

Contents

Chapter 1	Environmental Chemistry: Chemical Fate and Transport	1
1.1	What Is Environmental Science?	1
1.2	Chemistry and the Environment	1
1.3	Water, Air, Earth, Life, and Technology	2
1.3.1	Water and the Hydrosphere	3
1.3.2	Air and the Atmosphere	3
1.3.3	Earth	3
1.3.4	Life	4
1.3.5	The Anthrosphere and Technology	4
1.4	Ecology, Ecotoxicology, and the Biosphere	5
1.4.1	The Biosphere	5
1.4.2	Ecology	6
1.4.3	Ecotoxicology	6
1.5	Energy and Cycles of Energy	7
1.5.1	Light and Electromagnetic Radiation	7
1.5.2	Energy Flow and Photosynthesis in Living Systems	8
1.5.3	Energy Utilization	8
1.6	Matter and Cycles of Matter	9
1.6.1	Endogenic and Exogenic Cycles	10
1.6.2	Carbon Cycle	12
1.6.3	Nitrogen Cycle	12
1.6.4	Oxygen Cycle	13
1.6.5	Phosphorus Cycle	14
1.6.6	Sulfur Cycle	14
1.7	Human Impact and Pollution	15
1.7.1	Some Definitions Pertaining to Pollution	15
1.7.2	Pollution of Various Spheres of the Environment	17
1.8	Chemical Fate and Transport	17
1.8.1	Physical Transport	18
1.8.2	Reactivity	19
1.8.3	The Mass Balance Expression	19
1.8.4	Distribution among Phases	20
1.9	Chemical Fate and Transport in the Atmosphere, Hydrosphere, and Geosphere	20
1.9.1	Pollutants in the Atmosphere	20
1.9.2	Pollutants in the Hydrosphere	21
1.9.3	Pollutants in the Geosphere	21
	Questions and Problems	22
	Literature Cited	23
	Supplementary References	23
Chapter 2	The Anthrosphere, Environmental Chemistry, and Green Chemistry	25
2.1	The Anthrosphere	25
2.1.1	Components of the Anthrosphere	25
2.2	Technology and the Anthrosphere	26
2.2.1	Engineering	27
2.3	Infrastructure	27
2.4	Dwellings	29
2.5	Transportation	30
2.6	Communications	31

2.7	Food and Agriculture	31
2.8	Manufacturing	33
2.8.1	Automation	33
2.8.2	Robotics	34
2.8.3	Computers	34
2.9	Effects of the Anthrosphere on Earth	35
2.10	Integration of the Anthrosphere into the Total Environment	36
2.10.1	The Anthrosphere and Industrial Ecology	38
2.11	Environmental Chemistry	38
2.12	Green Chemistry	39
2.12.1	Green Synthetic Chemistry	40
2.12.2	Risk Reduction	41
2.12.3	Specific Aspects of Green Chemistry	41
2.12.4	Three Undesirable Characteristics of Chemicals: Persistence, Bioaccumulation, and Toxicity	42
2.12.5	Green Chemistry and Environmental Chemistry	42
	Questions and Problems	42
	Literature Cited	43
	Supplementary References	44
Chapter 3	Fundamentals of Aquatic Chemistry	47
3.1	The Importance of Water	47
3.1.1	Sources and Uses of Water: The Hydrologic Cycle	48
3.2	The Properties of Water, a Unique Substance	50
3.2.1	The Water Molecule	50
3.3	The Characteristics of Bodies of Water	52
3.4	Aquatic Life	53
3.5	Introduction to Aquatic Chemistry	54
3.6	Gases in Water	55
3.6.1	Oxygen in Water	55
3.7	Water Acidity and Carbon Dioxide in Water	56
3.7.1	Carbon Dioxide in Water	57
3.8	Alkalinity	60
3.8.1	Contributors to Alkalinity at Different pH Values	61
3.8.2	Dissolved Inorganic Carbon and Alkalinity	62
3.8.3	Influence of Alkalinity on CO ₂ Solubility	63
3.9	Calcium and Other Metals in Water	63
3.9.1	Hydrated Metal Ions as Acids	64
3.9.2	Calcium in Water	65
3.9.3	Dissolved Carbon Dioxide and Calcium Carbonate Minerals	65
3.10	Complexation and Chelation	67
3.10.1	Occurrence and Importance of Chelating Agents in Water	69
3.11	Bonding and Structure of Metal Complexes	70
3.11.1	Selectivity and Specificity in Chelation	70
3.12	Calculations of Species Concentrations	70
3.13	Complexation by Deprotonated Ligands	71
3.14	Complexation by Protonated Ligands	72
3.15	Solubilization of Lead Ion from Solids by NTA	74
3.15.1	Reaction of NTA with Metal Carbonate	76
3.15.2	Effect of Calcium Ion upon the Reaction of Chelating Agents with Slightly Soluble Salts	77

3.16	Polyphosphates and Phosphonates in Water.....	79
3.16.1	Polyphosphates	79
3.16.2	Hydrolysis of Polyphosphates	80
3.16.3	Complexation by Polyphosphates	80
3.16.4	Phosphonates.....	80
3.17	Complexation by Humic Substances	81
3.18	Complexation and Redox Processes.....	83
	Questions and Problems.....	83
	Literature Cited	85
	Supplementary References.....	86
Chapter 4	Oxidation-Reduction	87
4.1	The Significance of Oxidation-Reduction	87
4.2	Electron and Redox Reactions.....	89
4.3	Electron Activity and pE.....	91
4.4	The Nernst Equation	92
4.5	Reaction Tendency: Whole Reaction from Half-Reactions	93
4.6	The Nernst Equation and Chemical Equilibrium.....	95
4.7	The Relationship of pE to Free Energy	95
4.8	Reactions in Terms of 1 Electron-Mole	96
4.9	The Limits of pE in Water.....	97
4.10	pE Values in Natural Water Systems	99
4.11	pE–pH Diagrams.....	100
4.12	Humic Substances as Natural Reductants	103
4.13	Photochemical Processes in Oxidation-Reduction.....	104
4.14	Corrosion.....	105
	Questions and Problems.....	106
	Literature Cited	107
	Supplementary References.....	107
Chapter 5	Phase Interactions	109
5.1	Chemical Interactions Involving Solids, Gases, and Water	109
5.2	Importance and Formation of Sediments	109
5.2.1	Formation of Sediments	110
5.2.2	Organic and Carbonaceous Sedimentary Materials	111
5.3	Solubilities.....	112
5.3.1	Solubilities of Solids	112
5.3.2	Solubilities of Gases.....	114
5.4	Colloidal Particles in Water	115
5.4.1	Contaminant Transport by Colloids in Water	115
5.4.2	Occurrence of Colloids in Water.....	116
5.4.3	Kinds of Colloidal Particles	116
5.4.4	Colloid Stability.....	117
5.5	The Colloidal Properties of Clays	119
5.6	Aggregation of Particles	120
5.6.1	Flocculation of Colloids by Polyelectrolytes.....	121
5.6.2	Flocculation of Bacteria by Polymeric Materials	121
5.7	Surface Sorption by Solids	122
5.8	Solute Exchange with Bottom Sediments	123
5.8.1	Trace-Level Metals in Suspended Matter and Sediments	124
5.8.2	Phosphorus Exchange with Bottom Sediments	125

5.8.3	Organic Compounds on Sediments and Suspended Matter	125
5.8.4	Bioavailability of Sediment Contaminants	127
5.9	Interstitial Water	128
5.10	Phase Interactions in Chemical Fate and Transport	129
5.10.1	Rivers	129
5.10.2	Lakes and Reservoirs	129
5.10.3	Exchange with the Atmosphere	130
5.10.4	Exchange with Sediments	130
	Questions and Problems	131
	Literature Cited	133
	Supplementary References	133
Chapter 6	Aquatic Microbial Biochemistry	135
6.1	Aquatic Biochemical Processes	135
6.1.1	Microorganisms at Interfaces	136
6.2	Algae	136
6.3	Fungi	138
6.4	Protozoa	138
6.5	Bacteria	139
6.5.1	Autotrophic and Heterotrophic Bacteria	140
6.5.2	Aerobic and Anaerobic Bacteria	140
6.5.3	Marine Bacteria	140
6.6	The Prokaryotic Bacterial Cell	141
6.7	Kinetics of Bacterial Growth	142
6.8	Bacterial Metabolism	143
6.8.1	Factors Affecting Bacterial Metabolism	144
6.8.2	Microbial Oxidation and Reduction	145
6.9	Microbial Transformations of Carbon	145
6.9.1	Methane-Forming Bacteria	147
6.9.2	Bacterial Utilization of Hydrocarbons	148
6.9.3	Microbial Utilization of Carbon Monoxide	148
6.10	Biodegradation of Organic Matter	149
6.10.1	Oxidation	149
6.10.1.1	Microbial Oxidation of Hydrocarbons	149
6.10.2	Other Biochemical Processes in Biodegradation of Organics	150
6.11	Microbial Transformations of Nitrogen	151
6.11.1	Nitrogen Fixation	152
6.11.2	Nitrification	153
6.11.3	Nitrate Reduction	154
6.11.4	Denitrification	155
6.11.5	Competitive Oxidation of Organic Matter by Nitrate Ions and Other Oxidizing Agents	155
6.12	Microbial Transformations of Phosphorus and Sulfur Phosphorus Compounds	156
6.12.1	Sulfur Compounds	156
6.12.1.1	Oxidation of H ₂ S and Reduction of Sulfate by Bacteria	157
6.12.2	Microorganism-Mediated Degradation of Organic Sulfur Compounds	158
6.13	Microbial Transformations of Halogens and Organohalides	158
6.14	Microbial Transformations of Metals and Metalloids	160
6.14.1	Acid Mine Waters	161
6.14.2	Microbial Transitions of Selenium	162
6.14.3	Microbial Corrosion	163

Questions and Problems.....	163
Literature Cited	166
Supplementary References.....	166
Chapter 7 Water Pollution.....	169
7.1 Nature and Types of Water Pollutants	169
7.2 Elemental Pollutants	169
7.3 Heavy Metals	171
7.3.1 Cadmium.....	171
7.3.2 Lead.....	171
7.3.3 Mercury.....	172
7.4 Metalloids.....	173
7.5 Organically Bound Metals and Metalloids.....	174
7.5.1 Organotin Compounds.....	175
7.6 Inorganic Species	176
7.6.1 Cyanide	176
7.6.2 Ammonia and Other Inorganic Pollutants	177
7.6.3 Asbestos in Water	178
7.7 Algal Nutrients and Eutrophication.....	178
7.8 Acidity, Alkalinity, and Salinity	179
7.9 Oxygen, Oxidants, and Reductants	180
7.10 Organic Pollutants.....	181
7.10.1 Sewage	181
7.10.2 Soaps, Detergents, and Detergent Builders.....	182
7.10.2.1 Soaps	182
7.10.2.2 Detergents	183
7.10.3 Pharmaceuticals and Their Degradation Products	185
7.10.4 Bactericides.....	186
7.10.5 Estrogenic Substances in Wastewater Effluents.....	186
7.10.6 Biorefractory Organic Pollutants.....	186
7.10.7 Naturally Occurring Chlorinated and Brominated Compounds	188
7.10.8 Microbial Toxins.....	188
7.11 Pesticides in Water.....	189
7.11.1 Natural Product Insecticides, Pyrethrins, and Pyrethroids	189
7.11.2 DDT and Organochlorine Insecticides.....	190
7.11.3 Organophosphate Insecticides	191
7.11.4 Carbamates.....	193
7.11.5 Fungicides	193
7.11.6 Herbicides	193
7.11.6.1 Bipyridilium Compounds.....	194
7.11.6.2 Herbicidal Heterocyclic Nitrogen Compounds	195
7.11.6.3 Chlorophenoxy Herbicides	195
7.11.6.4 Miscellaneous Herbicides	196
7.11.7 By-Products of Pesticide Manufacture.....	197
7.12 Polychlorinated Biphenyls	199
7.12.1 Biodegradation of PCBs.....	199
7.13 Radionuclides in the Aquatic Environment.....	200
Questions and Problems.....	204
Literature Cited	206
Supplementary References.....	207

Chapter 8	Water Treatment	209
8.1	Water Treatment and Water Use	209
8.2	Municipal Water Treatment	209
8.3	Treatment of Water for Industrial Use	210
8.4	Sewage Treatment	211
8.4.1	Primary Treatment of Wastewater	212
8.4.2	Secondary Wastewater Treatment by Biological Processes	212
8.4.3	Tertiary Waste Treatment	215
8.4.4	Physical-Chemical Treatment of Municipal Wastewater	215
8.5	Industrial Wastewater Treatment	216
8.6	Removal of Solids	217
8.6.1	Membrane Filtration Processes	218
8.7	Removal of Calcium and Other Metals	219
8.7.1	Removal of Iron and Manganese	223
8.8	Removal of Dissolved Organics	224
8.8.1	Removal of Herbicides	225
8.9	Removal of Dissolved Inorganics	225
8.9.1	Ion Exchange	226
8.9.2	Electrodialysis	226
8.9.3	Reverse Osmosis	227
8.9.4	Phosphorus Removal	228
8.9.5	Nitrogen Removal	229
8.10	Sludge	230
8.11	Water Disinfection	232
8.11.1	Chlorine Dioxide	233
8.11.2	Ozone and Other Oxidants	234
8.12	Natural Water Purification Processes	235
8.12.1	Industrial Wastewater Treatment by Soil	235
8.13	Water Reuse and Recycling	236
	Questions and Problems	237
	Literature Cited	239
	Supplementary References	239
Chapter 9	The Atmosphere and Atmospheric Chemistry	241
9.1	Introduction	241
9.1.1	Photochemistry and Some Important Terms	241
9.1.2	Atmospheric Composition	242
9.1.3	Gaseous Oxides in the Atmosphere	242
9.1.4	Atmospheric Methane	243
9.1.5	Hydrocarbons and Photochemical Smog	244
9.1.6	Particulate Matter	244
9.1.7	Primary and Secondary Pollutants	244
9.2	Importance of the Atmosphere	244
9.3	Physical Characteristics of the Atmosphere	245
9.3.1	Variation of Pressure and Density with Altitude	245
9.3.2	Stratification of the Atmosphere	246
9.4	Energy Transfer in the Atmosphere	248
9.4.1	Earth's Radiation Budget	249
9.5	Atmospheric Mass Transfer, Meteorology, and Weather	250
9.5.1	Atmospheric Water in Energy and Mass Transfer	251
9.5.2	Air Masses	251

9.5.3	Topographical Effects	252
9.5.4	Movement of Air Masses	252
9.5.5	Global Weather	253
9.5.6	Weather Fronts and Storms	254
9.6	Inversions and Air Pollution	255
9.7	Global Climate and Microclimate	255
9.7.1	Atmospheric Carbon Dioxide and Human Modifications of Climate.....	256
9.7.2	Microclimate	257
9.7.3	Effects of Urbanization on Microclimate.....	257
9.8	Chemical and Photochemical Reactions in the Atmosphere	258
9.8.1	Photochemical Processes	259
9.8.2	Ions and Radicals in the Atmosphere	261
9.8.2.1	Free Radicals.....	262
9.8.3	Hydroxyl and Hydroperoxyl Radicals in the Atmosphere	263
9.8.4	Chemical and Biochemical Processes in the Evolution of the Atmosphere	265
9.9	Acid-Base Reactions in the Atmosphere	266
9.10	Reactions of Atmospheric Oxygen	267
9.10.1	Ozone in the Stratosphere	269
9.10.2	Ozone in the Troposphere	270
9.10.3	Oxygen-Containing Ions in the Atmosphere.....	271
9.11	Reactions of Atmospheric Nitrogen	271
9.12	Atmospheric Water.....	272
9.13	Influence of the Anthrosphere.....	273
9.14	Chemical Fate and Transport in the Atmosphere.....	273
	Questions and Problems.....	274
	Literature Cited	276
	Supplementary References.....	277
Chapter 10	Particles in the Atmosphere	279
10.1	Introduction	279
10.2	Physical Behavior of Particles in the Atmosphere.....	280
10.2.1	Size and Settling of Atmospheric Particles.....	281
10.3	Physical Processes for Particle Formation	282
10.4	Chemical Processes for Particle Formation.....	283
10.4.1	Inorganic Particles	283
10.4.2	Organic Particles.....	284
10.4.3	PAH Synthesis	284
10.5	The Composition of Inorganic Particles.....	285
10.5.1	Fly Ash.....	287
10.5.2	Asbestos	288
10.6	Toxic Metals.....	288
10.6.1	Atmospheric Mercury	288
10.6.2	Atmospheric Lead.....	288
10.6.3	Atmospheric Beryllium	289
10.7	Radioactive Particles	289
10.8	The Composition of Organic Particles	290
10.8.1	Polycyclic Aromatic Hydrocarbons.....	290
10.8.2	Carbonaceous Particles from Diesel Engines	291
10.9	Effects of Particles	291
10.9.1	Partitioning of Semivolatile Organic Substances between Air and Particles.....	292

10.10	Water as Particulate Matter.....	293
10.11	Atmospheric Chemical Reactions Involving Particles.....	293
10.12	Control of Particulate Emissions.....	295
10.12.1	Particle Removal by Sedimentation and Inertia.....	295
10.12.2	Particle Filtration.....	296
10.12.3	Scrubbers.....	296
10.12.4	Electrostatic Removal.....	297
	Questions and Problems.....	298
	Literature Cited.....	299
	Supplementary References.....	300
Chapter 11	Gaseous Inorganic Air Pollutants.....	301
11.1	Inorganic Pollutant Gases.....	301
11.2	Production and Control of Carbon Monoxide.....	301
11.2.1	Control of CO Emissions.....	302
11.3	Fate of Atmospheric CO.....	302
11.4	Sulfur Dioxide Sources and the Sulfur Cycle.....	302
11.5	Sulfur Dioxide Reactions in the Atmosphere.....	304
11.5.1	Effects of Atmospheric Sulfur Dioxide.....	306
11.5.2	Sulfur Dioxide Removal.....	306
11.6	Nitrogen Oxides in the Atmosphere.....	310
11.6.1	Atmospheric Reactions of NO _x	312
11.6.2	Harmful Effects of Nitrogen Oxides.....	314
11.6.3	Control of Nitrogen Oxides.....	315
11.7	Acid Rain.....	316
11.8	Ammonia in the Atmosphere.....	317
11.9	Fluorine, Chlorine, and Their Gaseous Compounds.....	317
11.9.1	Chlorine and Hydrogen Chloride.....	318
11.10	Reduced Sulfur Gases.....	319
	Questions and Problems.....	321
	Literature Cited.....	322
	Supplementary References.....	323
Chapter 12	Organic Air Pollutants.....	325
12.1	Organic Compounds in the Atmosphere.....	325
12.1.1	Loss of Organic Substances from the Atmosphere.....	325
12.1.2	Global Distillation and Fractionation of Persistent Organic Pollutants.....	325
12.2	Biogenic Organic Compounds.....	326
12.2.1	Removal of Atmospheric Organic Compounds by Plants.....	328
12.3	Pollutant Hydrocarbons.....	329
12.3.1	Aromatic Hydrocarbons.....	331
12.3.2	Reactions of Atmospheric Aromatic Hydrocarbons.....	333
12.4	Carbonyl Compounds: Aldehydes and Ketones.....	334
12.5	Miscellaneous Oxygen-Containing Compounds.....	336
12.5.1	Alcohols.....	336
12.5.2	Phenols.....	337
12.5.3	Ethers.....	337
12.5.4	Oxides.....	338
12.5.5	Carboxylic Acids.....	338
12.6	Organonitrogen Compounds.....	339
12.7	Organohalide Compounds.....	341

12.7.1	Chlorofluorocarbons	343
12.7.2	Atmospheric Reactions of Hydrofluorocarbons and Hydrochlorofluorocarbons	345
12.7.3	Perfluorocarbons	345
12.7.4	Chlorinated Dibenzo- <i>p</i> -Dioxins and Dibenzofurans.....	346
12.7.5	Marine Sources of Organohalogen Compounds	346
12.8	Organosulfur Compounds	346
12.9	Organic Particulate Matter	347
12.10	Hazardous Air Pollutants: Organic Compounds	348
	Questions and Problems.....	351
	Literature Cited	352
	Supplementary References.....	353
Chapter 13	Photochemical Smog.....	355
13.1	Introduction	355
13.2	Smog-Forming Emissions.....	356
13.2.1	Control of Exhaust Hydrocarbons.....	356
13.2.2	Automotive Emission Standards	359
13.2.3	Polluting Green Plants.....	360
13.3	Smog-Forming Reactions of Organic Compounds in the Atmosphere	360
13.3.1	Photochemical Reactions of Methane.....	360
13.4	Overview of Smog Formation	362
13.5	Mechanisms of Smog Formation.....	363
13.5.1	Nitrate Radical	370
13.5.2	Photolyzable Compounds in the Atmosphere	371
13.6	Reactivity of Hydrocarbons	371
13.7	Inorganic Products from Smog.....	372
13.8	Effects of Smog.....	373
	Questions and Problems.....	375
	Literature Cited	376
	Supplementary References.....	377
Chapter 14	The Endangered Global Atmosphere.....	379
14.1	Climate Change and Anthropogenic Effects	379
14.1.1	Changes in Climate	380
14.2	Global Warming	381
14.2.1	Atmospheric Carbon Dioxide.....	381
14.2.2	Methane and Other Greenhouse Gases	384
14.2.3	Particles and Global Warming.....	385
14.2.4	The Outlook for Global Warming	386
14.2.5	Serious Concern over Changes in Climate	387
14.3	Acid Rain	388
14.4	Ozone Layer Destruction	391
14.4.1	Chlorofluorocarbon Substitutes and Ozone Depletion	394
14.5	Photochemical Smog.....	394
14.6	Nuclear Winter	397
14.6.1	Doomsday Visitors from Space.....	398
14.7	What Is To Be Done?	398
	Questions and Problems.....	401
	Literature Cited	401
	Supplementary References.....	402

Chapter 15	The Geosphere and Geochemistry	405
15.1	Introduction	405
15.2	The Nature of Solids in the Geosphere	406
15.2.1	Structure and Properties of Minerals	406
15.2.2	Kinds of Minerals	407
15.2.3	Evaporites	407
15.2.4	Volcanic Sublimates	408
15.2.5	Igneous, Sedimentary, and Metamorphic Rocks	408
15.2.5.1	Rock Cycle	409
15.2.5.2	Stages of Weathering	409
15.3	Physical Form of the Geosphere	410
15.3.1	Plate Tectonics and Continental Drift	410
15.3.2	Structural Geology	411
15.4	Internal Processes	411
15.4.1	Earthquakes	412
15.4.2	Volcanoes	412
15.5	Surface Processes	413
15.6	Sediments	414
15.7	Clays	415
15.8	Geochemistry	417
15.8.1	Physical Aspects of Weathering	417
15.8.2	Chemical Weathering	417
15.8.3	Biological Aspects of Weathering	419
15.9	Groundwater in the Geosphere	419
15.9.1	Water Wells	421
15.9.2	Qanats	421
15.10	Environmental Aspects of the Geosphere	421
15.10.1	Natural Hazards	423
15.10.2	Anthropogenic Hazards	423
15.11	Earthquakes	423
15.12	Volcanoes	424
15.13	Surface Earth Movement	425
15.14	Stream and River Phenomena	426
15.15	Phenomena at the Land–Ocean Interface	428
15.15.1	The Threat of Rising Sea Levels	429
15.16	Phenomena at the Land–Atmosphere Interface	430
15.17	Effects of Ice	431
15.18	Effects of Human Activities	431
15.18.1	Extraction of Geospheric Resources: Surface Mining	432
15.18.2	Environmental Effects of Mining and Mineral Extraction	432
15.19	Air Pollution and the Geosphere	432
15.20	Water Pollution and the Geosphere	433
15.21	Waste Disposal and the Geosphere	434
15.21.1	Municipal Refuse	434
	Questions and Problems	436
	Literature Cited	437
	Supplementary References	438
Chapter 16	Soil and Agricultural Environmental Chemistry	441
16.1	Soil and Agriculture	441
16.1.1	Agriculture	441
16.1.2	Pesticides and Agriculture	442

16.2	Nature and Composition of Soil.....	443
16.2.1	Water and Air in Soil.....	444
16.2.2	The Inorganic Components of Soil.....	446
16.2.3	Organic Matter in Soil.....	446
16.2.4	Soil Humus	447
16.2.5	The Soil Solution.....	449
16.3	Acid-Base and Ion Exchange Reactions in Soils.....	449
16.3.1	Production of Mineral Acid in Soil.....	449
16.3.2	Adjustment of Soil Acidity.....	450
16.3.3	Ion Exchange Equilibria in Soil.....	450
16.4	Macronutrients in Soil	451
16.5	Nitrogen, Phosphorus, and Potassium in Soil.....	452
16.5.1	Nitrogen	453
16.5.2	Phosphorus.....	455
16.5.3	Potassium.....	455
16.6	Micronutrients in Soil	456
16.6.1	Hyperaccumulators	456
16.7	Fertilizers.....	457
16.7.1	Fertilizer Pollution.....	458
16.8	Pollutants from Livestock Production	459
16.9	Pesticides and Their Residues in Soil	459
16.9.1	Soil Fumigants.....	460
16.10	Wastes and Pollutants in Soil	461
16.10.1	Biodegradation and the Rhizosphere	463
16.11	Soil Loss and Degradation.....	463
16.11.1	Soil and Water Resources.....	465
16.12	Genetic Engineering and Agriculture	465
16.13	Green Chemistry and Sustainable Agriculture	466
16.14	Agriculture and Health.....	469
16.14.1	Chemical Contamination	469
	Questions and Problems.....	469
	Literature Cited	470
	Supplementary References.....	471
Chapter 17	Industrial Ecology and Green Chemistry	473
17.1	Introduction and History.....	473
17.1.1	Sustainability.....	474
17.1.2	Earth Systems Engineering and Management	474
17.2	Industrial Ecosystems	474
17.3	The Five Major Components of an Industrial Ecosystem	476
17.3.1	Primary Materials and Energy Producers	477
17.3.2	Materials Processing and Manufacturing Sector	478
17.3.3	Consumer Sector.....	478
17.3.4	Waste Processing Sector.....	478
17.4	Industrial Metabolism	478
17.4.1	Industrial Metabolism and Biological Analogies.....	479
17.5	Levels of Materials Utilization	481
17.6	Links to Other Environmental Spheres	482
17.6.1	Fossil Fuel Combustion.....	482
17.6.2	Industrial Manufacturing and Processing.....	482
17.6.3	Crop Production.....	483
17.6.4	Livestock Production (Domestic Animals)	483

17.7	Consideration of Environmental Impacts in Industrial Ecology.....	483
17.8	Three Key Attributes: Energy, Materials, and Diversity.....	484
17.8.1	Unlimited Energy.....	485
17.8.2	Industrial Ecology and Material Resources.....	485
17.8.2.1	Dematerialization.....	486
17.8.2.2	Substitution of Materials.....	486
17.8.2.3	Recycling.....	487
17.8.2.4	Extraction of Useful Materials from Wastes.....	488
17.8.3	Diversity and Robust Character of Industrial Ecosystems.....	488
17.9	Life Cycles: Expanding and Closing the Materials Loop.....	489
17.9.1	Product Stewardship.....	490
17.9.2	Embedded Utility.....	490
17.10	Life Cycle Assessment.....	491
17.10.1	Scoping in Life Cycle Assessment.....	492
17.11	Consumable, Recyclable, and Service (Durable) Products.....	492
17.11.1	Desirable Characteristics of Consumables.....	492
17.11.2	Desirable Characteristics of Recyclables.....	493
17.11.3	Desirable Characteristics of Service Products.....	493
17.12	Design for Environment.....	494
17.12.1	Products, Processes, and Facilities.....	494
17.12.2	Key Factors in Design for Environment.....	495
17.12.3	Hazardous Materials in Design for Environment.....	495
17.13	Overview of an Integrated Industrial Ecosystem.....	495
17.14	The Kalundborg Example.....	497
17.15	Inherent Safety.....	498
17.15.1	Increased Safety with Smaller Size.....	499
17.16	Societal Factors and the Environmental Ethic.....	500
17.17	Twelve Principles of Green Engineering.....	500
17.17.1	Industrial Ecology and Ecological Engineering.....	502
17.18	Green Polymers.....	502
	Questions and Problems.....	503
	Literature Cited.....	504
	Supplementary References.....	504
Chapter 18	Industrial Ecology, Resources, and Energy.....	507
18.1	Introduction.....	507
18.2	Minerals in the Geosphere.....	507
18.2.1	Evaluation of Mineral Resources.....	508
18.3	Extraction and Mining.....	508
18.4	Metals.....	510
18.5	Metal Resources and Industrial Ecology.....	512
18.5.1	Aluminum.....	512
18.5.2	Chromium.....	512
18.5.3	Copper.....	513
18.5.4	Cobalt.....	514
18.5.5	Lead.....	514
18.5.6	Zinc.....	515
18.5.7	Potassium.....	515
18.6	Nonmetal Mineral Resources.....	515
18.7	Phosphates.....	517

18.8	Sulfur	518
18.9	Gypsum	518
18.10	Wood: A Major Renewable Resource	519
18.11	The Energy Problem	520
18.12	World Energy Resources	520
18.13	Energy Conservation	521
18.14	Energy Conversion Processes	523
18.14.1	Fuel Cells	525
18.15	Petroleum and Natural Gas	525
18.16	Coal	528
18.16.1	Coal Conversion	529
18.17	Using Fossil Fuels with Carbon Sequestration	530
18.18	Nuclear Fission Power	531
18.19	Nuclear Fusion Power	533
18.20	Geothermal Energy	534
18.21	The Sun: An Ideal Energy Source	535
18.21.1	The Surprising Success of Wind Power	537
18.22	Energy from Biomass	537
18.22.1	Gasohol	538
18.23	Future Energy Sources	539
18.24	Extending Resources through the Practice of Industrial Ecology	540
18.24.1	Metals	540
18.24.2	Plastics	540
18.24.3	Lubricating Oil	541
	Questions and Problems	541
	Literature Cited	542
	Supplementary References	543
Chapter 19	Nature, Sources, and Environmental Chemistry of Hazardous Wastes	545
19.1	Introduction	545
19.1.1	History of Hazardous Substances	545
19.1.2	Legislation	546
19.2	Classification of Hazardous Substances and Wastes	547
19.2.1	Characteristics and Listed Wastes	547
19.2.2	Hazardous Wastes	548
19.2.2.1	Hazardous Wastes and Air and Water Pollution Control	548
19.3	Sources of Wastes	548
19.3.1	Types of Hazardous Wastes	549
19.3.2	Hazardous Waste Generators	550
19.4	Flammable and Combustible Substances	550
19.4.1	Combustion of Finely Divided Particles	551
19.4.2	Oxidizers	551
19.4.3	Spontaneous Ignition	552
19.4.4	Toxic Products of Combustion	553
19.5	Reactive Substances	553
19.5.1	Chemical Structure and Reactivity	553
19.6	Corrosive Substances	555
19.6.1	Sulfuric Acid	555
19.7	Toxic Substances	556
19.7.1	Toxicity Characteristic Leaching Procedure	556

19.8	Physical Forms and Segregation of Wastes	556
19.9	Environmental Chemistry of Hazardous Wastes	557
19.10	Physical and Chemical Properties of Hazardous Wastes	558
19.11	Transport, Effects, and Fates of Hazardous Wastes	559
19.11.1	Physical Properties of Wastes	559
19.11.2	Chemical Factors	560
19.11.3	Effects of Hazardous Wastes	560
19.11.4	Fates of Hazardous Wastes	560
19.12	Hazardous Wastes and the Anthrosphere	561
19.13	Hazardous Wastes in the Geosphere	562
19.14	Hazardous Wastes in the Hydrosphere	564
19.15	Hazardous Wastes in the Atmosphere	566
19.16	Hazardous Wastes in the Biosphere	567
19.16.1	Microbial Metabolism in Waste Degradation	568
	Questions and Problems	569
	Literature Cited	570
	Supplementary References	571
Chapter 20	Industrial Ecology for Waste Minimization, Utilization, and Treatment	573
20.1	Introduction	573
20.2	Waste Reduction and Minimization	574
20.3	Recycling	576
20.3.1	Examples of Recycling	576
20.3.2	Waste Oil Utilization and Recovery	577
20.3.2.1	Recycling Waste Oil	577
20.3.2.2	Waste Oil Fuel	577
20.3.3	Waste Solvent Recovery and Recycling	577
20.3.4	Recovery of Water from Wastewater	578
20.4	Physical Methods of Waste Treatment	579
20.4.1	Methods of Physical Treatment	579
20.4.1.1	Phase Separations	580
20.4.1.2	Phase Transition	580
20.4.1.3	Phase Transfer	581
20.4.1.4	Molecular Separation	582
20.5	Chemical Treatment: An Overview	582
20.5.1	Acid-Base Neutralization	583
20.5.1.1	Acid Recovery	583
20.5.2	Chemical Precipitation	584
20.5.2.1	Precipitation of Metals	584
20.5.2.2	Coprecipitation of Metals	585
20.5.3	Oxidation-Reduction	585
20.5.4	Electrolysis	586
20.5.5	Hydrolysis	587
20.5.6	Chemical Extraction and Leaching	587
20.5.7	Ion Exchange	588
20.6	Green Waste Treatment by Photolysis and Sonolysis	588
20.7	Thermal Treatment Methods	589
20.7.1	Incineration	590
20.7.1.1	Incinerable Wastes	590
20.7.2	Hazardous Waste Fuel	590
20.7.3	Incineration Systems	590

20.7.4	Types of Incinerators	591
20.7.5	Combustion Conditions	592
20.7.6	Effectiveness of Incineration	592
20.7.7	Wet Air Oxidation.....	592
20.7.8	UV-Enhanced Wet Oxidation	593
20.8	Biodegradation of Wastes	593
20.8.1	Biodegradability.....	593
20.8.2	Aerobic Treatment	594
20.8.3	Anaerobic Treatment	594
20.8.4	Reductive Dehalogenation.....	594
20.9	Phytoremediation	595
20.10	Land Treatment and Composting	595
20.10.1	Land Treatment.....	595
20.10.2	Composting.....	596
20.11	Preparation of Wastes for Disposal	596
20.11.1	Immobilization.....	596
20.11.2	Stabilization	597
20.11.3	Solidification.....	597
20.11.3.1	Sorption to a Solid Matrix Material.....	597
20.11.3.2	Thermoplastics and Organic Polymers.....	597
20.11.3.3	Vitrification	598
20.11.3.4	Solidification with Cement	598
20.11.3.5	Solidification with Silicate Materials	598
20.11.3.6	Encapsulation	599
20.11.3.7	Chemical Fixation.....	599
20.12	Ultimate Disposal of Wastes.....	599
20.12.1	Aboveground Disposal	599
20.12.2	Landfills	599
20.12.3	Surface Impoundment of Liquids.....	600
20.12.4	Deep-Well Disposal of Liquids	600
20.13	Leachate and Gas Emissions	601
20.13.1	Leachate	601
20.13.1.1	Hazardous Waste Leachate Treatment.....	601
20.13.2	Gas Emissions.....	601
20.14	<i>In Situ</i> Treatment.....	602
20.14.1	<i>In Situ</i> Immobilization.....	602
20.14.2	Vapor Extraction	602
20.14.3	<i>In Situ</i> Solidification.....	602
20.14.4	<i>In Situ</i> Detoxification.....	603
20.14.5	Permeable Bed Treatment	603
20.14.6	<i>In Situ</i> Thermal Processes	603
20.14.7	Soil Washing and Flushing.....	604
	Questions and Problems.....	604
	Literature Cited	605
	Supplementary References.....	606
Chapter 21	Environmental Biochemistry	609
21.1	Biochemistry	609
21.1.1	Biomolecules.....	610
21.2	Biochemistry and the Cell	610
21.2.1	Major Cell Features	610

21.3	Proteins.....	611
21.3.1	Protein Structure.....	612
21.3.2	Denaturation of Proteins.....	614
21.4	Carbohydrates.....	614
21.5	Lipids.....	616
21.6	Enzymes.....	619
21.7	Nucleic Acids.....	621
21.7.1	Nucleic Acids in Protein Synthesis.....	624
21.7.2	Modified DNA.....	625
21.8	Recombinant DNA and Genetic Engineering.....	625
21.9	Metabolic Processes.....	625
21.9.1	Energy-Yielding Processes.....	625
21.10	Metabolism of Xenobiotic Compounds.....	626
21.10.1	Phase I and Phase II Reactions.....	627
	Questions and Problems.....	627
	Literature Cited.....	629
	Supplementary References.....	629
Chapter 22	Toxicological Chemistry.....	631
22.1	Introduction to Toxicology and Toxicological Chemistry.....	631
22.1.1	Toxicology.....	631
22.1.2	Synergism, Potentiation, and Antagonism.....	633
22.2	Dose–Response Relationships.....	633
22.3	Relative Toxicities.....	634
22.3.1	Nonlethal Effects.....	635
22.4	Reversibility and Sensitivity.....	635
22.4.1	Hypersensitivity and Hyposensitivity.....	636
22.5	Xenobiotic and Endogenous Substances.....	636
22.6	Toxicological Chemistry.....	637
22.6.1	Toxicants in the Body.....	637
22.6.2	Phase I Reactions.....	637
22.6.3	Phase II Reactions.....	638
22.7	Kinetic and Dynamic Phases.....	639
22.7.1	Kinetic Phase.....	639
22.7.2	Dynamic Phase.....	640
22.7.2.1	Primary Reaction in the Dynamic Phase.....	640
22.7.2.2	Biochemical Effects in the Dynamic Phase.....	640
22.7.2.3	Responses to Toxicants.....	641
22.8	Teratogenesis, Mutagenesis, Carcinogenesis, and Effects on the Immune and Reproductive Systems.....	642
22.8.1	Teratogenesis.....	642
22.8.2	Mutagenesis.....	642
22.8.2.1	Biochemistry of Mutagenesis.....	642
22.8.3	Carcinogenesis.....	644
22.8.3.1	Biochemistry of Carcinogenesis.....	644
22.8.3.2	Alkylating Agents in Carcinogenesis.....	645
22.8.4	Testing for Carcinogens.....	646
22.8.4.1	Bruce Ames Test.....	647
22.8.5	Immune System Response.....	647
22.8.6	Endocrine Disruption.....	647

22.9	Health Hazards	648
22.9.1	Assessment of Potential Exposure	649
22.9.2	Epidemiological Evidence	649
22.9.3	Estimation of Health Effects Risks	649
22.9.4	Risk Assessment	649
	Questions and Problems	650
	Literature Cited	650
	Supplementary References	651
Chapter 23	Toxicological Chemistry of Chemical Substances	653
23.1	Introduction	653
23.1.1	ATSDR Toxicological Profiles	653
23.2	Toxic Elements and Elemental Forms	653
23.2.1	Ozone	653
23.2.2	White Phosphorus	654
23.2.3	Elemental Halogens	655
23.2.4	Heavy Metals	655
23.3	Toxic Inorganic Compounds	656
23.3.1	Cyanide	656
23.3.2	Carbon Monoxide	656
23.3.3	Nitrogen Oxides	657
23.3.4	Hydrogen Halides	657
23.3.4.1	Hydrogen Fluoride	657
23.3.4.2	Hydrogen Chloride	657
23.3.5	Interhalogen Compounds and Halogen Oxides	657
23.3.6	Inorganic Compounds of Silicon	658
23.3.7	Asbestos	658
23.3.8	Inorganic Phosphorus Compounds	658
23.3.9	Inorganic Compounds of Sulfur	659
23.3.10	Perchlorate	659
23.3.11	Organometallic Compounds	660
23.3.11.1	Organolead Compounds	660
23.3.11.2	Organotin Compounds	660
23.3.11.3	Carbonyls	661
23.3.11.4	Reaction Products of Organometallic Compounds	661
23.4	Toxicology of Organic Compounds	661
23.4.1	Alkane Hydrocarbons	661
23.4.2	Alkene and Alkyne Hydrocarbons	661
23.4.3	Benzene and Aromatic Hydrocarbons	662
23.4.3.1	Toluene	663
23.4.3.2	Naphthalene	663
23.4.3.3	Polycyclic Aromatic Hydrocarbons	663
23.4.4	Oxygen-Containing Organic Compounds	663
23.4.4.1	Oxides	663
23.4.4.2	Alcohols	664
23.4.5	Phenols	665
23.4.5.1	Aldehydes and Ketones	666
23.4.5.2	Carboxylic Acids	666
23.4.5.3	Ethers	667

23.4.5.4	Acid Anhydrides	667
23.4.5.5	Esters	667
23.4.6	Organonitrogen Compounds	668
23.4.6.1	Aliphatic Amines	668
23.4.6.2	Carbocyclic Aromatic Amines	668
23.4.6.3	Pyridine	669
23.4.6.4	Acrylamide: Toxic Potato Chips?	669
23.4.6.5	Nitriles	669
23.4.6.6	Nitro Compounds	670
23.4.6.7	Nitrosamines	670
23.4.6.8	Isocyanates and Methyl Isocyanate	670
23.4.6.9	Organonitrogen Pesticides	670
23.4.7	Organohalide Compounds	671
23.4.7.1	Alkyl Halides	671
23.4.7.2	Alkenyl Halides	671
23.4.7.3	Aryl Halides	672
23.4.8	Organohalide Pesticides	673
23.4.8.1	TCDD	673
23.4.8.2	Chlorinated Phenols	674
23.4.9	Organosulfur Compounds	674
23.4.9.1	Sulfur Mustards	674
23.4.10	Organophosphorus Compounds	675
23.4.10.1	Organophosphate Esters	675
23.4.10.2	Phosphorothionate and Phosphorodithioate Ester Insecticides	676
23.4.10.3	Organophosphorus Military Poisons	676
23.5	Toxic Natural Products	677
	Questions and Problems	678
	Literature Cited	679
	Supplementary References	680
Chapter 24	Chemical Analysis of Water and Wastewater	681
24.1	General Aspects of Environmental Chemical Analysis	681
24.1.1	Error and Quality Control	681
24.1.2	Water Analysis Methods	682
24.2	Classical Methods	682
24.3	Spectrophotometric Methods	683
24.3.1	Absorption Spectrophotometry	683
24.3.2	Atomic Absorption and Emission Analyses	685
24.3.3	Atomic Emission Techniques	686
24.4	Electrochemical Methods of Analysis	687
24.5	Chromatography	688
24.5.1	High-Performance Liquid Chromatography	689
24.5.2	Chromatographic Analysis of Water Pollutants	690
24.5.3	Ion Chromatography	691
24.6	Mass Spectrometry	691
24.7	Analysis of Water Samples	691
24.7.1	Physical Properties Measured in Water	692
24.7.2	Water Sampling	692
24.7.2.1	Extractors	692
24.7.3	Water Sample Preservation	693
24.7.4	Total Organic Carbon in Water	694

24.7.5	Measurement of Radioactivity in Water.....	694
24.7.6	Biological Toxins.....	695
24.7.7	Summary of Water Analysis Procedures.....	695
24.8	Automated Water Analyses.....	695
24.9	Speciation.....	695
24.10	Emerging Contaminants in Water Analysis.....	698
	Questions and Problems.....	698
	Literature Cited.....	699
	Supplementary References.....	700
Chapter 25	Analysis of Wastes and Solids.....	701
25.1	Introduction.....	701
25.2	Sample Digestion for Elemental Analysis.....	702
25.3	Analyte Isolation for Organics Analysis.....	702
25.3.1	Solvent Extraction.....	703
25.3.2	Supercritical Fluid Extraction.....	703
25.3.3	Pressurized Liquid Extraction and Subcritical Water Extraction.....	703
25.4	Sample Cleanup.....	704
25.5	Sample Preparation for Volatile Organic Compounds.....	705
25.6	Immunoassay Screening of Wastes.....	706
25.7	Determination of Chelating Agents.....	707
25.8	Toxicity Characteristic Leaching Procedure.....	707
	Questions and Problems.....	709
	Literature Cited.....	709
	Supplementary References.....	710
Chapter 26	Air and Gas Analysis.....	711
26.1	Atmospheric Monitoring.....	711
26.1.1	Air Pollutants Measured.....	711
26.2	Sampling.....	712
26.3	Methods of Analysis.....	714
26.4	Determination of Sulfur Dioxide.....	714
26.5	Nitrogen Oxides.....	716
26.6	Analysis of Oxidants.....	717
26.7	Analysis of Carbon Monoxide.....	717
26.8	Determination of Hydrocarbons and Organics.....	718
26.8.1	Determination of Specific Organics in the Atmosphere.....	719
26.9	Analysis of Particulate Matter.....	719
26.9.1	Collection by Filtration.....	719
26.9.2	Collection by Impactors.....	721
26.9.3	Particle Analysis.....	721
26.9.4	X-Ray Fluorescence.....	722
26.9.5	Determination of Lead in Particulate Matter.....	723
26.10	Direct Spectrophotometric Analysis of Gaseous Air Pollutants.....	723
	Questions and Problems.....	725
	Literature Cited.....	725
	Supplementary References.....	727
Chapter 27	Analysis of Biological Materials and Xenobiotics.....	729
27.1	Introduction.....	729
27.2	Indicators of Exposure to Xenobiotics.....	729

27.3	Determination of Metals	731
27.3.1	Direct Analysis of Metals	731
27.3.2	Metals in Wet-Ashed Blood and Urine	731
27.3.3	Extraction of Metals for Atomic Absorption Analysis	731
27.4	Determination of Nonmetals and Inorganic Compounds	732
27.5	Determination of Parent Organic Compounds	732
27.6	Measurement of Phase I and Phase II Reaction Products	733
27.6.1	Phase I Reaction Products	733
27.6.2	Phase II Reaction Products	734
27.6.3	Mercapturates	735
27.7	Determination of Adducts	736
27.8	The Promise of Immunological Methods	737
	Questions and Problems	738
	Literature Cited	739
	Supplementary References	740
Chapter 28	Terrorism, Red Chemistry, and Threats to the Environment	743
28.1	Introduction	743
28.1.1	Environmental Chemistry, Green Chemistry, and Terrorism	744
28.2	The Vulnerable Infrastructure	744
28.3	Protecting the Food Supply	746
28.4	Protecting the Water Supply	746
28.5	Protecting the Energy Supply	747
28.6	Protecting Transportation Systems	748
28.7	The Chemical Industry and National Security	748
28.8	Toxic Chemical Agents	749
28.8.1	Military Poisons	750
28.9	Biotoxins	752
28.10	Infectious Agents	753
28.10.1	Designer Diseases	754
28.11	Reactive, Flammable, and Explosive Substances	755
28.11.1	Detection of Hazardous Substances	756
28.11.2	Removing Hazardous Agents	757
28.12	Nuclear and Radiation Hazards	757
28.12.1	Nuclear Explosives	757
28.12.2	Dispersion of Radioactive Substances: Dirty Bombs	758
28.13	Detecting Threats	758
28.14	The Role of Green Chemistry and Engineering	759
28.14.1	Sustainable Prosperity for a Safer World	760
	Questions and Problems	761
	Literature Cited	762
	Supplementary References	763
Index		765