6.00 Introduction

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The 13th of December 2018 marked the 50th anniversary of the seminal research article of the ecologist Garrett Hardin, "*The Tragedy of the Commons*", in which he argued that the unconstrained and unrestricted use of an open access resource leads to its collapse.[1] Six years before G. Hardin, Rachel Carson sounded the environmental alarm by publishing her influential book, "*Silent Spring*", describing the adverse ecological effects of uncontrolled and excessive use of pesticides to achieve the Green Revolution.[2] Many other forceful warnings on human-dominated ecosystems and resource scarcity on Earth were issued in the 1960s and 1970s, such as "*The Limits to Growth*", a report for the Club of Rome which also celebrated its 50th anniversary in 2018.[3] Recurrent voices to raise the specter of nature deterioration and unsustainable development were gaining ground and resonating more and more with the public consciousness. They provided a powerful impetus for the development of environmentalism, environmental protection policies, new clean technologies for waste treatment and site bioremediation, and new governance of shared resources,[4] including natural ecosystems or intellectual knowledge.[5–8] In this context, environmental biotechnology has been playing a decisive role by adopting holistic approaches in environmental problem solving and by taking advantage of new generation methodologies in environmental microbiology and analytical chemistry to acquire the necessary knowledge on the contaminated systems and the mechanisms and processes to rehabilitate them.

Historically, environmental biotechnology has been relying on microorganisms (mainly in mixed cultures) and their enzymes to protect, improve, or restore environmental quality. Its applications range from the traditional processes of municipal wastewater treatment to the latest bioremediation technologies aiming at cleaning up sites contaminated with hazardous industrial chemicals. They are progressively encompassing activities with a decisive dimension of sustainability. More recently, industrial biotechnology, which exploits pure biocatalysts in bioreactors to synthesize commercial products, is merged with environmental biotechnology, aimed at both maximizing product space-time-yields and profitability from carbon-based renewable resources and minimizing waste streams and contamination by reaching the ecotoxicological-safety endpoints for regulatory compliance. One of the flagship technologies from this combined discipline is the development of biorefinery platforms that valorize biomass and residues, such as sewage sludge, lignin fractions of lignocellulosic biomass or syngas from gasification, into a spectrum of marketable products. In addition, thanks to notable breakthroughs in metabolic engineering of microorganisms and systems biology and meta-omic approaches applied to complex microbial communities, we can engineer new solutions to tackle the environmental challenges we have been facing by opening and mastering the 'black box' of microbial-driven processes. This is only possible with the development of computational tools for the analysis of meta-omic data and a shared resource system of the available datasets. Frischmann et al.[9] highlighted a tragedy-of-the-commons-like allegory for shared intellectual resources and the need for knowledge commons governance, which is directly addressed in the recent opinion article of a panel of experts in meta-omic technologies and computational analysis for the unrestricted sharing and use of public genomic data.[10] Taken all together, environmental biotechnology is an evolving discipline that integrates the recent advances in metabolic engineering and molecular systems ecology on one hand and the global goals of sustainable development on the other, with the protection of the planet and the development of new production chains within the bio-based economy.

The remarkable capacities of microorganisms in the environmental arena have been recognized and domesticated for several decades, ever since urban wastewater-treatment systems such as activated sludge and anaerobic digestion of biosolids were introduced at the beginning of the 20th century. Over the last several decades, environmental biotechnology has been extended to surface and groundwater cleanup, soil and sediment remediation, industrial effluent detoxification, landfill deposition and composting of organic residues, as well as other emerging techniques, that are now seeking not only to mitigate the adverse effects of pollution but also to give added value to waste. This paradigm shift is perfectly exemplified by the transformation of the traditional wastewater treatment plants (WWTPs) into water resource recovery facilities (WRRFs) in which microbial communities are used both as biodegradation machineries and functional cell factories.

The dual nature of environmental biotechnology, which is both reliably traditional and refreshingly modern, is captured in the present volume. In addition to offering a survey of the current and evolving status of mainstays, such as the widespread aerobic and anaerobic technologies of water and solid waste treatment that had been one of the key features in the first and second editions of *Comprehensive Biotechnology* (CB1 and CB2, respectively), this volume reflects the extended range of possibilities that are offered to scientists, engineers, and other practitioners in environmental management by advances in meta-omics and systems microbiology, metabolic engineering, synthetic ecology, biodiversity-function coupling, and process control. In CB1, environmental biotechnology represented a section of a volume (Section 3, Waste Management and Pollution Control within Volume 4: "*The Practice of Biotechnology: Specialty Products and Service Activities*") and contained 27 articles divided among topics grouped under Chemistry of Waste Treatment, Microbiology and Ecology, Activated Sludge Type Processes, Fixed Film Systems, Anaerobic Reactors, Solid Wastes, and Control and Instrumentation. In CB2, the entire Volume 6 under the title "*Environmental Biotechnology and Safety*" was divided into four sections: Section 1, Industrial and Toxic Wastes (from microbial ecology to bioremediation); Section 2, Municipal Wastes; Section 3, Wastes from Agriculture, Forestry and Food Processing (strategies and biotechnologies for their integrated valorization); and Section 4, Related Considerations.

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In the current third edition of *Comprehensive Biotechnology* (CB3), the entire Volume 6 under the title '*Environmental Biotechnology and Safety*' includes 43 articles and is divided into four sections: Section 1, Environmental Biotechnology Fundamentals; Section 2, Bioremediation; Section 3, Wastewater Treatment Plants and Water Resource Recovery Facilities; and Section 4, Resource Recovery from (Agro)-Industry, Forestry, and Food Processing. The vibrancy and promise of new methodological breakthroughs in high-throughput sequencing, meta-omics, and bioinformatics coupled with an emerging consolidated view of microbial ecology and its pivotal role in the biodegradation of environmental pollutants are reflected in Sections 1 and 2. The recent advances in the understanding of the coupling between biodiversity and functioning are presented using manipulated, natural microbial ecosystems or synthetic microbial communities within the framework of microbial synthetic ecology. The relationships between microbial community functionalities and their spatial organization (in the form of microbial landscapes) are also discussed in the light of specific biotechnological objectives. New and rapidly accumulating insights in the functioning of microorganisms in natural and polluted ecosystems allow a more rational exploitation of their biocatalytic power and provide the impetus for the expansion of bioremediation on the field scale. The biochemical transformation (biodegradation) of xenobiotics and other mostly recalcitrant pollutants is to be understood primarily on the basis of relevant catabolic enzymes and the genes that encode them, thus linking the articles of the two first sections with the fundamentals expounded in the biochemical and genetic sections of Volume 1 (Scientific Fundamentals of Biotechnology). The applications of microbiome-based analysis, such as targeted and shotgun metagenomic sequencing, for different types of ecosystems, from built environments to oil-contaminated marine ecosystems, are the scope of several chapters, with special emphases on the computational analysis of high-dimensional meta-omic datasets using bioinformatic pipelines and high performance computing. The resulting, high-resolution picture of microbial community biodiversity and dynamics provide an unprecedented tool for environmental biotechnology to steer the activities of microbial communities and to optimize microbial-driven processes.

Since bioremediation of polluted environments involves complex interactions among chemicals (most often in mixtures) with multispecies microbial communities and their intricate metabolic networks, such complexity can be analyzed within the conceptual framework and with the tools of systems biology. The availability of genes, genomes, and metagenomes as well as the growing understanding of their functionalities ((meta)-proteomics and metabolomics) provide a concrete connection between the conceptual and methodological principles of Volume 1 and the articles on metagenomics and microarrays in the two first sections of our volume.

Subsequent articles in Sections 1 and 2 focus on the state of the art and the significant progress accomplished in the elimination of important recalcitrant pollutants such as aromatic hydrocarbons, (poly)chlorinated compounds, chlorinated ethenes, nitroaromatic explosives, heavy metals etc., with considerations spanning genetics, biochemistry, and molecular microbial ecology for implementation in bioremediation scenarios. In addition, the environmental context that defines the boundary conditions affecting the outcome of such scenarios is tackled in articles on the concepts of bioaugmentation and bioavailability. The section is rounded out with selected contributions on technologies such as phytoremediation and phycoremediation that tend to complement the role of bacteria in environmental applications as well as on combinations of different biotic and abiotic technologies for complex contamination mitigation issues like oil spills.

In Section 3, the theory and practice of technologies for the biological treatment of municipal wastes (sewage and solids) are examined. The long-established processes of aerobic wastewater treatment, including activated sludge in its different variants and configurations as well as alternatives that depend on space availability (lagoons or constructed wetlands when land is abundant and compact fixed-film processes in the alternative case), have advanced from the original, mostly empirical design to conceptions based on sound microbiological and process engineering principles. This is also reflected in the quantitative analysis and modeling of their performance which are making more and more ample use of benchmarking tools and are recognized widely as robust and predictive. Current rethinking and retooling of the design of conventional wastewater-treatment plants can lead to remarkable gains in energy sustainability and drastic reduction of greenhouse gas (GHG) footprint.

Additional articles recognize the increasing importance of 'greener', more sustainable technologies, such as anaerobic treatment processes not only for wastewater streams but also for municipal biosolids and the greater flexibility afforded by biotransformation processes involving terminal electron acceptors other than oxygen. Micropollutants (pharmaceuticals, endocrine disruptors, etc.) are also emerging as a major concern in the treatment of both urban wastewater and drinking-water purification; hence, biotechnological processes are being adapted to this increasingly pervasive environmental problem.

Although most activated sludge and anaerobic treatment methodologies predominantly target the removal of carbonaceous organic load (biochemical or chemical oxygen demand), recently significant progress has been achieved in the field of domestic sewage treatment to remove inorganic nitrogen and phosphorous nutrients that are at the root of eutrophication phenomena in natural receiving water bodies. Newly developed biological processes for N and P elimination with a minimal (or no) requirement for an additional carbon source are starting to be applied in some wastewater-treatment plants and their potential importance in the future is reflected in several contributions to this section.

A special branch of today's bio-economy that involves agricultural and related processes, including the forest and the food and beverage industry, deserves particular consideration from the environmental biotechnology viewpoint and is addressed in Section 4.

Agro-food industry waste, residues, and effluents are extensively produced on a worldwide scale. In many countries, they are mainly managed as wastes of environmental concern with relevant negative effects on the environment and on the sustainability of the agro-food industry. These should more appropriately be viewed as raw materials rather than wastes, especially in view of the quest for sustainable processing that is becoming increasingly noticed in the first decades of the 21st century. Such materials are mostly composed of proteins, sugars, and/or lipids, along with a number of aromatic and aliphatic hydrocarbons. Therefore, such matrices can be inexpensive and quite abundant feedstocks for the obtainment of bio-based chemicals, materials, and fuels. Indeed, after pretreatments with physical and biological agents, they can generate a number of value-added natural fine chemicals, such as antioxidants, vitamins, etc., along with macromolecules, such as cellulose, starch, lignin, pigments, etc. Some of these types of compounds along with the polysaccharide and protein fraction of hydrolyzed material can be transformed into more sophisticated chemicals (such as flavors, amino acids, vitamins, and organic acids), bio-based products (e.g., biopolymers, biosurfactants, and microbial enzymes), and biofuels (i.e., bioethanol, biogas, and biohydrogen) through tailored biological conversion processes, similar to those described for the production of commodity or specialized products in Volume 3 (Industrial Biotechnology and Commodity Products). These processes are inherently interdependent and can be integrated using the biorefinery concept by analogy to traditional petrochemical refineries.

All the cited bioproducts are natural, biodegradable, and biocompatible compounds, and, therefore, of special interest for the modern industries of the food, pharmaceutical, cosmetic, chemical, textile, and energy sectors. The market for several of them is increasing rapidly and remarkably. Thus, the adoption of some biotechnology tools and strategies could enable to convert the highly environmentally impacting matrices into new and value-added chemicals and materials with notable environmental advantages and a new competitiveness for several prominent industrial sectors that need innovation and/or an improved environmental sustainability.

The globalization linking our entire planet in a tight and intricate network of economic and informational interdependence together with the unprecedented mobility of people, goods, and ideas that is occurring in the 21st century is also a globalization of environmental problems and opportunities. Environmental biotechnology as a composite but increasingly integrated discipline, which relies on a deep appreciation of the molecular nature of life and a detailed understanding of microbial biodiversity to engineer systems for environmental quality, is capable of injecting innovation and prosperity into human society. This branch of biotechnology may yet be our best and brightest hope for saving our biosphere and ensuring the welfare of future generations.

The editors hope that the integration of scientific depth and application breadth that is evident in the articles of this volume will prove valuable to the scientists, engineers, and other practitioners involved in the development, evaluation, or implementation of environmental principles and solutions. The international dimension of environmental biotechnology is reflected in a very effective manner in the fact that the contributions to this final volume of CB3 originate from many countries and continents. The editors express their warmest appreciation to all the authors.

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