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Manish Kumar
Sanjeeb Mohapatra *Editors*

Impact of COVID-19 on Emerging Contaminants

One Health Framework for Risk Assessment and Remediation

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Dedicated to all the Researchers working tirelessly during the COVID-19 Pandemic

Foreword

I am delighted to note that Springer Nature will publish a book project entitled *Impact of COVID-19 on Emerging Contaminants—One Health Framework for Risk Assessment and Remediation* under the dynamic editorship of Dr. Manish Kumar and Dr. Sanjeeb Mohapatra. The focal theme is aptly chosen when people worldwide face many challenges with the rise of emerging contaminants (ECs) during this unprecedented time of the COVID-19 pandemic.

Scanty information is available on the ECs specifically their sources, occurrence, fate and transport under different environmental conditions across the world during this COVID-19 pandemic. I am happy to know that around 17 contributed chapters on ECs are embedded under the three parts in this book project by the learned experts of their respective fields. The book depicts the sampling, distribution and occurrence of ECs in Part I, whereas Part II on emerging, geogenic and microbial contaminants has highlighted sources, ecotoxicity, human health effect and risk assessment techniques, and strategies to provide safe and clean drinking water. On the other hand, the final part explores the drawbacks of conventional wastewater treatment and advanced treatment technologies to mitigate ECs in water and wastewater. Therefore, this book will enlighten a comprehensive and succinct idea about ECs and further finding suitable ways for the scientific evaluation of complex multidisciplinary problems during the COVID-19 pandemic.

The persistent discharge of ECs in regulated or unregulated manners during this COVID-19 pandemic has resulted in their high concentration in different environmental compartments. Even at low concentrations, these contaminants can pose acute or chronic toxicity and could further accelerate the rate of damage to human and ecosystem health due to their rapid use during the pandemic. Continuous release of antibiotics may further lead to the development and transfer of antibiotic resistance genes (ARGs) in microorganisms and humans. These contaminants mainly derive from residential, agricultural, commercial and industrial institutions, and residential activities mainly contribute to their high concentration at municipal wastewater treatment plants. Persistent contaminants may further seep through the soil system and pollute the groundwater. Thus, systemic monitoring of these contaminants in the environment is essential from a controlling and risk assessment point of view. Recently, passive sampling techniques using a polar organic chemical integrative sampler (POCIS), a diffusive gradient in thin-film (DGT) and Chemcatcher® have been widely used in the aquatic environment. Contaminants such as perfluorobutanoic acid (PFBA), perfluorooctanoic acid (PFOA) and perfluorononanoic acid (PFNA) have also been detected in several surface water samples with the highest concentration for PFAS (13 μg/L). Similarly, the rapid use of facemasks has resulted in a high concentration of microplastics in the environment.

Advanced analytical techniques have provided vital information about the concentration and structural information for both parent and daughter compounds in the environment. Thus, there is an urgent need to assess the toxicological impact of ECs to protect human health, aquatic biota and the ecosystem. Additional studies may be conducted to explore the effect of these contaminants using model organisms and complex agricultural soil microbial enrichments, as has been studied for nitrate pollution. Such techniques could help in developing novel strategies for ECs' management in agroecosystems to safeguard the food industry. In addition to food, safeguarding the water resources and continuous supply of good quality water during the pandemic requires special attention. By discussing the problems associated with the community-based water management practices and strategic management practices with modern technology such as the Internet of Things, emerging contaminant-free water can be provided during and post-COVID-19 pandemic. I am happy to know that these aspects are covered in Part II while enlisting various sources of the ECs in different water bodies, potential health risks associated with the widespread distribution of these ECs in water and a detailed assessment of phase-changing methods for water management.

The recent developments in environmental engineering, biotechnology and nanotechnology open a new dimension to establishing novel and advanced wastewater remediation methodologies. Progress made in the adsorptive–photocatalytic dual-modality approach for remediation of PPCPs, adsorbent–photocatalyst combination used to remove contaminants and the design approaches used to increase the effectiveness of dual-modality actions has multiplied the mitigation strategies. Specifically, the self-rejuvenation mechanism of the adsorbents through complete or partial photocatalytic mineralization of adsorbed organic matters has opened new dimensions by challenging designing limitation of effective adsorption–photocatalysis materials that could lead to the large-scale applications of novel materials to remove ECs from the environment. Chapters highlighting the advanced oxidation processes (AOPs) over other conventional wastewater treatment processes along with the current global status of water pollution and the role of transition metal carbides (TMCs) introduced in Part III illustrate the low-temperature synthesis and the effect of structural properties (lattice strain, particle size, surface area and chemical composition) of novel materials on their photocatalytic activity with excellent photostability. Such novel materials could enhance the degradation of ECs, including SARS-CoV-2 in water and wastewater while minimizing exposed biological entities' potential risks.

I feel this book would encourage young minds to follow the newer global trends of monitoring, risk assessment and mitigation strategies of ECs to generate awareness, learning, policy and management strategies. I am particularly pleased to note the unique interface that this book is providing for the environmental engineers, civil engineers, microbiologists, material scientists, data scientists, virologists and modellers to integrate their findings on common and transient sources; co-occurrence; exposure, migration and mobilization (preferential/induced) pathways; and control of ECs to etch out the probability of relative environmental risks and human health challenges. I wish the readers a great time, as the efforts of each contributor and the editors and the publishers are so well evident.

October 2021

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Preface

It has been an exciting endeavour as the editors of the book *Impact of COVID-19 on Emerging Contaminants—One Health Framework for Risk Assessment and Remediation* published by Springer Nature. At the same time, it was a daunting task for us editors to thoroughly select only the ones we thought were unique and matched the scope of this book. This book selected 17 excellent chapters distributed into three broad parts. This book contains several research and review papers and case studies to broaden the critical concept of researchers and engineers about the mitigation strategies and is intended for the students, professionals and researchers working on the occurrence, analysis, fate, transport and treatment of emerging chemical and microbial contaminants.

Emerging contaminants (ECs) are broadly categorized as pharmaceuticals and personal care products (PPCPs), perfluoroalkyl substances (PFAS), including perfluorobutanoic acid (PFBA), perfluorooctanoic acid (PFOA) and perfluorononanoic acid (PFNA), microplastics, food additives, surfactants, detergents and cleaning agents, natural and synthetic hormones, industrial compounds and agrochemicals (fertilizers, pesticides and herbicides). COVID-19 pandemic has led to increases in the consumption of PPCPs and other ECs resulting in their high concentration in the aquatic body. Even at a low level (ng/L), they may pose chronic and acute harmful effects on human health and the ecosystem. Regular monitoring of PPCPs in the water system is essential to estimate the risk associated with their toxicity. Passive sampling techniques have recently received increasing attention due to their significant advantages over active sampling techniques. These techniques could provide the real-time concentration of ECs which would help to plan appropriate mitigation strategies to safeguard the water resources. Considering these, we divided the book into three major parts, i.e. (i) *Monitoring and Occurrence of Contaminants*; (ii) *Sources and Effects of Contaminants*; and (iii) *Mitigation and Removal Strategies.*

Part I on *Monitoring and Occurrence of Contaminants* deals with an array of ECs focusing on the advanced monitoring techniques and occurrence of several contaminants relevant to the pandemic scenario. The present part summarizes the current literature on the most applied passive sampling devices for monitoring of PPCPs in an aquatic environment, such as polar organic chemical integrative sampler (POCIS), a diffusive gradient in thin-film (DGT) and Chemcatcher® with emphasis given to the theory, main components of passive sampling devices, methods of calibration, the application and analytical performance. A chapter titled "A First Report of Perfluoroalkyl Substances (PFAS) in a Large West Flowing River in Southern India" reported PFBA, PFNA and PFOA concentration in a river where PFAS concentrations up to 12,958 ng/L were found. PFBA, PFOA and PFNA are the most detected compounds in the river, followed by PFHxS and PFOS. Compared to upstream, the downstream of the rivers is more polluted due to higher population density and continuous discharge of ECs from several industries.

Part II on *Sources and Effects of Contaminants* deals with various sources of ECs, including their ecotoxicity and health effects. Although PPCPs are majorly produced from household activities, there is an exponential increase in face masks, a significant source of microplastics in the aquatic body. Additionally, inappropriate disposal of contaminated face masks may further transmit the novel viral strain, develop resistant viruses and even pose an ecotoxic effect due to micro/nanoplastics. Specifically, due to their recalcitrant nature and reduced biodegradability, ECs induce chronic effects ranging from antibiotic resistance and endocrine disruption. They are even known to increase the chances of Alzheimer's disease and cancer. In addition to PPCPs, the forever chemicals or PFAS detected in the human blood and mother's milk may pose an additional threat. Appropriate waste disposal is mandatory in such an unprecedented time, but a community-based water management practice is the need of the hour to safeguard public health. Community-based water management practices can be the answer to the water crisis problem in the post-COVID-19 world. Though these practices are decades old and have survived many generations, they have some practical issues in the present-day scenario. Internet of Things can be used to solve the problem associated with traditional community-based water management practices without compromising the quality of surface water. This part has discussed various sources of ECs, ecotoxicity, health risk assessment and water resource management which have been covered in this part.

The last and final part of this book on *Mitigation and Removal Strategies* focuses on the drawbacks of the conventional wastewater treatment technologies, integrated algal bioremediation options and advanced treatment options but not limited to the applications of membrane filtration, adsorption, electrochemical oxidation, ozonation, Fenton and photo-Fenton processes, catalytic oxidation, photocatalysis and heterogeneous photocatalysis. The chapter titled "Emerging Contaminants in Water and Wastewater: Remediation Perspectives and Innovations in Treatment Technologies" discusses membrane technology involving ultrafiltration, nanofiltration and reverse osmosis, adsorption using carbonaceous adsorbent, metal-laden spent biosorbent, industrial sludge, carbon nanotubes and metallic nanoparticles and future challenges. Progress in adsorptive–photocatalytic dual-modality design approaches used to increase the effectiveness, self-rejuvenation mechanism and challenges in designing effective adsorption-photocatalysis materials and their large-scale applications have been covered in this part. Besides summarizing the recent literatures, the mechanism of ECs' removal by simultaneous adsorption and catalytic oxidation on the activated carbon surfaces have also been discussed. Various responsible factors, modelling and thermodynamic, feasibility of the adsorption process, strategies for the regeneration of the saturated adsorbents and cost–benefit analysis of the treatment method have been presented in detail. With an increased demand for wastewater reuse, groundwater recharge with treated wastewater has been practised worldwide and persistent ECs may seep into the groundwater. Combining variously constructed wetland (CW) systems in different configurations and other natural treatment techniques may enhance the removal of recalcitrant ECs and restrict the transport of ECs to groundwater. Thus, this part also presents the hybrid systems combining CWs with tertiary treatment methods as the most promising and sustainable solution for PPCPs' removal from wastewater. Nature-based subsurface flow constructed wetlands (SFCWs) as a polishing step with an insight to process parameters are also discussed in depth. Finally, the last and most exciting chapter, titled "Tackling COVID-19 in Wastewater: Treatment Technologies for Developing Nations" discusses the environmental and health impact of COVID-19 with emphasis on the primary, secondary and tertiary treatment technologies to combat SARS-CoV-2. While doing so, the persistence of SARS-CoV-2 in human wastes and raw wastewater, sludge and surface water in different environmental conditions at various temperature conditions was also explored. Among various disinfection techniques, chlorine-based disinfection, ozonation and ultraviolet (UV) irradiation could successfully control the spread of SARS-CoV-2.

Without departing from the broader framework of the COVID-19 impact, the topics are centred on sources of emerging contaminants, partitioning, formation of transformed products, several mitigation strategies and, finally, environmental assessment pathways, socio-ecosystem framework and health and ecotoxicity.

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Second wave of the COVID-19 was such an impactful and severe that all of us have lost someone from far or near. Amidst that dark time, we thought to write a book on COVID-19, and I reached out to Ms. Swati Meherishi, Editorial Director, Springer Nature. The proposal was approved quite swiftly, with feedback on changes. All involved agreed that a collaborative and swift publication was needed in this area.

This book project would not have been possible without the active support of many individuals, including the authors and the staff at Springer Nature, but also our family and friends who kept us motivated. The result is this book comprehensively covering emerging and geogenic contaminants and their management in the environment of the post-COVID-19 Anthropocene.

We acknowledge the constant support and co-operation of the University of Petroleum and Energy Studies, Dehradun, India, and National University of Singapore, Singapore. We would like to express our sincere thanks to the Series Editor of the Series *Springer Transactions in Civil and Environmental Engineering,* Prof. T. G. Sitharam, Director IIT Guwahati. We are thankful also to all the Springer Nature staff involved in the book, especially to Shalini Selvam and Ashok Kumar, for their persistent hard work in coordinating this book project.

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Finally, we acknowledge the constant care and support of our families, parents and well-wishers with which this book project came into reality. Although it is impossible to list all the names, we are thankful to our colleagues, students, peers and notable academicians without whom we would not have been completed our editorial responsibilities in time. Last but not least, we dedicate this book to all the researchers around the world who kept working tirelessly during COVID-19. This book will keep reminding us of all loving souls that departed untimely owing to the COVID-19 pandemic.

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Dr. Manish Kumar is a Professor and Head of the Sustainability Cluster at School of Engineering, University of Petroleum and Energy Studies, Dehradun, Uttarakhand, India. He is Ph.D. in Urban Engineering from the University of Tokyo, Japan, and has received several prestigious recognitions/fellowship, such as Water Advanced Research and Innovation (WARI) Fellowship, Japan Society for the promotion of Science (JSPS) foreign research fellowship, Brain Korea (BK)-21 postdoctoral fellowship, Monbukagakusho scholarship, Linnaeus-Palme stipend from SIDA, Sweden, Research Fellowship from CSIR, India and others. Prof. Kumar is active in the fields of contaminant transport and modeling, heavy metal speciation and toxicity, wastewater surveillance, emerging contaminants and water supply. He has over 200 publications to his credit. He is a Fellow of Royal Society for Chemistry (FRSC), London, UK. He is among the top 2% of researchers as per the list of Stanford University, USA. His ResearchGate score is above 97.5 percentile of the researchers in the world.

Dr. Sanjeeb Mohapatra after finishing his Ph.D. degree at Environmental Science and Engineering Department, Indian Institute of Technology (IIT) Bombay, India, joined the National University of Singapore (NUS), Singapore, to pursue his postdoctoral degree. His research interest broadly covers the monitoring of emerging contaminants (ECs), photo-degradation and enzymatic degradation of ECs, and the role of dissolved organic matter in deciding the fate of such contaminants. He is a recipient of the Water Advanced Research Innovation (WARI) Fellowship awarded by the Department of Science and Technology (DST), India, University of Nebraska Lincoln, USA, Daugherty Water for Food Global Institute (DWFI), USA and Indo-U.S. Science and Technology Forum (IUSSTF). He is a recipient Newton-Bhabha Fellowship jointly awarded by Department of Science and Technology (DST), Government of India, and British Council, U.K. and DST-INSPIRE fellowship offered by DST, India. Dr. Mohapatra also won several international and local awards for his research work for the last couple of years and has many publications in reputed journals, book chapters, and refereed conferences to his credit.

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Chapter 6
Co-occurrence of Geogenic, Microbial, and Anthropogenic Emerging Contaminants: Ecotoxicity and Relative Environmental Risks

D. N. Magana-Arachchi and R. P. Wanigatunge

6.1 Introduction

Water is a fundamental requirement for any living being, and dropping the quality of water used in drinking due to geogenic, microbial, and anthropogenic activities is a global concern. Recent attention has been drawn to "contaminants of emerging concern" (CEC) or to "emerging contaminants" in nature (Dulio et al. 2018) as they have continuously been generated and released to the environment by natural or artificial processes polluting both the terrestrial and aquatic ecosystems. Present in tracer levels, the use and occurrence patterns associated with CECs are wide ranging. Some CECs are similar to conventional toxic pollutants generated due to industrial release, whereas the people in their everyday life use many others in homes, workplaces, agricultural activities, and even during their recreational activities categorized as CECs of anthropogenic origin. Antibiotics and hormones are vital for the health of humans and animals but are identified as the major source for the presence of antibiotic-resistant bacteria and antibiotic-resistant genes in nature. Most CECs, such as trace metals of geogenic origin, persist in the environment getting accumulated in biota causing contamination in the food chain. Though many researches have been conducted on CECs of geogenic, microbial, and anthropogenic origin on individual basis, studies about their coexistence are limited.

Continuous research on these CECs is vital because though the health risks on human beings and their impact on aquatic biota are known for some of the CECs, there is a gap in knowledge on the adverse ecological risks or human toxicological effects about CECs of geogenic, microbial, and anthropogenic origin coexist together.

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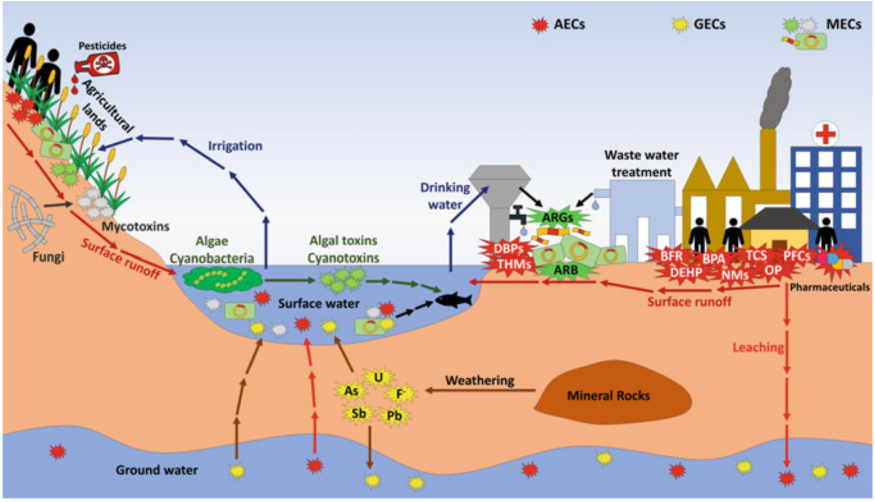

Fig. 6.1 The origin of geogenic, anthropogenic, and microbial emerging contaminants in the environment

Furthermore, these CECs of different origins are subjected to natural and synthetic degradative processes, also reacting with each other and as such the attention should also be drawn to the resultant products and byproducts. Hence, the holistic approach is vital when managing and monitoring the waterbodies for CECs' presence. In Europe, CECs are monitored by a network called NORMAN that included reference laboratories, research centers, and related organizations, promoting consolidative mechanisms to rank the CECs (Dulio et al. 2018).

The objective of this chapter is to analyze recent outcomes on the CECs, their co-occurrence in nature, and their effects on humans and the ecosystem as a whole. Fig. 6.1 summarizes the origin of three types of CECs (geogenic, anthropogenic, and microbial emerging contaminants) in the environment.

6.1.1 Geogenic Emerging Contaminants (GECs)

Geogenic toxic substances are released to the environment due to the natural geogenic process such as volcanic activities or weathering of rocks but could get aggravated with anthropogenic interferences. Humans get exposed to the geogenic pollutants either through inhaling pollutants in the air, by drinking contaminated water, by consuming crops that have been irrigated with geogenically polluted waters, in the fishery, or even use of these waters in recreational activities (Finkelman et al. 2018). Fossils due to the process of carbonization have been converted to carbon which gets deposited as coal, petroleum, or as slates. These fuels of geogenic nature contain many organic toxic compounds such as polycyclic aromatic and aliphatic hydrocarbons, terpenoids, heterocyclic compounds, aromatic amines. When released to nature, there is a possibility of acute toxicity from these geogenic substances and the highest vulnerable group at risk are the workers in the energy industry (Finkelman et al. 2018).

The elements arsenic (As) and antimony (Sb) are known for their possible toxicity. Frequently As and Sb occur together, and most of the time, they are being released due to natural activities such as volcanic discharges or weathering out of rocks. Soils surrounding the mines get polluted with these elements, and according to the research of Zeng et al. (2015) hazard quotient (HQ) values recorded in the analysis of vegetables that were grown in close proximity were ranging from 1.61–3.33 to 0.09–0.39 for Sb and As. The Sb values recorded for chronic daily intake and HQ were over the advocated limits of the Food and Agriculture Organization (FAO) and World Health Organization (WHO) (Zeng et al. 2015). This confirms the contamination of soils that are close to the Xikuangshan Sb mine as these vegetables were grown on the soils in the vicinity of the Sb mining site. Furthermore, results indicate the uptake and accumulation of Sb in vegetables and the health risks that are faced by the residents if they continuously eat the vegetables grown in soils close to the mines in Hunan, China.

Water is essential to humans, and the trace elements it contains are also vitally important to maintain a healthy life. Nevertheless, the presence of these elements in excess causes widespread illnesses and deaths. Toxicity of As in drinking water is a global issue. The presence of As in the well waters of Bangladesh and West Bengal is a familiar example (Finkelman et al. 2018). According to many researchers, higher As concentrations were mostly detected in narrow aquifers with heights lesser than 100 m (Mahmud et al. 2017). Lead (Pb) is also labeled as a toxic element in drinking water. Pb toxicity was apparent from the 2016 crisis in the USA. The administration changed Flint's main water source as river water that was rich in chlorides. Their main water supply lines to residents consisted of outdated pipes and the excessive chlorides made the Pb leak (Finkelman et al. 2018). The roles of the trace elements in human health are still not clearly understood. Guidelines are set for a range of elements in water (Finkelman et al. 2018). The human body is rich in calcium, and it is vital for bones and teeth. Magnesium is crucial to the heart, but calcium is an antagonist to magnesium, which prevents magnesium's uptake. Hence, maintaining the equilibrium between calcium and magnesium in drinking water is uppermost important. Further, reports about health impacts from macro-elements, namely sodium, potassium, and sulfate, needed to be considered (Finkelman et al. 2018). Coal considered a geochemically complex natural resource is derived from peat. The main constituent of coal is carbon from plants and animal remains, while it contains hydrogen, oxygen, nitrogen, and sulfur as the other major elements. Minor elements include minerals such as silicon, aluminum, etc., and halogens fluorine, chlorine, bromine, and iodine, and almost all the trace elements, for example, As, barium, etc. Coal geochemistry and the consumption of coal in vast amounts (almost 8 billion tons in 2015) (Finkelman et al. 2018) brought about extensive and severe health problems globally.

6.1.2 Anthropogenic Emerging Contaminants (AECs)

The number of toxic organic compounds that are being released into nature is increasing rapidly with the fast growth rate in the human population resulting in increased human activities. These pollutants are commonly termed as emerging organic contaminants of anthropogenic origin (AOECs) as they were not categorized as contaminants before. These AOECs are released from the essential items used in day-to-day life, whether a person is living in a town or the countryside. AOECs are a diverse collection of chemicals that could be excessive or degraded byproducts of medicine, processed food, materials used for individual up keeping such as pharmaceuticals and personal care products (PPCPs), insect or pest killers, wetting agents, substances used in fire controllers, additives used in industry, and many more. The constant presence of these AOECs in the environment is not necessary for their adverse effects as they are being introduced endlessly and at a faster rate than the rate of removal and transformation. Considering AECs, specific attention needs to be paid to polar AECs which containing acidic functional groups (specifically in medicinal drugs, chemicals in pest killers, intermediates formed from non-ionic wetting agents). They are highly water-soluble, and the degrading rate is comparatively slow. These AECs easily diffuse through normal purifications and also manufactured plants, hence considered as a possible hazard in the water supply systems. Furthermore, their presence had been recorded from beaches and though in minute concentrations, could be destructive to biota.

6.1.2.1 Pharmaceuticals and Hormones

Pharmaceuticals and hormones in the environment are considered as AECs due to their ability to produce adverse human and ecological health effects. With the increasing global population, pharmaceutical usage was increased by leaps, and it is estimated that the global market for active pharmaceutical ingredients abbreviated as API will escalate in the coming years due to the current coronavirus (COVID-19) pandemic. According to an estimation of the Food and Drug Administration (FDA) in the USA, selling/purchasing 80% of cephalosporin, 64% sulfa-containing medication, and 49% of tetracycline were for the cattle industry (FDA 2017). Wilkinson et al. (2017) discussed how these used drugs get into nature with the available various routes such as the effluents, disposals from industry, metropolitan runoffs, precipitation, and leakages from landfills. Furlong et al. (2017) performed an in-depth analysis on the presence and ambient concentrations of pharmaceuticals in water sources as well as in treated waters by collecting samples throughout America, and the analysis was conducted in two phases. In the first phase, 24 pharmaceuticals and in the second phase 118 pharmaceuticals were analyzed.

Excessive and indiscriminate usage of antimicrobials that are being released to the surrounding is a global concern. Studies conducted worldwide have identified unusually high concentrations of medications in different water sources such as supply systems providing water to the public for drinking, in the ground waters, surface waters, and also in wastewater treatment plants (Menon et al. 2020; Mohapatra et al. 2018, 2021; Priyanka et al. 2021). Normally, these compounds differ in their removal efficiencies. In addition to normal medications, antidepressants present in surface waters disturb the life cycles by influencing the behavioral patterns, breeding, and growth of the animals in water bodies mainly invertebrates, fish, and amphibians. The critical issue with these leftover substances (e.g., antibiotics, pesticides, and biocides) is that these get accumulated in the aquatic ecosystems and the bacteria present in these environments develop resistance against these compounds. Further, adverse effects on plants are numerous such as effects on chloroplasts and metabolic pathways and thereby disturbing food chains in these ecosystems.

6.1.2.2 Endocrine Disruptors

Endocrine-disrupting chemicals (EDCs) have received the most attention because field studies globally have revealed the drastic impact on aquatic vertebrates. These include synthetic estrogens, androgens, naturally occurring estrogens, organochlorine pesticides, alkylphenols, etc. EDCs include persistent organic pollutants in the food of animal origin, perfluoroalkyl substances due to their resistant properties to water and oil, parabens as food preservatives, veterinary drugs used in animal husbandry, from processed food, which could have been derived due to environmental contamination during processing procedures and through agricultural practices. Research conducted on 112 infant formulas (such as vegetables, fruits, cheese, meat, etc.) by Nobile et al. (2020) detected 4-hydroxybenzoic acid, which is the main metabolite of parabens (alkyl esters of 4-hydroxybenzoic acid), in the entire tested set. The presence of 4-hydroxybenzoic acid has been categorized as a byproduct of degradation. However, the researchers have not ruled out the possibility of the substance being discharged when vegetables and fruits were subjected to processing**.** The study by Arguello-Pérez et al. (2019) provides a reference on how to detect, forecast, and methodically assess the toxicity of CECs on the environment. Wastewaters released by the communities living in the coastal towns and villages of Cihuatlan, Jalisco, were analyzed for the CECs. The tested AECs included diclofenac, ibuprofen, ketorolac, pentachlorophenol, which were within the toxic range while concentrations of estradiol were high. It is assumed that these endocrine disruptive pharmaceutical drugs, diclofenac, ibuprofen, and ketorolac in combination, could significantly impact the environment. This underlines the necessity of an inventory of the possible compounds in a water sample to estimate the realistic level of ecotoxicological effect that CEC represents.

6.1.2.3 Rare Earth Elements (REEs)

Rare earth elements (REEs) are a group of 15–17 elements comprising 15 lanthanides, i.e., elements in the periodic table from 57 to 71, which include lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium, and the other two being yttrium and scandium. These REEs are vital to modern high technologies but now considered as emerging contaminants of anthropogenic origin getting accumulated in aquatic environments even in marine systems (Abbott et al. 2015). Anthropogenic gadolinium had been spotted in aquatic systems globally including the USA, Switzerland, and even from the UK. Due to the low presence of radioactive thorium in these REEs, they are considered as toxicants. Modern anthropogenic activities such as the equipment used in health care facilities, processes involved in petroleum cleaning, enrichments used in agriculture, extraction of non-renewable resources, hi-tech-based industries, supplementation in animal fodders, electronic waste, and recycling plants are the major sources that REEs are emitted to nature (Gwenzi et al. 2018).

6.1.2.4 Perfluorinated Compounds (PFCs)

Perfluorinated compounds (PFCs) are made up of carbon chains with bound fluorine atoms. These PFCs are a broad range of compounds' main constituents being perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA), and their salts. Recently, some of the complex PFCs which have other functional groups were renamed as per- and polyfluoroalkyl substances (PFASs) to separate them from the regular PFCs (Richardson and Kimura 2019). These are commonly found in fluoropolymer coatings; fire extinguishers, grease, electroplating, cleansers, plastics, resins, polishes, leather protectors, waterproof and greaseproof paper, packaging, fabrics, and even in landfills. These PFCs constantly get bioaccumulated and subjected to biomagnification in aquatic environments and considered a risk to biota as they cannot be easily degraded by microbial metabolism and due to their chemical stability (Lei et al. 2015). Environmental Protection Agency (EPA) Method 537 identified PFOA and PFOS compounds used as substituents for PFASs in the industry capable of contaminating the drinking water (Shoemaker and Tettenhorst 2018). This updated method could detect 18 types (previously 14) of PFAS molecules, including hexafluoropropylene oxide dimer acid (GenX) with three extra PFASs. 4,8-dioxa-3H-perfluorononanoic acid and GenX are substituents for PFOA. 6:2 chlorinated polyfluorinated ether sulfonate (F53B) contains PFASs and is used in chrome plating and as a mist suppressing agent, and China has been using F53B since the 1970s (Richardson and Kimura 2019).

6.1.2.5 Disinfection Byproducts (DBPs)

Most disinfection products (DBPs) are oxidizing agents with vigorous chemical activities used to remove pathogens. During disinfection procedures, they react with many deoxidizers forming many undesired byproducts such as chlorinated DBPs in purified waters (Lei et al. 2015). By 2015, there were more than recorded six hundred

DBPs, which included iodinated trihalomethanes and iododihalomethanes, dihalo aldehydes, bromonitromethanes, hydroxy acids, iodo carboxylic acids, 3- chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone esters, nitrosodimethylamines, etc. (Lei et al. 2015). Some studies have shown the association of DBPs with different types of cancers, but data is minimal about risks to humans upon trihalomethane (THM) exposure, and still, no real proof to advocate a link to cancer and the dose of THMs on animals (Lei et al. 2015). Research is ongoing to determine the health hazards concerning DBPs, but most studies end up with negative outcomes due to limitations in study designs.

6.1.2.6 Nanomaterials

Synthetic nanomaterials of approximately 1–100 nm are another group of pollutants that have been categorized under the AECs. The most widely used nanomaterial is nanosilver which had been added to consumer products such as clothing (baby blankets, towels, T-shirts, undergarments) and children's soft toys (Richardson and Kimura 2019). Furthermore, synthetic nanomaterials could be arranged into four groups as carbonic (fullerenes, carbon nanotubes (CNT)), metal oxides (silicon dioxide, titanium dioxide, etc.), semiconductors (cadmium tellurite, silicon, etc.), and metals (gold, silver, etc.). These manmade nanomaterials are used in multiple products and processes, ranging from sun cream products to IT technologies, transport, or agriculture. It is assumed that these nanoscale materials enjoy specific physical and chemical properties, for example, surface effects, small size, quantum effects, resistance to chemical and biological degradation, capable of generating undefined outcomes affecting humans and the ecosystem as a whole (Lei et al. 2015).

Effects of nanoparticles on humans, animals, or plants are not yet fully identified or studied thoroughly as the global use of these nanomaterials started recently. Therefore, understanding and documentation of the changes from macro- to nanoscale on biota will need some time.

It has been shown that when particles are prepared from the same material, in comparison to bigger particles, the smaller size of the particles is more lethal which means alterations in sizes can change the physical and chemical properties of a substance. Many have listed the risks of CNTs in agriculture, but advantages of CNTs on mustard plant growth have been documented (Stuart and Compton 2015).

6.1.2.7 Sunscreens and or Ultraviolet Filters (UV Filters), Perchlorates, Artificial Sweeteners, and 1,4-Dioxane

Sunscreens and or ultraviolet filters (UV filters) are another set of chemical components that have been categorized under AECs. These are mainly included in a diverse range of cosmetic products; fragrances, lipsticks, in hair caring such as shampoos, conditioners coloring, sprays, skin care creams and lotions, furnishings, and even in laundry products (Lei et al. 2015). Formulations of UV filters could be organic chemicals or inorganic minerals. As most of these are personal care products, they enter the water bodies due to the variety of anthropogenic activities mainly human cleansing. Humans and animals mostly get exposed to these through the food chain (Lei et al. 2015). Salts or esters of perchloric acids, named as perchlorates mostly used as oxidizers, are also considered as emerging contaminants. The attention of regulating perchlorates was considered in 2011 by the US EPA, but the maximum contaminant level (MCL) has not been set yet. In early 2019, the EPA requested feedback for perchlorates from the general public mainly about the MCL and a health-based maximum contaminant-level goal (MCLG) at 56 μg/L. Furthermore, observations were requested on three different monitoring choices in their drinking water policy, and one of them was the removal of the 2011 guideline of perchlorate in drinking water (Richardson and Kimura 2019). 1,4-Dioxane is an additive, used as a stabilizer for chlorinated solvents. Other sources that release dioxane are the coating industry, agriculture, landfill leachate, treating leather, and even pharmaceuticals. Studies have shown the human and animal risks due to the exposure to 1,4-Dioxane which route of exposure varying from drinking water, food, or occupational. Though cataloged as potentially carcinogenic, in most countries no guidelines are imposed for monitoring 1,4-Dioxane in the surroundings.

Sucralose is one of the artificial sweeteners made from sugar and sweeter than sugar. These artificial sweeteners are widely used in the food industry but even found in medicinal drugs. These chemical compounds are stable and persist in aquatic environments and as such grouped as an emerging contaminant of global concern. Many researchers probe the presence of these artificial sweeteners in water sources by observing their specific influence on biota. Many review articles have been published on artificial sweeteners even considering them as a wastewater indicator (Richardson and Kimura 2019).

6.1.2.8 Microplastics (MPs)

Microplastics (MPs) are considered CECs with their continuous accumulation in aquatic environments such as within rivers and lakes as well as in oceans. These MPs are minute, less than 5 mm and formed either by the degradation of larger plastics or directly from used products. The impact from MPs in marine environments is well documented, and most affected are the biota in the ecosystems ranging from animals including fish, marine reptiles, and birds to plants and microorganism (Kumar et al. 2020; Richardson and Kimura 2019). These MPs get bioaccumulated into organisms and subjected to biomagnification in the food webs. Microbeads are a particular type of MP used for multivariant purposes mainly in personal care products but due to the global understanding of the risks from these microbeads many countries including the USA, UK, and Korea have banned the usage of these while others are in the process of prohibiting of using such items.

6.1.3 Microbial Emerging Contaminants (MECs)

6.1.3.1 Antibiotic-Resistant Bacteria (ARB) and Antibiotic-Resistant Genes (ARGs)

The use of antibiotics started centuries ago, saving many lives from microbial infections. The extensive use of these substances for humans and in veterinary medicine started a few decades ago. These antibiotics and their metabolites are excreted from the treated organisms' bodies within a few days of consumption, and most of these end up in water bodies. Exposure of bacteria to these excessive drugs will make them resistant to particular antibiotics. They are named antibiotic-resistant bacteria (ARB), and these antibiotics are capable of exerting pressure on the microbial genes, thereby making specific genes resistant (ARGs) to these antibiotics (Bird et al. 2019).

The feasibility of genetic exchanges between bacteria is the key factor that drives the occurrence of ARB that containing ARGs in the surroundings of hospitals and patient care facilities as these environments are full of used antibiotics as wells antibiotics and ARB released from patients. ARBs manipulate the other bacteria in the environment by dispatching the ARGs through horizontal gene transfer (Bird et al. 2019). These ARBs are capable of self-replicating or vertical gene transfer for their continuity (Bird et al. 2019). Many studies have shown the excessive use of antibiotics as the principal cause for the development of drug resistance in bacteria. However, certain scientists are in the view that resistance occurs due to natural process which has been evolved from the past, by listing shreds of evidence such as the presence of ARGs in organisms collected from extreme environments such as ocean bottoms and hydrothermal vents which were not exposed to any human activities. Furthermore, antibiotic resistive elements had been discovered from ancient DNA dating back to 30,000 years.

Worldwide urban effluents containing hospital waste are the major releaser of ARB and ARGs while litter from animals and plants used in landfills, treatments of drinking water are some of the other avenues that ARB and ARGs get into water bodies (Richardson and Kimura 2019).

Studies carried on conventional sewage treatment plants have shown that these plants do not have the competence to eliminate most of the PPCPs, antibiotics, ARB, and or ARGs. When these treated waters are released to aquatic environments, they carry a mixture of biologically active components including bacteria, and the result is the contamination of the biotas with these pollutants (Cacace et al. 2019). ARBs and fungi were listed as causative agents for the 2.8 million infections and 35,000 deaths reported from America in 2019 (Centers for Disease Control and Prevention 2019). Bacteria can withstand the pressure from antibiotics due to the presence of various genes in their systems. According to the literature, bacteria possess 38 different tetracycline resistance genes (Grabert et al. 2018). Antibiotics can survive extensively in nature, but ARGs or DNA can survive only two years in the soil. Global reports on contamination of beaches by ARGs and ARB are enormous. A study by Belding and Boopathy (2018) recorded a significant amount of ARGs and ARB in natural surface waters closer to Chauvin and Port Fourchon, outlets of the lower Mississippi River. People in Louisiana engage in fishing and use these waters for the activities they conduct during their leisure. Bayou Lafourche is a 106-mile waterway, a key drinking water source for people in southeastern Louisiana, and the report by Bird and his team confirmed the presence of ARB and ARGs in the slow-flowing waters of Bayou Lafourche (Bird et al. 2019). A report of the Louisiana Department of Environmental Quality stated that deteriorating septic tanks and excess domestic wastes were the causes of fecal coliforms in Bayou Lafourche. Studies have shown that a large amount of PPCPs could be retained in sludge but released back into the environment with the application of biosolids into lands.

Treatment processes that are being practiced at sewage treatment plants are another source that generates more ARB and ARGs in wastewater. A study conducted at a municipal treatment system in south Louisiana reported that raw sewage and secondary effluents were containing methicillin-resistant *Staphylococcus aureus*, and free DNA of the *mec*A gene (Boopathy 2017). Interestingly, a higher antibiotic resistance was observed in treated sewage in comparison to untreated dirt, a clear indication of bacterial transformation with ARGs during the treatment process. Earlier it was thought that antibiotic resistance was due to the misuse of antibiotics in medical settings. The public alarm is mounting about the ARGs and ARB as they know how the particular AR genes and bacteria getting adapted and continuous survival in the wastewater treatment plants and the consequences when these treated waters are being discharged into aquatic environments (Cacace et al. 2019).

6.1.3.2 Algal Toxins

Toxins produced by dinoflagellates, diatoms, or cyanobacteria are a global problem owing to their possible adverse toxicity on living beings. Harmful Algal Bloom (HAB) species produce a wide array of toxins (mainly cyanotoxins), and people are exposed to those toxins through drinking water, consuming seafood, contact with contaminated water and aerosols during showering or recreational activities, and consumption of food crops irrigated with contaminated water (Liyanage et al. 2016). HABs are increasing in many geographical areas globally. Eutrophication in aquatic systems and the climatic changes favor the bloom formation. The well-documented algal toxins, anatoxin-a, cylindrospermopsin, microcystins, and saxitoxin produced by cyanobacteria are on the EPA Contaminant Candidate List 4 (CCL4). Recent reviews by Bouaïcha and Corbel (2016) and Testai et al. (2016) have emphasized cyanotoxins as an emerging freshwater contaminant citing examples in agroecosystems. It has been recorded that when plants are irrigated with cyanotoxin-containing water, the cyanotoxins are being absorbed into the plants through roots and transported into various plant parts and getting accumulated. Furthermore, a drop in crop production has been observed. Liang et al. (2016) displayed microcystin bioaccumulation in *Oryza sativa* plants irrigated with microcystin (MC)-contaminated water. When plant parts were examined at harvesting, MCs were detected in all tissues even in rice grains. These results highlighted the importance of monitoring and controlling irrigation water to avoid the harmful accumulation of MCs in food webs. Further, during rain, MCs can penetrate through soil particles drifting from the surface to the bottom layers, paying the way for groundwater contamination. Yang et al. (2016) confirmed that measurable amounts of MCs were present in groundwater samples that had been collected in the vicinity of Lake Chaohu, China. These waters are constantly used by the residents for drinking and also for their day-to-day activities even as water for irrigation making them a vulnerable group. Additional information on emerging and potential microbial contaminants can be found elsewhere (Magana-Arachchi and Wanigatunge 2020).

6.1.3.3 Mycotoxins

Mycotoxins, secondary metabolites of several fungi, are now classified as emerging contaminants found mostly in cereals and their products. Vaclavikova et al. (2013) defined them as "Emerging mycotoxins, that are not monitored customarily, and no guideline values are imposed but continuously detected mostly in food products as a natural toxicant". Recent studies have shown fusaproliferin, moniliformin, beauvericin, NX-2 toxin, and enniatins as emerging mycotoxins which are produced by *Fusarium* species colonized mainly in corn, rice, wheat, etc. used in the production of food and fodder (Jajić et al. 2019; Yoshinari et al. 2016). A particular interest is placed on emerging mycotoxins because of their constant occurrence in food and feedstuff. Many studies are being conducted to determine the level of contamination when processing food starting from raw materials, intermediate products to end product as well as adverse risks to people and animals by unknown exposure.

Further, *Alternaria* species that grow on vegetables, fruits, and cereals during their secondary metabolism release *Alternaria* mycotoxins considered as emerging hazardous pollutants. Considering the chemical structure, *Alternaria* mycotoxins have grouped into five major chemical classes; dibenzo pyrone derivatives (altenuene, alternariol, etc.), tetramic acid derivatives (tenuazonic acid and isotenuazonic acid), perylene quinones (altertoxins, alterperylenol or alteichin), stemphyltoxin, and anthraquinones (Macrosporin A, Altersolanol A) (Escrivá et al. 2017).

Infant formulae or substituents for breast milk are introduced to an infant's diet after the first few months of babies' birth. Development of the human immunity system completes by the time of puberty, as such infant's immunity systems are not capable enough to fight against food contaminants. An assessment for 46 mycotoxins and their major metabolites in infant food was carried out by Braun et al. (2021), by screening 59 samples and were able to detect trace levels of 17 mycotoxins. Among recorded were aflatoxin B_1, zearalenone, deoxynivalenol, and fumonisin B_1. When compared the infant formulas with products from cereal grains, the level of contamination was lesser in infant formulae. According to their conclusions, the majority of toxins had lower concentrations or were closer to their relevant limit of quantitation (LOQ) values. Nevertheless, two flour samples used in preparing infant food contained aflatoxin $B_{1,}$ which was above the standard value. The two toxins aflatoxin and sterigmatocystin had been present in 3 and 17% of infant foods, and it was the first record about those toxins.

6.2 Co-occurrence of AECs, MECs, and GECs in Nature

Toxicants originated due to geogenic and human activities are subjected to natural geochemical processes thereby getting transported to various ecosystems and ending up in different environments sometimes even with alterations in their chemical compositions. These heavy metals and metalloids can form stable complexes and with the assistance of temperature and pressure, and with pH variations in surface and ground waters, could persist in the environment for a long time (Finkelman et al. 2018). Naturally, As and Sb occur in the soil in trace amounts but human activities, such as extraction of minerals from the earth, metal processing, farming and husbandry, and the burning of fossil fuels are some of the processes that release As and Sb to the environment (Fei et al. 2017). Antimony mining is renowned as the key factor that releases and Sb into nature, and this can be due to both current activities as well as the past activities where the release of wastes from the abandoned, unmanaged contaminated sites. Soils of these deserted lands could be contaminated with these elements, and when the soils are used for cultivation or used for grazing, many pasture plant species and crops uptake water that is being contaminated with these As and Sb. These elements get transported and bioaccumulated to different plant organs and tissues (Abad-Valle et al. 2018). There is a possibility of As and Sb in the soil getting washed off to surrounding water bodies and also to groundwater, causing water deterioration and biomagnification into the food web causing adverse effects on biota and ecosystems (Abad-Valle et al. 2018; Fei et al. 2017).

Mbadugha et al. (2020) concentrated their study on an abandoned mine catchment in Southern Scotland, but their research outcomes are of global importance. Louisa mine share similarities with other antimony mining sites worldwide, both derelict and operational, and have shown the impact of geogenic and anthropogenic activities on the water quality. The technology incorporated in the analysis could discriminate the source of pollution of soil as anthropogenic while the As to Sb ratio in surface water confirmed the source as geogenic in origin. The study outlined the importance of identifying the source and form of the contaminants to minimize the risks due to unwanted exposure to them (Mbadugha et al. 2020).

Identified as a productive land for agriculture, the region of Holocene quaternary alluviums of Middle-Ganga Plain (MGP) is full of As buildups. As passes to groundwater system by the overuse of hand pumping and also due to differences in redox potentials causing iron-oxy-hydroxides (Fe-OOH) to dissolve. In the presence of O_2 and NO_3^- microbes are capable of degrading the sedimentary organic deposits thereby releasing As to the environment. The process gets speeded up with favorable mineralogical and geological conditions. According to Singh et al. (2020), human activities disturb the groundwater symmetry of the balance between the oxic and anoxic zones increasing the buildup of metal oxyhydroxides. The uptake mechanism of As into organisms including plants is unintentional. Singh et al. (2020) had assessed the anthropogenic forcing and exceedance probability of As exposure in the particular site at MGP through inverse modeling and many other techniques. The change in exceedance probability of arsenic concentration measurements was observed during pre-and post-monsoon times. Above 5 μgL^{-1} concentration fell radically from greater than 0.8 in the pre-monsoon to 0.5 during the post-monsoon, which was attributed to the natural recharge in the plain. The study indicates the necessity of monitoring the groundwater pumping during the pre-monsoon. Furthermore, the emphasis was made on proper discarding of chemicals that are affecting the pH and oxidation–reduction potential. Particularly As mobilization needs to be minimized as though the natural recharge is high. The study recommends cooperating probable exceedance and saturation status of groundwater in calculations and also not to limit the susceptibility estimates to current situations.

Studies of Saha et al. (2019) have shown the coexistence of CECs of geogenic and microbial origin in their study area in Bangladesh and how water quality in groundwater gets deteriorated by a large number of salts and high As concentrations. Offensive levels of As, Fe, and salinity were recorded in most sampling sites, with the point of use having the greatest number of coliform bacteria.

The poor quality of potable-water sources is a substantial problem faced by a majority of Brazilians, living in heavily populated southeastern states of Sao Paulo, Rio de Janeiro, and Minas Gerais. The presence of CECs in the vicinity of towns was reported by several authors (Campestrini and Jardim 2017; Montagner et al. 2019). In addition to pharmaceuticals, surfactants, and parabens, Campestrini and Jardim (2017) examined the presence of illicit substances in drinkable-water sources. Cocaine (COC) and its metabolite benzoylecgonine (BLGN) were detected in water samples taken from reservoirs and rivers that supplying water to inhabitants in Sao Paulo. The concentrations of COC and BLGN were 62 and 1019 ngL^{-1}. Further, in tap water, values recorded were around 22 and 652 ngL^{-1} for COC and BLGN, respectively. Another study done in Southern Brazil analyzed PPCPs in WTP and bottled mineral water. Methylparaben (MeP) was detected below the LOQ in the water samples from the WTP but was quantified as 10 ngg^{-1} in one of the WTP sludge samples, demonstrating that the sludge behaves as a basin for MeP. The values reported in mineral water samples were higher than the WTP (< LOQ-242 ngL^{-1}), implying the contamination may have happened either in the mineral water source or during the process of water bottling (Marta-Sanchez et al. 2018).

A study by González-Plaza et al. (2019) on antibiotics shows the effect of AECs on the environment. The study was designed on antibiotic production plants where he analyzed ARG effluents released from azithromycin synthesis and veterinary drug formulations. The analysis was also conducted on residues in receiving waters (river and creek). According to observations, the release of ARGs *sul*1, *sul*2, *qac*E/*qac*EΔ1, tet(A), class 1 integrons (intI1), was similar in both production processes, and lncP-1 plasmids (*kor*B) were present in high numbers in receiving waters. The action of zinc orthophosphate (prevent eroding in the drinking water supply) on ARB and ARGs in drinking water was investigated by Kappell and coworkers. The analysis included nine antibiotics, and results indicated a considerable variation in numbers of ARB. Gene expression analysis confirmed the differences in the abundance of *intI*1, *sul*2, and *qac*H genes and how the concentration of zinc orthophosphate influences the level of expression (Kappell et al. 2019).

A joint study conducted by researchers from India and Sri Lanka has shown the vulnerability of surface waters by evaluating the selected river waters that flow through urban cities of two countries. Focus of the research was on the relationship between coexisting PPCPs, enteric virus, ARB, metal, fecal contamination, and ARGs with climatic changes. According to findings, antibiotic resistance was not correlated with the prevalence of PPCPs and *Escherichia coli*, but with anthropogenic pollution and lifestyle. Furthermore, most of the tested isolates were resistant to multiple drugs, and interestingly, the resistance was greater for older generation antibiotics and the detected resistant genes *gyr*A, *tet*W, *sul*1, and *amp*C were common to both countries (Kumar et al. 2019).

Soils containing toxic metal pollutants tend to attract metal-resistant bacteria, but there is mounting anxiety that metal contaminants can also act as co-selective agents triggering antibiotic resistance in nature. Zhao et al. (2019) were able to calculate the ARGs and selected mobile genetic elements (MGEs) present in possible potential ARG hosts of fifty samples that were collected from metropolitan and suburban soils from the city of Belfast. Analysis recorded 164 ARGs with an average absolute abundance of 3.4×10^7 ARG gene copies/g of soil. The value of horizontal gene transfer in ARG distribution was emphasized by Yuan et al. (2019), and a correlation was noted between the abundance of ARGs and MGEs.

Additionally, a concurrence was observed between a certain group of metals (As, Cd, Co, Cr, Cu. Hg, Ni, and Zn) with ARGs. Furthermore, the influence of soil metal toxicity index on the number of detected ARGs ($\lambda = 0.32$, $P < 0.001$) and the abundance of metal co-occurring ARGs ($\lambda = 0.612$, $P < 0.001$) via effects on MGEs were exposed (Yuan et al. 2019).

Cyanotoxins, well known for their potential toxicity, are the outcome of endless urbanization and irregular bad practices in agriculture which release excessive nutrients to both marine and freshwater ecosystems. A country-wide survey in USA consisting of 1161 lakes and reservoirs discovered that hepatotoxic microcystins were prevalent in 32% of the sampled lakes with a mean concentration of 3.0 $\mu g\ L^{-1}$ (Loftin et al. 2016). Cylindrospermopsins were present in 4.0% of sampled lakes while saxitoxin, anatoxin-a, and nodularin-R were also detected in 7.7%, 15%, and 3.7% of the samples, respectively. However, any significant co-occurrence of cyanotoxins among the surveyed sites was not detected.

6.3 Ecotoxicological and Relative Environmental Risks from AECs, MECs, and GECs

If to answer the question of what ecotoxicology is, it is a tool that serves for the evaluation of environmental quality. With ecotoxicology, one can identify both the disturbances and the impacts on an ecosystem, or the environment generated by toxic pollutants. Aquatic environments adjacent to the agricultural fields are influenced by a wide array of CECs. Snow et al. (2017) have focused their comprehensive review on ECs including hormones, steroids, antibiotics, and antibiotic resistance genes and their environmental risk in agricultural environments.

Steroid hormones are frequently found in soil and aquatic environments and have gained notable attention recently due to their endocrine-disrupting effects. Zhang et al. (2016) showed the effects of co-occurrence and persistence of two steroids isomers in a sandy and a silt loam sediment. According to their findings, β-isomers degrade more rapidly than the α-isomers in both sediment types, demonstrating that stereoselectivity in steroid degradation. Further, observation was that the rate of degradation is decreased when both isomers were present together in the sandy sediment. However, no significant changes were observed in the silt loam sediment. This sediment type-specific behavior of isomers could be possibly explained by the abundance of organic carbon and nutrients present in the sediments. Their findings highlight the co-occurrence of stereoisomers of steroids could persistence in the soil for a prolonged time could pose a significant environmental risk.

According to the WHO estimates, 10% of the global population consumes food produced from crops irrigated with wastewater. Consequently, it can cause severe damages to groundwater, soil, crops, and human health. The Mezquital Valley in Mexico is involved in agriculture, and the waters to irrigate these lands are from the City of Mexico. The wastewaters are pumped to the city by using a complex system comprising of dams and irrigation channels. Lesser et al. (2018) analyzed untreated water collected from dams and canals for different classes of chemicals and revealed the presence of 14 volatile and semi-volatile organic compounds, naphthalene, 65 pharmaceuticals, and 3 hormones. Metformin (MET) was the most abundant pharmaceutically active compound and the highest concentration was 107 mgL^{-1} indicating the diverse range of toxic compounds that are present in wastewaters being used for irrigation which could pose adverse effects on human health.

A recent study conducted by Rivera-Jaimes et al. (2018) has detected three common pharmaceuticals namely, naproxen, paracetamol, and diclofenac, with concentrations up to 14.9 mgL^{-1} in a wastewater treatment plant (WWTP) in Cuernavaca, Mexico. Moreover, a study conducted in Bogota, Colombia, by Bedoya-Ríos et al. (2018) showed the presence of endocrine disruptors predominantly pharmaceuticals, plasticizers, and hormones in tested water sources. The highest bis(2-ethylhexyl) phthalate and diphenyl phthalate were identified in wastewater with a concentration of 309.6 mgL^{-1}, while bisphenol A and carbamazepine were amounting to 22.73 mgL^{-1} and 15.15 mgL^{-1} respectively. There is a possibility of higher concentrations of pharmaceuticals in hospital effluents than in domestic sewage due to the wide usage of antibiotics on patients in hospitals. Porto et al. (2019) analyzed hospital effluents in Sao Paulo, Brazil, and showed the presence of antiparasitic drugs in concentrations up to 3.81 mgL^{-1}. Also, a study conducted by Chiarello et al. (2016) in Southern Brazil, tested for pharmaceuticals in hospital sewage samples and reported MET, paracetamol, and enalapril with concentrations of 2 mgL^{-1}, 7.5 mgL^{-1}, and 1 mgL^{-1} respectively.

Estrada-Arriaga et al. (2016) conducted a study in Mexico, to evaluate the emerging pollutants in the waste coming out of two biological nutrient removal wastewater treatment plants (WWTPs). They found out low removal efficiency in the first plant with the final effluent concentration ranged from < LOQ to 3.77 mgL^{-1}. During dry periods, increased effluent concentrations were observed. Most of the compounds reported in the influent of the second plant were moderately or completely removed and the final effluent concentrations were below 0.21 mgL^{-1}. A study conducted by Rozas et al. (2016) showed the presence of organic micropollutants such as atrazine (ATZ), caffeine (CAF), diclofenac (DIC), and triclosan (TCS) in the effluent of two WWTPs near Biobío River, Chile. The removal efficiencies of CAF and TCS were higher while ATZ and DIC were still reported in high concentrations. Further, Díaz and Peña-Alvarez (2017) performed a study in the highly polluted Tula River in Mexico, to determine pharmaceuticals and personal care products in both water and sediment samples. The highest naproxen (NAP) concentration (250 ngL^{-1}) was detected in river water samples while TCS, NAP, and ibuprofen (IBU) concentrations were below 5 ngg^{-1} in sediment samples.

Elliott et al. (2017) carried out a study to determine CECs in 12 US tributaries to the Laurentian Great Lakes. The number analyzed included 292 samples from surface waters and 80 from sediment for approximately 200 chemicals. One-third of the tested water and sediment samples had a total of 32 and 28 chemicals. Concentrations of indole in water were 0.0284 μg/L, and cholesterol was 72.2 μg/L, while in sediments it was 1.75 μg/kg for diphenhydramine and 20,800 μg/kg for fluoranthene. Cluster analysis observed that sites receiving similar inputs contain specific distinct CECs. As an example, pharmaceuticals and flame retardants co-occurred in WWTP effluents. Comparison of the obtained values to water and sediment-quality standards indicated how these polycyclic aromatic hydrocarbon concentrations have surpassed the set limits in both water and sediment samples. Moreover, in some rivers noted values for bis(2-ethylhexyl) phthalate and dichlorvos were above the standard levels.

Antibiotic resistance bacteria and antibiotic resistance genes are frequently found in different environments which are contaminated with wastewater releasing from industrial plants, healthcare services, and agricultural fields. ARGs are commonly recorded from Latin American countries, such as Argentina, Southeastern and Southern Brazil, and Mexico. Recent findings also demonstrated domestic sewage is another culprit for ARB since antibiotic resistance could transfer from domestic WWTP sewage to water bodies. Lopes et al. (2016) evaluated the occurrence and risk of spreading the antibiotic-resistant bacterial strains belonging to species *E. coli* in WWTP in western Parana State, Brazil. The results showed the occurrence of cephalothin, streptomycin, and amoxicillin resistance *E. coli* isolates in the WWTP effluents and sediment samples. A study conducted in Southeastern Brazil found

ARGs in raw sewage and activated sludge from a WWTP based on a culture-dependent and metagenomic approach (Paiva et al. 2017). Resistance ranged from 62.5 to 100% and 25.4 to 86.2% to quinolones and aminoglycosides, respectively. Further, multi-resistance was high in raw sewage at least for three antimicrobials. Moreover, a study conducted by Oliveira et al. (2018) appraised the resistance profiles of *Pseudomonas aeruginosa* strains from a domestic WWTP in Southeastern Brazil. *P. aeruginosa* strains showed the maximum resistance to Imipenem and Meropenem among the tested antibiotics. This study also showed the frequency of occurrence of ARB was higher in raw sewage than in the effluent which may due to the removal of bacteria during the treatment process.

Antimicrobial resistance had also been detected in a solid waste sorting plant in Southern Brazil. Among the tested 344 bacterial isolates, 89.5% were resistant to at least one antibiotic and 60% of them displayed a multi-resistant profile. Also, the isolated strains showed high resistance to ampicillin (AMP) (Heck et al. 2015).

However, wastes from households and healthcare facilities are not the sole sources for ARB and ARGs in the environment. Livestock wastewaters originating from animal husbandry are also a source for the ARB and ARGs since antibiotics are regularly used to control bacterial infections. A study conducted by Gambero et al. (2018) showed the occurrence of antibiotic-resistant *E. coli* in an agroecosystem in the Barranquita-Knutzen basin, Argentina. *E. coli* present in both surface and groundwater ecosystems showed higher resistance to AMP and tetracycline which are frequently used as veterinary antimicrobials. Furthermore, in comparison to surface waters, antibiotic-resistant strains were more prevalent in groundwater. Furlan and Stehling (2018) showed the presence of β lactamases encoding genes in feces, soil, and water samples collected from a Brazilian pig farm and their findings highlighted the potential of spreading β-lactam antibiotic-resistant bacteria in the surrounding environment. Another study conducted in pig farms of Southern Brazil showed the presence of antibiotic-resistant *E. coli* strains in manure, water, and soil samples (Brisola et al. 2019), displaying the highest resistance to trimethoprim, colistin, and enrofloxacin with percentage values of 63.70, 45.19, and 39.26, respectively. Also, 37.04% of the isolates showed multi-drug resistance against at least three antimicrobials.

Contamination of aquatic biota by ECs was supported by the studies conducted in Brazil. These analyses emphasize the risks faced by humans due to the consumption of edible fishes that contain CECs in their tissues. Guidi et al. (2018) evaluated 14 antimicrobials in muscles of Nile tilapia and rainbow trout and only detected enrofloxacin above the limit of quantification. Moreover, Monteiro et al. (2016) conducted research to determine antibiotic residues in muscles of cage farm nurtured Nile tilapia in the border between Southeastern and Central-West Brazil. Oxytetracycline (OXTC), florfenicol (FFC), and TC were detected above the limit of quantification, the highest concentrations were reported in small fishes, and the concentration of OXTC and TC in large fishes was below the maximum residue limits established by the European Union regulation (Monteiro et al. 2016).

Gomes et al. (2017), in their review, discuss the hazardous effects of ECs on soil biota and the limitations in existing data as well as what soil ecotoxicologists can do to minimize bioaccumulation of these ECs on the soil. Study points out the need to focus on developing standard protocols for more soil species and more sensitive endpoints; in getting information about the real impacts on natural communities by ECs and especially on soil functions, which are still poorly addressed in studies related to emerging contaminants (Gomes et al. 2017).

European Union in order to protect both human and environmental health had recommended critical limits of 50–100 and 10–50 mgkg^{-1}, respectively for As and Sb in risk assessment of soil (Tóth et al. 2016). The current drinking water criterion for As is around 10 μgL^{-1}. A study by Saha et al. (2019) recorded that in their study sites of Bangladesh had AECs and MECs coexisting in the most drinking water sources and those are not suitable for drinking water purposes. Around 0.12 million or 40% of the residents in the study area fulfill their drinking water requirements from these polluted waters and as such are vulnerable to acute and chronic health effects.

Plant growth and nutritional quality reduction, gene mutations or toxicity on genetic material, neurotoxic effects in animals, bioaccumulation in food chains, the chronic and acute risk to soil organisms are some ecotoxicological effects cause by REEs of anthropogenic origin. People can contact REEs through consuming contaminated water and food, inhaling with air, or direct intake in medical treatments (Gwenzi et al. 2018). REEs also found in body samples such as hair, nails, and biofluids. Listed risks from REEs to humans include damages to kidneys such as nephrogenic systemic fibrosis and severe damage to nephrological systems associated with Gd-based contrast agents, in the proper functioning of the nerves or dysfunctional neurological disorder, fibrotic tissue injury, oxidative stress, pneumoconiosis, cytotoxicity, anti-testicular effects, and male sterility (Gwenzi et al. 2018). Moreover, Perrat et al. (2017) showed a positive correlation between Gd concentration and mortality of daphnids.

In this chapter, we have discussed the three types of CECs (GEC, AECs, and MCEs) and their global presence in diverse environments. Table 6.1 summarizes the facts we have considered in the above sections, but as new CECs are being identified daily this table needs to be revised constantly.

6.4 Conclusions

Humans and the ecosystem are exposed both knowingly or unknowingly to emerging contaminants either microbial, geogenic, or anthropogenic in origin through different methods. Our BC demonstrates how these ECs originate from different sources, their coexistence, potential challenges to the soil, water, air, ecosystem, and human health. Often these emerging contaminants could be detected in aquatic ecosystems, and due to their low level of presence, sensitive analytical equipment is necessary for continuous monitoring. Study about emerging contaminants is vital as some of the health hazards they cause to human beings and the impact on aquatic biota are known, with

Table 6.1 Emerging contaminants: their source and potential health risks

Category	Contaminants	Source/exposure route	Potential health risk	Guideline values	References
Geogenic emerging contaminants	Uranium (U)	Groundwater: Drinking water source Naturally occurring mineral: From soils and high uranium-containing rocks such as granite	Chronic kidney disease (CKD)	30 µg/L	Coyte et al. (2019), WHO (2017)
	Fluoride (F^-)	Groundwater: Drinking water source Fluoride-bearing minerals: fluorite (CaF_2), cryolite (Na_3AlF_6), fluorapatite ($Ca_5(PO_4)_3F$)	Fluorosis: mottling of teeth; deformed, brittle bones	1.5 mg/L	Coyte et al. (2019), Finkelman et al. (2018), WHO (2017)
	Arsenic (As)	Volcanic emissions or mineral weathering Groundwater: Drinking water source As-bearing solids: Inhalation and ingestion	Vomiting, diarrhea, hyperpigmentation, keratosis, hypertension, skin cancer, bladder cancer, lung cancer, kidney cancer	10 µg/L	Finkelman et al. (2018), WHO (2017)
	Antimony (Sb)	Volcanic emissions or mineral weathering Groundwater: Drinking water source Inhalation, food, and dermal exposure	Irritation of the eyes, skin, and lungs	20 µg/L	Fei et al. (2017), WHO (2017)

(continued)

Table 6.1 (continued)

Category	Contaminants	Source/exposure route	Potential health risk	Guideline values	References
	Lead (Pb)	Ingestion by hand–mouth contact, inhalation Groundwater: Drinking water source Heavy metal in mines	Loss of appetite, fatigue, renal dysfunction, hypertension, birth defects, mental retardation, autism, paralysis, kidney damage, brain damage, coma, peripheral neuropathy	10 μg/L	Michaels (2020), WHO (2017)
Microbial emerging contaminates	Mycotoxins: Beauvericin (BEA)	Wheat flour, corn, durum wheat	In vitro cytotoxic activity[a] (Human cell lines)	Guideline values have not been established	Yoshinari et al. (2016)
	Mycotoxins: Enniatins (ENNS)	Wheat flour, maize	In vitro cytotoxic activity[a] (Mammalian cell lines)	Guideline values have not been established	Jajic et al. (2019), Yoshinari et al. (2016)
	Algal toxins: Cyanotoxins [microcystins, nodularins, anatoxins, cylindrospermopsin, and saxitoxins]	Drinking water, consuming seafood, contact with contaminated water and aerosols during showering or recreational activities, consumption of food crops irrigated with contaminated water	Skin irritation, chronic kidney disease, neurodegenerative diseases, abdominal pain, muscle and joint pain, headache, fever, vomiting, nausea, dry cough, diarrhea, pneumonia, liver damages	Microcystin- LR: 1 μg/L	Liyanage et al. (2016), Yang et al. (2016), WHO (2017)

(continued)

Table 6.1 (continued)

Category	Contaminants	Source/exposure route	Potential health risk	Guideline values	References
	Algal toxins: Brevetoxins	Consuming contaminated shellfish, inhalation	Gastrointestinal illness reduced respiratory function acute and subacute respiratory effects	No specific guideline value[c] 0.8 mg brevetoxin-2 equivalent per kg (in edible portion) in USA, New Zealand, and Australia	Turner et al. (2015)
	Antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs)	Urban wastewater treatment plants (UWTPs), sludge, animal waste, hospital wastewaters, municipal wastewaters Drinking water, irrigational activities, recreational and occupational activities	Death due to ARB-related illnesses	Guideline values have not been established	Michael-Kordatou et al. (2017), Richardson and Kimura (2019)
Anthropogenic emerging contaminants	Surfactants	Laundry detergents, emulsifiers, pesticides, or resins Drinking water, bathing, recreational activities	Dermatitis, aphthous ulcer	No specific guideline value[c]	Barroso et al. (2019)

(continued)

Table 6.1 (continued)

Category	Contaminants	Source/exposure route	Potential health risk	Guideline values	References
	Perfluorinated compounds (PFCs)/ Per- and polyfluoroalkyl substances (PFASs)	Textiles, food wrappers, non-stick cooking pans, building paints, adhesives, electronics, cosmetics, and firefighting foam, groundwater (drinking water), accumulation in plants and crops	Bladder and prostate cancer, low birth weights of infants, effects on the vaccine-induced immunity in children, thyroid hormone disruption	No specific guideline value[c]	Richardson and Kimura (2019)
	Disinfection byproducts (DBPs)	Drinking water, swimming pool	Bladder, colon and rectal cancer, fetal loss, birth defects, asthma	Chloroform: 0.3 mg/L Bromoform: 0.1 mg/L Dibromochloromethane: 0.1 mg/L Bromodichloromethane: 0.06 mg/L	Li and Mitch (2018), Richardson and Kimura (2019), WHO (2017)
	Nanomaterials (NMs): Nanosilver (nAg), $nTiO_2$, nZnO, and $nCeO_2$	Food and food packaging, medical products, pharmaceuticals, paints, cosmetics, sunscreens, sewage spills, surface waters, soil, crops Inhalation, injection into the bloodstream, passage through the skin	Lung inflammation, allergic response	Guideline values have not been established	Richardson and Kimura (2019)

(continued)

Table 6.1 (continued)

Category	Contaminants	Source/exposure route	Potential health risk	Guideline values	References
	Flame retardants: Brominated (BFR) and organophosphorus flame retardants (OP)	Electronics and electric devices, household appliances, tools, and utensils	Potential reproductive, developmental, and neurological effects	Guideline values have not been established	Barroso et al. (2019)
	Plasticizers	Polyvinylchlorine products, building materials, toys, clothing, perfumes, and food packaging	Endocrine disruptors	Phthalates (DEHP): 8 μg/L	Barroso et al. (2019), WHO (2017)
	Sunscreens and or ultraviolet filters (UV filters)	Wastewater, WWTP, rivers, lakes, and ocean	Endocrine disruptors	Guideline values have not been established	Ramos et al. (2016)
	Sweeteners: Acesulfame	Foods, soft drinks Surface waters: Raw sewage and WWTP effluents, groundwater	Genotoxicity, cardiac diseases	Guideline values have not been established	Buchner et al. (2019)
	Pharmaceuticals: Naproxen, acetaminophen, diclofenac, lipid regulator bezafibrate Organic micropollutants: Paracetamol and ibuprofen	Wastewater, atmospheric particulates and precipitation, landfill leachate, groundwater, drinking water	Low risk due to acute exposure while chronic toxicity is not known[b]	Guideline values have not been established	Koopaei and Abdollahi (2017), Wilkinson et al. (2017)

(continued)

Table 6.1 (continued)

Category	Contaminants	Source/exposure route	Potential health risk	Guideline values	References
	Triclosan (TCS, 5-chloro-2-(2,4-dichlorophenoxy) phenol	Personal care products: soaps, toothpaste, hand sanitizers; household items: fabrics, trash bags, ceramics, children's toys; healthcare products: gloves	Skin irritation, endocrine disruption, allergies, effect on thyroid hormone metabolism	0.17 nmol/kg/day (Daily intake)	Olaniyan et al. (2016)
	1,4-Dioxane (Solvent stabilizer)	Detergent and chrome-plating plants, WWTPs, surface water, groundwater Consuming contaminated food and water, dermal contact, breathing contaminated air	Eyes, nose and skin irritation, nausea, headache	50 µg/L	McElroy et al. (2019), EPA (2017), WHO (2017)
	Microplastics	Oceans, lakes, and rivers, landfill leachates, drinking water, foods Ingestion, inhalation, dermal contact	Oxidative stress, inflammation, cancer	Acrylamide: 0.0005 mg/L Epichlorohydrin: 0.0004 mg/L 1,4-dichlorobenzene: 0.3 mg/L Styrene: 0.02 mg/L Vinyl chloride: 0.0003 mg/L	Sana et al. (2020), WHO (2017)

[a] Confirmed only by in vitro assays
[b] Based on the available toxicological data
[c] Guideline values differ among countries. Most of the countries do not have stipulated guideline values

their coexistence there could be suspected adverse ecological risks or human toxicological effects not yet entirely determined. Additionally, these emerging contaminants can undergo natural and chemical degradation processes, and therefore the attention should also be drawn to the resultant products. Further, careful monitoring and detection of ECs are vital for minimizing the potential human health impacts since the effects of some ECs remain largely unknown.

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