Employed in Packaging	289
12.6.1	Nanoclay	290
12.6.2	Titanium Dioxide	290
12.6.3	Zinc Oxide Nanoparticles	291
12.6.4	Graphene-Based Nanomaterials	291
12.6.5	Silver Nanoparticles	292
12.7	Issues Associated with the Nanoparticle Incorporation	292
12.8	Characterization of Nanoparticles in the Packaging Materials	293
12.8.1	FTIR	294
12.8.2	Electron Microscopic Techniques	296
12.8.2.1	Scanning Electron Microscopy	296
12.8.2.2	Transmission Electron Microscopy	297
12.8.3	Thermal Analysis of the Packaging Material Containing Nanoparticles	299
12.8.4	X-Ray Photoelectron Spectroscopy	300
12.8.5	XRD	300
12.8.6	ICPMS	301
12.8.7	Raman Spectroscopy	302
12.9	Conclusions	302
	References	302
13	Biodegradability Assessment of Biopolymer-Based Films	307
	<i>Andrelina Maria Pinheiro Santos, Betty Del Carmen Jarma Arroyo, Luana de Souza Cavalcante Carnaval, and Enayde de Almeida Melo</i>	
13.1	Introduction	307
13.2	Commercial and Renewable Biodegradable Polymers and Plasticizers	308
13.2.1	Thermoplastic Starch (TPS)	309
13.2.2	Polylactic Acid (PLA)	310
13.2.3	Polyhydroxyalkanoates (PHAs)	310
13.2.4	Plasticizers	311
13.3	Biodegradation Mechanism	312
13.4	Biodegradation of Biopolymers with Additives	314
13.5	Considerations	316
	References	317
14	Nanobiotechnology in Food Preservation and Molecular Perspective	327
	<i>S. Agriopoulou, E. Stamatelopoulou, V. Skiada, and T. Varzakas</i>	
14.1	Introduction	327
14.2	Nanobiotechnology Aspects in Food Preservation and Food Packaging	328

14.3	Classification of Nanomaterials and Molecular Basis of Application	329
14.3.1	Nanoparticles	330
14.3.1.1	Silver-Based Nanoparticles	330
14.3.1.2	Titanium Dioxide (TiO ₂) Nanoparticles	331
14.3.1.3	Zinc Oxide (ZnO) Nanoparticles	331
14.3.2	Nanocomposites	331
14.3.2.1	Cellulose-Based Nanocomposites	331
14.3.2.2	Chitosan-Based Nanocomposites	332
14.3.2.3	Protein-Derived Bionanocomposites	332
14.3.2.4	Polylactic Acid Nanobiocomposites	333
14.3.3	Nanoclays	334
14.3.4	Nanoemulsions	334
14.3.5	Nanosensors	334
14.3.6	Nanostructures	337
14.4	Nanomaterials and Active and Intelligent Food Packaging Applications	338
14.4.1	Active Packaging	338
14.4.2	Intelligent (“Smart”) Packaging	339
14.5	Nanomaterials and Postharvest Quality Parameters	341
14.5.1	Edible Coatings and Films in Food Packaging	341
14.5.2	Nanomaterials and the Potential against Postharvest Disease and Ethylene Production	342
14.6	Regulations and Safety Aspects	345
14.7	Conclusions and Outlook	347
	References	347
15	Environmental and Toxicological Aspects of Nanostructures in Food Packaging	361
	<i>Sabarish Radoor, Jasila Karayil, Jyothi M. Shivanna, Aswathy Jayakumar, Sandhya A. Varghese, Radhakrishnan E. Krishnankutty, Jyotishkumar Parameswaranpillai, and Suchart Siengchin</i>	
15.1	Introduction	361
15.2	Nanoparticles in Food Packaging	362
15.2.1	Nanoclay	362
15.2.2	Nanosilver	362
15.2.3	Zinc Oxide (ZnO) NP	363
15.2.4	Titanium Dioxide (TiO ₂)	363
15.2.5	Silicon Dioxide (SiO ₂)	363
15.3	Toxicity Measurement of Nanoparticles Used in Food Industry	364
15.4	Nanotoxicity	365
15.4.1	Silver Nanoparticles (Ag NPs)	365
15.4.2	Titanium Nanoparticles (TiO ₂ NPs)	366
15.4.3	Silica Nanoparticle	367
15.4.4	Clay Nanoparticle	368

15.5	Migration Issues of Nanoparticles	369
15.6	Environmental Impacts of Nanoparticles	370
15.7	Conclusion	371
	Acknowledgments	371
	References	371
	Index	379