

# Contents

|   |            |
|---|------------|
| Acknowledgements                                      | v          |
| Preface to the Second Edition                         | xvii       |
| <b>1 How Nature Deals with Waste</b>                  | <b>1</b>   |
| 1.1. Introduction . . . . .                           | 1          |
| 1.1.1. The wastewater problem . . . . .               | 1          |
| 1.1.2. Legislation . . . . .                          | 4          |
| 1.2. Nature of Wastewater . . . . .                   | 14         |
| 1.2.1. Sources and variation in sewage flow . . . . . | 15         |
| 1.2.2. Composition of sewage . . . . .                | 26         |
| 1.2.3. Other wastewaters . . . . .                    | 47         |
| 1.3. Micro-organisms and Pollution Control . . . . .  | 55         |
| 1.3.1. Nutritional classification . . . . .           | 56         |
| 1.4. Microbial Oxygen Demand . . . . .                | 63         |
| 1.4.1. Self purification . . . . .                    | 63         |
| 1.4.2. Biochemical oxygen demand . . . . .            | 93         |
| 1.4.2.1. The test . . . . .                           | 93         |
| 1.4.2.2. Methodology . . . . .                        | 101        |
| 1.4.2.3. Factors affecting the test . . . . .         | 112        |
| 1.4.2.4. Sources of error . . . . .                   | 124        |
| <b>2 How Man Deals with Waste</b>                     | <b>133</b> |
| 2.1. Basic Treatment Processes . . . . .              | 133        |
| 2.1.1. Preliminary treatment . . . . .                | 138        |
| 2.1.2. Primary treatment . . . . .                    | 146        |

|          |  |            |
|----------|--|------------|
| 2.1.3.   | Secondary treatment . . . . .                                    | 147        |
| 2.1.4.   | Tertiary treatment . . . . .                                     | 148        |
| 2.1.5.   | Examples of treatment plants . . . . .                           | 148        |
| 2.2.     | Sedimentation . . . . .  | 151        |
| 2.2.1.   | The settlement process . . . . .                                 | 151        |
| 2.2.2.   | Design of sedimentation tanks . . . . .                          | 157        |
| 2.2.3.   | Performance evaluation . . . . .                                 | 163        |
| 2.3.     | Secondary (Biological) Treatment . . . . .                       | 173        |
| 2.4.     | Tertiary and Advanced Treatment . . . . .                        | 178        |
| 2.4.1.   | Tertiary treatment . . . . .                                     | 179        |
| 2.4.2.   | Advanced wastewater treatment . . . . .                          | 190        |
| <b>3</b> | <b>The Role of Organisms</b>                                     | <b>191</b> |
| 3.1.     | Stoichiometry and Kinetics . . . . .                             | 191        |
| 3.1.1.   | Stoichiometry . . . . .  | 195        |
| 3.1.2.   | Bacterial kinetics . . . . .                                     | 204        |
| 3.1.3.   | The BOD test . . . . .   | 217        |
| 3.2.     | Energy Metabolism . . . . .                                      | 223        |
| 3.3.     | Aerobic Heterotrophic Micro-organisms . . . . .                  | 230        |
| 3.3.1.   | The organisms . . . . .  | 230        |
| 3.3.2.   | Nutrition . . . . .  | 245        |
| 3.3.3.   | Environmental factors . . . . .                                  | 253        |
| 3.3.4.   | Inhibition . . . . .   | 257        |
| 3.4.     | Anaerobic Heterotrophic Micro-organisms . . . . .                | 259        |
| 3.4.1.   | Introduction . . . . .   | 259        |
| 3.4.2.   | Presence in the treatment plant . . . . .                        | 260        |
| 3.4.3.   | Anaerobic digestion . . . . .                                    | 262        |
| 3.4.4.   | Sulphide production . . . . .                                    | 271        |
| 3.4.5.   | Denitrification . . . . .  | 272        |
| 3.4.6.   | Redox potential . . . . .  | 275        |
| 3.5.     | Autotrophic Micro-organisms . . . . .                            | 277        |
| 3.5.1.   | Introduction . . . . .   | 277        |
| 3.5.2.   | Nitrification . . . . .  | 282        |
| 3.6.     | Assessing Treatability, Toxicity, and Biodegradability . . . . . | 290        |
| 3.6.1.   | Introduction . . . . .   | 290        |
| 3.6.2.   | Biochemical tests . . . . .                                      | 291        |
| 3.6.3.   | Bacterial tests . . . . .  | 297        |
| 3.6.4.   | Other approaches . . . . .                                       | 317        |
| 3.6.5.   | Continuous simulation tests . . . . .                            | 320        |
| 3.6.6.   | Conclusion . . . . .   | 324        |

|          |   |            |
|----------|---|------------|
| <b>4</b> | <b>Fixed-Film Reactors</b>                        | <b>325</b> |
| 4.1.     | Percolating Filters . . . . .                     | 326        |
| 4.1.1.   | Design and operation . . . . .                    | 330        |
| 4.1.2.   | Process modifications . . . . .                   | 356        |
| 4.1.3.   | The organisms and their ecology . . . . .         | 364        |
| 4.1.4.   | Factors affecting performance . . . . .           | 417        |
| 4.1.5.   | Nitrifying filters . . . . .                      | 440        |
| 4.2.     | Rotating Biological Contactors . . . . .          | 441        |
| 4.3.     | Submerged Fixed Film Systems . . . . .            | 450        |
| 4.3.1.   | Introduction . . . . .                            | 450        |
| 4.3.2.   | Fluidised bed reactors . . . . .                  | 451        |
| 4.3.3.   | Biological aerated flooded filters . . . . .      | 455        |
| 4.3.4.   | Submerged aerated filters . . . . .               | 460        |
| 4.3.5.   | Moving bed biofilm reactor . . . . .              | 462        |
| <b>5</b> | <b>Activated Sludge</b>                           | <b>465</b> |
| 5.1.     | Flocculation . . . . .                            | 469        |
| 5.2.     | Operating Factors . . . . .                       | 477        |
| 5.2.1.   | Process control . . . . .                         | 477        |
| 5.2.1.1. | Mixed liquor suspended solids . . . . .           | 477        |
| 5.2.1.2. | Sludge residence time or sludge age . . . . .     | 478        |
| 5.2.1.3. | Plant loading . . . . .                           | 479        |
| 5.2.1.4. | Sludge settleability . . . . .                    | 483        |
| 5.2.1.5. | Sludge activity . . . . .                         | 484        |
| 5.2.1.6. | Recirculation of sludge . . . . .                 | 487        |
| 5.2.2.   | Factors affecting the process . . . . .           | 488        |
| 5.2.3.   | Aeration methods . . . . .                        | 496        |
| 5.2.3.1. | Surface aeration . . . . .                        | 497        |
| 5.2.3.2. | Air diffusion . . . . .                           | 504        |
| 5.2.3.3. | Testing aerators . . . . .                        | 511        |
| 5.3.     | Modes of Operation . . . . .                      | 516        |
| 5.3.1.   | Conventional activated sludge processes . . . . . | 517        |
| 5.3.1.1. | Plug-flow systems . . . . .                       | 519        |
| 5.3.1.2. | Completely mixed systems . . . . .                | 528        |
| 5.3.1.3. | Sequencing batch reactor technology . . . . .     | 530        |
| 5.3.2.   | Extended aeration . . . . .                       | 532        |
| 5.3.2.1. | Oxidation ditches . . . . .                       | 532        |
| 5.3.2.2. | Packaged plants . . . . .                         | 539        |
| 5.3.3.   | High-rate activated sludge processes . . . . .    | 541        |
| 5.3.3.1. | A–B process . . . . .                             | 543        |

|          |   |            |
|----------|---|------------|
| 5.3.4.   | Advanced activated sludge systems . . . . .         | 544        |
| 5.3.4.1. | ICI Deep Shaft® process . . . . .                   | 545        |
| 5.3.4.2. | Pure oxygen systems . . . . .                       | 548        |
| 5.4.     | Sludge Problems . . . . .                           | 556        |
| 5.4.1.   | Deflocculation . . . . .                            | 558        |
| 5.4.2.   | Pin-point floc . . . . .                            | 560        |
| 5.4.3.   | Foaming . . . . .                                   | 561        |
| 5.4.4.   | Filamentous bulking . . . . .                       | 569        |
| 5.4.5.   | Identifying problems . . . . .                      | 583        |
| 5.4.6.   | Non-filamentous bulking . . . . .                   | 592        |
| 5.4.7.   | Denitrification . . . . .                           | 592        |
| 5.5.     | Ecology . . . . .                                   | 593        |
| 5.5.1.   | Bacteria . . . . .                                  | 596        |
| 5.5.2.   | Fungi . . . . .                                     | 599        |
| 5.5.3.   | Protozoa . . . . .                                  | 599        |
| 5.5.4.   | Other groups . . . . .                              | 615        |
| 5.6.     | Nutrient Removal . . . . .                          | 618        |
| 5.6.1.   | Denitrification . . . . .                           | 622        |
| 5.6.2.   | Phosphorus removal . . . . .                        | 628        |
| <b>6</b> | <b>Natural Treatment Systems</b>                    | <b>641</b> |
| 6.1.     | Land Treatment . . . . .                            | 643        |
| 6.1.1.   | Purification process . . . . .                      | 644        |
| 6.1.2.   | On-site subsurface infiltration . . . . .           | 646        |
| 6.1.3.   | Slow rate land application . . . . .                | 651        |
| 6.1.4.   | Rapid infiltration land treatment systems . . . . . | 654        |
| 6.1.5.   | Overland flow . . . . .                             | 656        |
| 6.2.     | Macrophyte-Based Systems . . . . .                  | 658        |
| 6.2.1.   | Algae and submerged macrophytes . . . . .           | 660        |
| 6.2.2.   | Floating macrophytes . . . . .                      | 663        |
| 6.2.3.   | Emergent macrophytes . . . . .                      | 673        |
| 6.3.     | Stabilisation Ponds . . . . .                       | 697        |
| 6.3.1.   | Anaerobic ponds and lagoons . . . . .               | 700        |
| 6.3.2.   | Oxidation ponds . . . . .                           | 704        |
| 6.3.3.   | Aeration lagoons . . . . .                          | 731        |
| <b>7</b> | <b>Anaerobic Unit Processes</b>                     | <b>735</b> |
| 7.1.     | Introduction . . . . .                              | 735        |
| 7.2.     | Flow-Through Systems (Digestion) . . . . .          | 743        |
| 7.2.1.   | Combined systems . . . . .                          | 744        |

|          |   |            |
|----------|---|------------|
| 7.2.2.   | Digestion . . . . .   | 754        |
| 7.3.     | Contact Anaerobic Systems . . . . .                         | 777        |
| 7.3.1.   | Anaerobic activated sludge process . . . . .                | 779        |
| 7.3.2.   | Sludge blanket process . . . . .                            | 781        |
| 7.3.3.   | Static media filter process . . . . .                       | 783        |
| 7.3.4.   | Fluidised and expanded media . . . . .                      | 790        |
| <b>8</b> | <b>Sludge Treatment and Disposal</b>                        | <b>793</b> |
| 8.1.     | Sludge Characteristics and Treatment . . . . .              | 793        |
| 8.1.1.   | Treatment options . . . . .                                 | 798        |
| 8.1.2.   | Disposal options . . . . .                                  | 819        |
| 8.2.     | Land Disposal . . . . .                                     | 829        |
| 8.2.1.   | Sludge disposal to land sites . . . . .                     | 829        |
| 8.2.2.   | Sludge utilisation to farmland . . . . .                    | 834        |
| 8.3.     | Sea Disposal . . . . .                                      | 864        |
| 8.3.1.   | Introduction . . . . .                                      | 864        |
| 8.3.2.   | Legislative control . . . . .                               | 866        |
| 8.3.3.   | Dumping sites . . . . .                                     | 871        |
| 8.3.4.   | Environmental impact . . . . .                              | 872        |
| <b>9</b> | <b>Public Health</b>  | <b>885</b> |
| 9.1.     | Disease and Water . . . . .                                 | 885        |
| 9.2.     | Water-Borne Diseases . . . . .                              | 888        |
| 9.2.1.   | Introduction . . . . .                                      | 888        |
| 9.2.2.   | Bacteria . . . . .  | 889        |
| 9.2.3.   | Viruses . . . . .   | 906        |
| 9.2.4.   | Protozoa . . . . .  | 914        |
| 9.2.5.   | Parasitic worms . . . . .                                   | 929        |
| 9.3.     | Indicator Organisms . . . . .                               | 931        |
| 9.3.1.   | Escherichia coli and coliforms . . . . .                    | 941        |
| 9.3.2.   | Faecal streptococci . . . . .                               | 953        |
| 9.3.3.   | Faecal coliform/faecal streptococci (FC/FS) ratio . . . . . | 959        |
| 9.3.4.   | Clostridium perfringens . . . . .                           | 962        |
| 9.3.5.   | Bacteriophage . . . . .                                     | 964        |
| 9.3.6.   | Bifidobacteria . . . . .                                    | 967        |
| 9.3.7.   | Rhodococcus spp. . . . .                                    | 968        |
| 9.3.8.   | Heterotrophic plate count bacteria . . . . .                | 969        |
| 9.3.9.   | Other indicator organisms . . . . .                         | 971        |
| 9.3.10.  | Chemical indicators . . . . .                               | 974        |
| 9.4.     | Hazards Associated with Wastewater and Sludge . . . . .     | 976        |

|           |   |             |
|-----------|---|-------------|
| 9.4.1.    | Water pollution . . . . .                           | 976         |
| 9.4.2.    | Land Pollution . . . . .                            | 996         |
| 9.4.3.    | Atmospheric pollution . . . . .                     | 1008        |
| 9.4.4.    | Antibiotic resistance in enteric bacteria . . . . . | 1011        |
| 9.5.      | Removal of Pathogenic Organisms . . . . .           | 1013        |
| 9.5.1.    | Environmental factors and survival . . . . .        | 1013        |
| 9.5.2.    | Treatment processes . . . . .                       | 1021        |
| 9.5.3.    | Sterilization and disinfection methods . . . . .    | 1040        |
| <b>10</b> | <b>Biotechnology and Wastewater Treatment</b>       | <b>1057</b> |
| 10.1.     | The Role of Biotechnology . . . . .                 | 1057        |
| 10.2.     | Resource Reuse . . . . .                            | 1060        |
| 10.2.1.   | Fertiliser value . . . . .                          | 1060        |
| 10.2.2.   | Reuse of effluents . . . . .                        | 1061        |
| 10.2.3.   | Metal recovery . . . . .                            | 1067        |
| 10.2.4.   | Phosphorus recovery . . . . .                       | 1078        |
| 10.3.     | Biological Conversion . . . . .                     | 1083        |
| 10.3.1.   | Bio-energy . . . . .                                | 1083        |
| 10.3.2.   | Single-cell protein and biomass . . . . .           | 1099        |
| 10.3.3.   | Composting . . . . .                                | 1124        |
| 10.4.     | Environmental Protection . . . . .                  | 1154        |
| 10.4.1.   | Breakdown of recalcitrants . . . . .                | 1155        |
| 10.4.2.   | Bioscrubbing . . . . .                              | 1160        |
| 10.4.3.   | Bioaugmentation . . . . .                           | 1164        |
| 10.4.4.   | Immobilised cells and biosensors . . . . .          | 1169        |
| <b>11</b> | <b>Sustainable Sanitation</b>                       | <b>1179</b> |
| 11.1.     | Introduction . . . . .                              | 1179        |
| 11.2.     | The Problems . . . . .                              | 1180        |
| 11.3.     | Sustainable Options . . . . .                       | 1190        |
| 11.3.1.   | Source contamination . . . . .                      | 1190        |
| 11.3.2.   | Treatment . . . . .                                 | 1196        |
| 11.3.3.   | Final disposal . . . . .                            | 1203        |
| 11.4.     | Implementation . . . . .                            | 1212        |
|           | References  | 1219        |
|           | Index   | 1395        |