

TABLE OF CONTENTS

1 INTRODUCTION	26
1.1 Aims and objectives of the study	26
1.2 Market definition.....	26
1.2.1 Properties of nanomaterials	27
1.2.2 Categorization.....	28
2 RESEARCH METHODOLOGY	30
3 EXECUTIVE SUMMARY.....	31
3.1 Antimicrobial additives and coatings market growing	31
3.1.1 Advantages	31
3.1.2 Properties	32
3.1.3 Applications.....	32
3.2 Nanocoatings	33
3.3 Antimicrobial and anti-viral coatings and surfaces.....	36
3.3.1 Self-cleaning antimicrobial coatings and surfaces	36
3.3.1.1 Bionic self-cleaning coatings	36
3.3.1.2 Photocatalytic self-cleaning coatings.....	38
3.3.1.3 Anti-fouling and easy-to-clean nanocoatings.....	40
3.3.2 Anti-viral coatings and surfaces.....	42
3.3.3 Nanomaterials applications	44
3.3.4 Cleanliness of indoor and public areas driving demand for antimicrobials	45
3.4 Anti-viral coatings.....	46
3.4.1 Reusable Personal Protective Equipment (PPE).....	48
3.4.2 Wipe on coatings.....	48
3.4.3 Facemask coatings	48
3.4.4 Long-term mitigation of surface contamination with nanocoatings.....	49
3.5 Main market players by antimicrobial technology area	50

3.6	Global market size and opportunity to 2033	51
3.6.1	End user markets for antimicrobial coatings	51
3.6.2	Global forecast for antimicrobial coatings to 2033	52
3.7	Market and technical challenges	55
3.8	Market drivers and trends.....	56

4 ADVANCED MATERIALS USED IN ANTI-MICROBIAL COATINGS 61

4.1	Metallic-based coatings.....	61
4.2	Polymer-based coatings.....	61
4.3	Antimicrobial nanomaterials	62
4.4	Organic nanoparticles	64
4.4.1	Types and properties	65
4.5	Nanocoatings	67
4.5.1	Properties of nanocoatings.....	67
4.5.2	Benefits of using nanocoatings.....	68
4.5.2.1	Types of nanocoatings	69
4.5.3	Production and synthesis methods.....	69
4.5.3.1	Depositing functional nanocomposite films.....	69
4.5.3.2	Film coatings techniques analysis	70
4.5.3.3	Superhydrophobic coatings on substrates.....	72
4.5.3.4	Electrospray and electrospinning	73
4.5.3.5	Chemical and electrochemical deposition	74
4.5.3.6	Aerosol coating	77
4.5.3.7	Layer-by-layer Self-assembly (LBL)	77
4.5.3.8	Sol-gel process	79
4.5.3.9	Etching.....	81
4.6	Nanosilver and silver-ion antimicrobial coatings and additives	82
4.6.1	Properties	82
4.6.1.1	Antiviral properties of AgNPs	83

4.6.2	Mode of action	85
4.6.3	Environmental and safety considerations	87
4.6.4	SWOT analysis	88
4.6.5	Products and applications	88
4.6.5.1	Silver nanocoatings.....	88
4.6.5.2	Antimicrobial silver paints.....	89
4.6.6	Markets	89
4.6.6.1	Textiles	90
4.6.6.2	Wound dressings and medical	90
4.6.6.3	Consumer products.....	90
4.6.6.4	Air filtration.....	91
4.6.7	Companies.....	91
4.7	Photocatalytic coatings (Titanium Dioxide).....	93
4.7.1	Development of photocatalytic coatings	94
4.7.1.1	Market drivers and trends.....	94
4.7.2	Mode of action	96
4.7.3	Glass coatings	97
4.7.4	Interior coatings	98
4.7.5	Improving indoor air quality	98
4.7.6	Disinfecting paints & coatings	99
4.7.7	Applications.....	100
4.7.7.1	Coatings.....	101
4.7.7.2	Non-coatings applications	107
4.7.8	Other metal based photocatalysts	109
4.7.8.1	ZNO	109
4.7.8.2	Bi-based photocatalysts	109
4.7.8.3	Binary or Ternary sulfides	109
4.7.8.4	Metal-organic frameworks (MOFs)	110
4.7.8.5	WO ₃	111

4.7.9	Metal free photocatalysts	111
4.7.9.1	Carbon nitride g-C ₃ N ₄	112
4.7.9.2	Silica carbide (SiC).....	113
4.7.9.3	Graphene oxide	113
4.7.9.4	Transition-metal dichalcogenide MoS ₂	113
4.7.9.5	Germanene.....	113
4.7.9.6	Graphdiyne	115
4.7.9.7	Bismuth oxychloride (BiOCl)	116
4.7.9.8	Black phosphorus.....	117
4.8	Zinc oxide coatings and additives.....	118
4.8.1	Properties	118
4.8.2	Mode of action	119
4.8.3	Application in antimicrobial coatings.....	119
4.9	Quaternary ammonium silane	122
4.9.1	Mode of action	122
4.9.2	Application in antimicrobial coatings.....	122
4.9.3	Companies.....	122
4.10	Bio-based antimicrobial coatings	124
4.10.1	Chitosan.....	124
4.10.1.1	Properties	124
4.10.1.2	Application in antimicrobial coatings.....	125
4.10.2	Antimicrobial peptide (AMP) coatings.....	127
4.10.2.1	Properties	127
4.10.2.2	Mode of action	127
4.10.2.3	Application in antimicrobial coatings.....	127
4.10.3	Nanocellulose (Nanocrystalline, Nanofibrillated, and Bacterial Cellulose)	130
4.10.3.1	Properties	130
4.10.3.2	Application in anti-microbial and anti-viral nanocoatings.....	131
4.10.4	Adaptive biomaterials.....	132

4.10.4.1	Properties	132
4.10.4.2	Application in antimicrobial coatings.....	132
4.11	Copper antimicrobial coatings and additives.....	133
4.11.1	Properties	133
4.11.2	Mode of action	134
4.11.3	SWOT analysis	135
4.11.4	Application in antimicrobial coatings.....	136
4.11.5	Companies.....	136
4.12	Gold nanoparticles (AuNPs)	137
4.12.1	Properties	137
4.12.2	Mode of action	137
4.13	Hydrogels	140
4.13.1	Properties	140
4.13.2	Application in antimicrobial coatings.....	140
4.14	Antibacterial liquid metals	142
4.14.1	Properties	142
4.15	Two-dimensional (2D) materials	143
4.15.1	Black phosphorus (BP)	143
4.15.2	Layered double hydroxides (LDHs)	143
4.15.3	Transition metal dichalcogenides (TMDs)	144
4.15.4	Graphitic carbon nitride (g-C ₃ N ₄).....	145
4.15.5	MXENE	145
4.16	Hydrophobic and hydrophilic coatings and surfaces	147
4.16.1	Hydrophilic coatings	147
4.16.2	Hydrophobic coatings.....	147
4.16.2.1	Properties	148
4.16.2.2	Application in facemasks.....	148
4.17	Superhydrophobic coatings and surfaces	149
4.17.1	Properties	149

4.17.1.1	Anti-microbial use.....	150
4.17.1.2	Durability issues.....	151
4.17.1.3	Nanocellulose	151
4.18	Oleophobic and omniphobic coatings and surfaces	152
4.18.1	SLIPS.....	152
4.18.2	Covalent bonding	153
4.18.3	Step-growth graft polymerization.....	153
4.18.4	Applications.....	153
4.19	Other advanced antimicrobial materials and additives in coatings	155
4.19.1	Graphene.....	155
4.19.1.1	Properties	155
4.19.1.2	Graphene oxide	157
4.19.1.3	Anti-bacterial activity	157
4.19.1.4	Reduced graphene oxide (rGO)	158
4.19.1.5	Application in antimicrobial coatings.....	159
4.19.1.6	Companies.....	159
4.19.2	Silicon dioxide/silica nanoparticles (Nano-SiO ₂)	161
4.19.2.1	Properties	161
4.19.2.2	Application in antimicrobial coatings.....	162
4.19.3	Polyhexamethylene biguanide (PHMB)	163
4.19.3.1	Properties	163
4.19.3.2	Application in antimicrobial coatings.....	163
4.19.4	Single-walled carbon nanotubes (SWCNTs)	163
4.19.4.1	Properties	163
4.19.4.2	Application in antimicrobial coatings.....	163
4.19.5	Fullerenes	164
4.19.5.1	Properties	164
4.19.5.2	Application in antimicrobial coatings.....	165
4.19.6	Cerium oxide nanoparticles.....	166

4.19.6.1	Properties	166
4.19.7	Iron oxide nanoparticles	167
4.19.7.1	Properties	167
4.19.8	Nitric oxide (NO) nanoparticles.....	168
4.19.8.1	Properties	168
4.19.8.2	Application in anti-microbial and anti-viral coatings	168
4.19.9	Aluminium oxide (Al ₂ O ₃) nanoparticles.....	169
4.19.9.1	Properties	169
4.19.9.2	Application in anti-microbial and anti-viral coatings	169
4.19.10	Magnesium oxide nanoparticles	170
4.19.10.1	Properties	170
4.19.11	Piezoelectrics	170
5	ENVIRONMENTAL AND REGULATORY	172
6	MARKETS FOR ADVANCED ANTIMICROBIAL COATINGS AND SURFACES.....	174
6.1	HOUSEHOLD AND INDOOR SURFACES.....	174
6.1.1	Market drivers and trends.....	174
6.1.2	Applications.....	174
6.1.2.1	Self-cleaning and easy-to-clean	174
6.1.2.2	Indoor pollutants and air quality.....	174
6.1.3	Global market size	176
6.2	MEDICAL & HEALTHCARE SETTINGS	178
6.2.1	Market drivers and trends.....	178
6.2.2	Applications.....	179
6.2.2.1	Medical surfaces and Hospital Acquired Infections (HAI)	180
6.2.2.2	Wound dressings	181
6.2.2.3	Medical equipment and instruments.....	181
6.2.2.4	Fabric supplies scrubs, linens, masks (medical textiles).....	182
6.2.2.5	Medical implants	182

6.2.3 Global market size 184

6.3 CLOTHING AND TEXTILES 186

6.3.1 Market drivers and trends..... 186

6.3.2 Applications..... 186

6.3.2.1 Antimicrobial clothing 187

6.3.3 Global market size 192

6.4 FOOD & BEVERAGE PRODUCTION AND PACKAGING..... 195

6.4.1 Market drivers and trends..... 195

6.4.2 Applications..... 196

6.4.2.1 Antimicrobial coatings in food processing equipment, conveyor belts and preparation surfaces 196

6.4.2.2 Antimicrobial coatings and films in food packaging..... 197

6.4.3 Global market size 198

6.5 OTHER MARKETS 200

6.5.1 Automotive and transportation interiors 200

6.5.2 Water and air filtration 202

**7 ADVANCED ANTIMICROBIAL COATINGS AND TECHNOLOGIES
COMPANIES..... 205**

7.1 [REDACTED] 205

7.2 [REDACTED] 206

7.3 [REDACTED] 206

7.4 [REDACTED] 207

7.5 [REDACTED] 208

7.6 [REDACTED] 208

7.7 [REDACTED] 209

7.8 [REDACTED] 210

7.9 [REDACTED] 211

7.10 [REDACTED] 212

7.11 [REDACTED] 212

7.12	██████████	.....	213
7.13	██████████	.....	214
7.14	██████████	.....	215
7.15	██████████	.....	216
7.16	██████████	.....	217
7.17	██████████	.....	217
7.18	██████████	.....	218
7.19	██████████	.....	219
7.20	██████████	.....	219
7.21	██████████	.....	220
7.22	██████████	.....	221
7.23	██████████	.....	221
7.24	██████████	.....	222
7.25	██████████	.....	222
7.26	██████████	.....	223
7.27	██████████	.....	224
7.28	██████████	.....	225
7.29	██████████	.....	226
7.30	██████████	.....	226
7.31	██████████	.....	227
7.32	██████████	.....	228
7.33	██████████	.....	229
7.34	██████████	.....	230
7.35	██████████	.....	230
7.36	██████████	.....	231
7.37	██████████	.....	232
7.38	██████████	.....	232
7.39	██████████	.....	233
7.40	██████████	.....	234

7.41	.....	235
7.42	.....	236
7.43	.....	236
7.44	.....	237
7.45	.....	238
7.46	.....	238
7.47	.....	239
7.48	.....	240
7.49	.....	240
7.50	.....	242
7.51	.....	242
7.52	.....	243
7.53	.....	243
7.54	.....	244
7.55	.....	245
7.56	.....	245
7.57	.....	246
7.58	.....	246
7.59	.....	247
7.60	.....	247
7.61	.....	248
7.62	.....	249
7.63	.....	250
7.64	.....	250
7.65	.....	251
7.66	.....	252
7.67	.....	252
7.68	.....	253
7.69	.....	254

7.70	.....	255
7.71	.....	256
7.72	.....	256
7.73	.....	257
7.74	.....	258
7.75	.....	259
7.76	.....	260
7.77	.....	260
7.78	.....	261
7.79	.....	263
7.80	.....	263
7.81	.....	264
7.82	.....	265
7.83	.....	266
7.84	.....	266
7.85	.....	267
7.86	.....	268
7.87	.....	269
7.88	.....	269
7.89	.....	270
7.90	.....	271
7.91	.....	272
7.92	.....	273
7.93	.....	274
7.94	.....	275
7.95	.....	276
7.96	.....	277
7.97	.....	278
7.98	.....	278

7.99	.....	279
7.100	.....	280
7.101	.....	280
7.102	.....	281
7.103	.....	282
7.104	.....	282
7.105	.....	283
7.106	.....	284
7.107	.....	284
7.108	.....	285
7.109	.....	286
7.110	.....	288
7.111	.....	288
7.112	.....	289
7.113	.....	290
7.114	.....	291
7.115	.....	291
7.116	.....	292
7.117	.....	293
7.118	.....	294
7.119	.....	295
7.120	.....	295
7.121	.....	296
7.122	.....	297
7.123	.....	297
7.124	.....	299
7.125	.....	300
7.126	.....	300
7.127	.....	301

7.128	████████████████████	302
7.129	████████████████████████████	303
7.130	████████████████████████████	303
7.131	████████████████	304
7.132	████████████████	305
7.133	████████████████	305
7.134	████████████████████	306
7.135	████████████	307
7.136	████████████████████	308
7.137	████████████████████████	308
7.138	████████████████████████	309
7.139	████████████████	310
7.140	████████████	311
7.141	████████████	312
7.142	██████	313
7.143	████████████	313
7.144	████████████████████████	314
7.145	████████████████████	316
7.146	████████████████	317
7.147	████████████████████	318
7.148	████████████████████████	318
7.149	████████████	319
7.150	████████████████████	321
7.151	████████████	321
7.152	████████████████	322
7.153	████████████	323
7.154	████████████████████████████	324
7.155	████████████████	324
7.156	████████████████████	325

7.157	██████████	.....	326
7.158	██████████	.....	326
7.159	██████████	.....	327
7.160	██████████	.....	328
7.161	██████████	.....	329
7.162	██████████	.....	330
7.163	██████████	.....	331
7.164	██████████	.....	331
7.165	██████████	.....	332
7.166	██████████	.....	333
7.167	██████████	.....	333
7.168	██████████	.....	334
7.169	██████████	.....	335
7.170	██████████	.....	335
7.171	██████████	.....	336
7.172	██████████	.....	337
7.173	██████████	.....	338
7.174	██████████	.....	338
7.175	██████████	.....	339
7.176	██████████	.....	339
7.177	██████████	.....	340
7.178	██████████	.....	341
7.179	██████████	.....	341
7.180	██████████	.....	342
7.181	██████████	.....	343
7.182	██████████	.....	343
7.183	██████████	.....	344
7.184	██████████	.....	344
7.185	██████████	.....	345

7.186	██████████	346
7.187	██████████████	347
7.188	██████████████	347
7.189	██████████████████	348
7.190	████	349
7.191	██████████████	349
7.192	██████████████████	350
7.193	██████████████████	351
7.194	████	352
7.195	██████████████	353
7.196	████	353
7.197	██████████████	354
7.198	██████████████	355
7.199	██████████████████	356
7.200	██████████████	357
7.201	██████████████	358
7.202	██████████████	358
7.203	██████████████	359
7.204	██████████	360
7.205	██████████████	360
7.206	██████████████████	362
7.207	████	363

8 REFERENCES 365

LIST OF TABLES

Table 1: Categorization of nanomaterials.....	28
Table 2: Properties of nanocoatings.	34
Table 3. Summary for bionic self-cleaning nanocoatings.	36

Table 4. Market summary for photocatalytic self-cleaning coatings.....	38
Table 5. Summary of anti-fouling and easy-to-clean coatings.	40
Table 6. Anti-viral nanomaterials that inactivate different types of viruses, in preclinical assays in vitro.	43
Table 7. Applications of nanomaterials used in Advanced Bactericidal & Viricidal Coatings and Surfaces..	44
Table 8. Main market players by antimicrobial technology area.....	50
Table 9. End user markets for antimicrobial coatings.....	51
Table 10. Total global revenues for antimicrobial coatings, 2018-2033, millions USD.....	52
Table 11. Total global revenues for antimicrobial coatings, 2018-2033, millions USD, conservative estimate, by coatings type.	54
Table 12. Market and technical challenges for antimicrobial coatings.	55
Table 13. Market drivers and trends in.....	56
Table 14: Nanomaterials used in nanocoatings and applications.....	62
Table 15. Types of organic nanoparticles and application in antimicrobials.	65
Table 16: Technology for synthesizing nanocoatings agents.....	69
Table 17: Film coatings techniques.....	70
Table 18. Antibacterial properties of AgNPs.	82
Table 19. Antiviral properties of AgNPs.	84
Table 20. SWOT analysis for application of nanosilver and silver-ion antimicrobial coatings.	88
Table 21. Markets and applications for nanosilver-based Advanced Bactericidal & Viricidal Coatings and Surfaces.....	89
Table 22. Companies developing antimicrobial silver nanocoatings.	91
Table 23. Photocatalytic coatings- principles, properties and applications.	93
Table 24. Development of photocatalytic coatings, by generation.....	94
Table 25. Photocatalysts used in building materials to reduce pollution.....	104
Table 26. Properties and applications of functionalized germanene.....	115
Table 27. Antibacterial effects of ZnO NPs in different bacterial species.	120
Table 28. Companies developing antimicrobial Silane Quaternary Ammonium Compounds.	122
Table 29. Mechanism of chitosan antimicrobial action.	125
Table 30. Types of antibacterial AMP coatings.	128
Table 31. AMP contact-killing surfaces.....	128

Table 32. Types of adaptive biomaterials in antimicrobial coatings.....	132
Table 33. Antibacterial applications of Cu and CuO-based nanoparticles.	133
Table 34. SWOT analysis for application of copper antimicrobial coatings.....	135
Table 35. Companies developing antimicrobial copper coatings.....	136
Table 36. Antibacterial applications of Au-based nanoparticles.	137
Table 37. Types of antibacterial hydrogels.....	140
Table 38: Contact angles of hydrophilic, super hydrophilic, hydrophobic and superhydrophobic surfaces.	148
Table 39: Disadvantages of commonly utilized superhydrophobic coating methods.	150
Table 40: Applications of oleophobic & omniphobic coatings.....	153
Table 41. Types of carbon-based nanoparticles as antimicrobial agent, their mechanisms of action and characteristics.	155
Table 42. Graphene properties relevant to application in coatings.....	156
Table 43. Bactericidal characters of graphene-based materials.....	158
Table 44. Markets and applications for antimicrobial and antiviral graphene coatings.	159
Table 45. Commercial activity in antimicrobial and antiviral graphene nanocoatings.	159
Table 46. Types of carbon-based nanoparticles as antimicrobial agent, their mechanisms of action and characteristics.	165
Table 47. Global antimicrobial technology regulations.	172
Table 48: Market drivers and trends for antimicrobial coatings in household and indoor surface market. .	174
Table 49. Global market for antimicrobial coatings in household and indoor surfaces 2018-2033, by revenues and types (millions USD).	176
Table 50: Market drivers and trends for antimicrobial coatings in medicine and healthcare.	178
Table 51: Nanocoatings applied in the medical industry-type of coating, nanomaterials utilized, benefits and applications.	180
Table 52. Types of advanced antimicrobial medical device coatings.	182
Table 53. Types of advanced coatings applied in medical implants.	183
Table 54. Nanomaterials utilized in medical implants.....	183
Table 55. Global market for antimicrobial coatings in medical and healthcare settings to 2033, by revenues and types (millions USD).....	185
Table 56: Market drivers and trends for antimicrobial coatings in the textiles and apparel industry.....	186

Table 57. Applications in textiles, by advanced materials type and benefits thereof.....	188
Table 58. Advanced coatings applied in the textiles industry-type of coating, nanomaterials utilized, benefits and applications.	189
Table 59. Global market for antimicrobial coatings in clothing and textiles 2018-2033, by revenues and types (millions USD).....	193
Table 60. Market drivers and trends for antimicrobial coatings in the packaging market.....	195
Table 61. Global market for antimicrobial coatings in food and beverage production & packaging to 2033, by revenues and types (millions USD).....	198
Table 62. Advanced coatings applied in the automotive industry.....	200
Table 63. Applications in air and water filters, by advanced materials type and benefits thereof.....	203
Table 64. Photocatalytic coating schematic.	251

LIST OF FIGURES

Figure 1. Self-cleaning superhydrophobic coating schematic.	38
Figure 2. Principle of superhydrophilicity.	39
Figure 3. Schematic of photocatalytic air purifying pavement.	40
Figure 4. Schematic of anti-viral coating using nano-actives for inactivation of any adhered virus on the surfaces.	43
Figure 5. Schematic of anti-viral coating using nano-actives for inactivation of any adhered virus on the surfaces.	47
Figure 6. Face masks coated with antibacterial & antiviral nanocoating.....	49
Figure 7. Global revenues for antimicrobial coatings, 2018-2033, millions USD, conservative estimate.	53
Figure 8. Total global revenues for Advanced Bactericidal & Viricidal Coatings, 2018-2033, millions USD, conservative estimate, by coatings type.	55
Figure 9: Hydrophobic fluoropolymer nanocoatings on electronic circuit boards.	67
Figure 10: Nanocoatings synthesis techniques.....	70
Figure 11: Techniques for constructing superhydrophobic coatings on substrates.....	72
Figure 12: Electrospray deposition.....	74
Figure 13. CVD technique.	75
Figure 14. Schematic of ALD.....	77

Figure 15. A substrate undergoing layer-by-layer (LbL) nanocoating.....	78
Figure 16. SEM images of different layers of TiO ₂ nanoparticles in steel surface.....	78
Figure 17. The coating system is applied to the surface. The solvent evaporates.....	80
Figure 18. A first organization takes place where the silicon-containing bonding component (blue dots in figure 2) bonds covalently with the surface and cross-links with neighbouring molecules to form a strong three-dimensional.....	80
Figure 19. During the curing, the compounds organise themselves in a nanoscale monolayer. The fluorine-containing repellent component (red dots in figure) on top makes the glass hydro- phobic and oleophobic.....	80
Figure 20. Antiviral mechanism of silver nanoparticles.....	84
Figure 21. Antibacterial modes of action of, and bacterial resistance towards silver.	86
Figure 22. Antibacterial activities of silver nanoparticles.	87
Figure 23. Titanium dioxide-coated glass (left) and ordinary glass (right).....	95
Figure 24. Schematic of photocatalytic indoor air purification filter.....	96
Figure 25. Schematic indoor air filtration.....	99
Figure 26. Mechanism of photocatalysis on a surface treated with TiO ₂ nanoparticles.....	99
Figure 27. Schematic showing the self-cleaning phenomena on superhydrophilic surface.	100
Figure 28. Schematic of photocatalytic air purifying pavement.....	102
Figure 29. Self-Cleaning mechanism utilizing photooxidation.	103
Figure 30. Photocatalytic oxidation (PCO) air filter.....	105
Figure 31. Mechanism of photocatalysis on a semiconductor particle surface for microbial treatment.	106
Figure 32. Schematic of photocatalytic water purification.....	108
Figure 33. Schematic showing photocatalysis and photothermal catalysis promoted by MOFs.	110
Figure 34. MOF derived nanocomposites for photocatalytic applications.....	111
Figure 35. Graphitic carbon nitride.....	112
Figure 36. Schematic of germanene.....	114
Figure 37. Graphdiyne structure.	116
Figure 38. Schematic of a monolayer of rhenium disulfide.....	116
Figure 39. Schematic of antibacterial activity of ZnO NPs.....	119
Figure 40. TEM images of Burkholderia seminalis treated with (a, c) buffer (control) and (b, d) 2.0 mg/mL chitosan; (A: additional layer; B: membrane damage).	125

Figure 41. Antimicrobial peptides mode of action.....	127
Figure 42: Types of nanocellulose.	130
Figure 43. Antibacterial modes of action of, and bacterial resistance towards copper.....	135
Figure 44. Antibacterial mechanisms and effects of functionalized gold nanoparticles.....	139
Figure 45. Applications of antibacterial hydrogels.....	140
Figure 46: Structure of 2D molybdenum disulfide.	144
Figure 47: Graphitic carbon nitride.....	145
Figure 48: (a) Water drops on a lotus leaf.....	147
Figure 49: A schematic of (a) water droplet on normal hydrophobic surface with contact angle greater than 90° and (b) water droplet on a superhydrophobic surface with a contact angle > 150°.....	148
Figure 50: Contact angle on superhydrophobic coated surface.	150
Figure 51: Self-cleaning nanocellulose dishware.	151
Figure 52: SLIPS repellent coatings.....	152
Figure 53: Omniphobic coatings.	154
Figure 54. Antimicrobial activity of Graphene oxide (GO).	157
Figure 55. Hydrophobic easy-to-clean coating.	162
Figure 56. Mechanism of antimicrobial activity of carbon nanotubes.....	164
Figure 57. Fullerene schematic.....	164
Figure 58. Schematic representation of the antibacterial mechanism of cerium-based materials.....	166
Figure 59. Piezoelectric antimicrobial mechanism.	171
Figure 60. Global market for antimicrobial coatings in household and indoor surfaces 2018-2033, by revenues and types (millions USD).	177
Figure 61. Nano-coated self-cleaning touchscreen.....	180
Figure 62. Anti-bacterial sol-gel nanoparticle silver coating.	181
Figure 63. Global market for antimicrobial coatings in medical and healthcare settings to 2033, by revenues and types (millions USD).....	185
Figure 64. Omniphobic-coated fabric.....	187
Figure 65. Global market for antimicrobial coatings in clothing and textiles 2018-2033, by revenues and types (millions USD).....	194
Figure 66. Steps during food processing and where contamination might occur from various sources.	197

Figure 67. Oso fresh food packaging incorporating antimicrobial silver.....	198
Figure 68. Global market for antimicrobial coatings in food and beverage production & packaging to 2033, by revenues and types (millions USD).....	199
Figure 69. CuanSave film.	241
Figure 70. Lab tests on DSP coatings.....	248
Figure 71. Laser-functionalized glass.	257
Figure 72. GrapheneCA anti-bacterial and anti-viral coating.....	262
Figure 73. NOx reduction with TioCem®.	268
Figure 74. Microlyte® Matrix bandage for surgical wounds.....	271
Figure 75. Self-cleaning nanocoating applied to face masks.	275
Figure 76. NanoSeptic surfaces.....	309
Figure 77. Nasc NanoTechnology personnel shown applying MEDICOAT to airport luggage carts.	316
Figure 78. Heavy bacterial recovery from untreated fiber (left) versus Ultra-Fresh antimicrobial treated fiber (right) after testing using the ISO 20743 test method (Staphylococcus aureus test organism).	350
Figure 79. V-CAT® photocatalyst mechanism.	356
Figure 80. Applications of Titanystar.....	361