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Advanced Chemical Approaches for Environmental Sustainability: Innovations in Pollution Remediation and Green Chemistry

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Annotation: The tremendous advances in chemical approaches to pollution remediation, bioremediation and genetic engineering, while exhibiting remarkable scientific innovations, have been and will continue to be revolutionary in chemical treatment methods for a more sustainable environment. The principles of green chemistry have provided a strong foundation for inventive chemical engineering to solve up-to-date industrial challenges associated with environmental sustainability. Easy-to-implement, on-demand, and sustainable chemical approaches to lower the pollution risk are practically important to achieve the goal of green and sustainable chemical industry. Pollutants exhibit a great variety of compositions, phases, and concentrations, which have required novel chemical approaches with specific ingenuity for their effective remediation.

Over the years, great efforts have been dedicated to conduct basic studies to better understand the characteristics of the new instantaneous air pollution sources. It has become a common belief that volatile organic compounds (VOCs), which severely deteriorate air quality, are mainly released to the atmosphere from the fast-developing chemical industrial

parks. The natural gas processing plants, oil and alkene field basins with over-800-kilometer-distance from populated cities bear a constant risk of releasing overwhelming quantities of aliphatic, aromatic, olefin, and alkyne hydrocarbon pollutants in accidents.

Despite their serious hazards to air quality, health and environment, few advances have been made in conducting air pollution treatment studies that are only practical in the atmospheric background. It is of necessity to develop portable and catalytic converters with low processing temperature, long-term desorption active sites, and low-cost catalysts. Reactive chemical station could be designed with wires carrying customizable oxidation products from pre-customized upstream units, which divert formal changeover points into gradual peaks. Tracked points would disperse flow smoothly before being directed to matched oxidation units but amount more to nitro-products. Robust stoichiometric design could efficiently avert wide-formulated thermal runaway in reactor structures before long-distance transport to selective combustive reactors.

Green bioremediation process is a sustainable biotechnology that uses microbes to eliminate waste pollution from contaminated environments. It draws from biological principles and design strategies that have evolved over the hundreds of millions of years of evolution on earth. In biological products biosorption/sequestration, contaminants are passively sorbed to cellular surfaces and then chemically modified through enzymatic reactions in biotransformation and bioaccumulation processes. The biological mechanism of the existing bioremediation methods and innovative and translational research into bioremediation by metabolic engineering and genetic engineering are discussed.

1. Introduction to Environmental Sustainability

Environmental sustainability (ES) has become an urgent global challenge, as environmental pollution, resource shortages, climate change, and biodiversity loss are threatened by rapid economic development. To promote the goal of sustainable development, various International Institutions strive to enhance environmental sustainability in industrial production processes, including. In national governments, environmental protection agencies, and policies focus on reducing and recycling pollutants, which will help achieve environmental sustainability.

Designing sustainable chemical processes using innovative innovations, including advanced chemical approaches for reducing, reusing, AND recycling pollutants, should be the first response in pollutant remediation. ES can be achieved by avoiding water pollution during coal mining, concentration, and gasification processes. Green chemistry and engineering have recently offered tremendous new techniques and innovations in sustainable industrial production practices. Advances in green chemistry and engineering include utilizing new nanomaterials in catalytic processes and pollutant remediation, developing enzymes for highly selective and green organic reactions, and sustainable synthesis of new biomaterials and polymers. Green chemical approaches for environmental sustainability are promising to minimize negative impacts on to develop new, green, carbon-neutral chemicals as renewable fuel precursors [1].

Innovative advanced chemical approaches must be developed to enhance environmental sustainability and achieve the goal of sustainable production practices. Environmental sustainability addresses the concept and importance of sustainability in general and environmental sustainability in specific fields. The role of chemical/polymers in environmental pollution and sustainability challenges is outlined, focusing on innovating advanced chemical approaches for pollution monitoring, prevention, analysis, and remediation. The advanced techniques and innovations include chemical sensors and sensors for monitoring pollutants, sustainable green chemistry for pollution prevention, and hybrid advanced nanomaterials for polluted environment remediation. Principles of innovative environmental aspects will be discussed to accommodate individual targets. The need for advanced chemical techniques will be summarized to enhance environmental sustainability in pollution remediation and green chemistry [2].

2. Overview of Pollution and Its Impact

Pollution is defined as the introduction of any substance in our surroundings that can cause adverse effects, including terrestrial, aquatic, and distracting. Pollution has been present for thousands of years, and as time progressed, pollution became largely man-made. Major cities experience air pollution, which can lead to respiratory problems. Contaminated drinking water and excess light in urban areas are also other forms of pollution. Catastrophic events such as oil spills can cause harm to local ecosystems. Fugitive emissions are released into the environment in unmeasured amounts and can include many toxic variables [1]. Carbon monoxide is a colorless, odorless, poisonous gas formed by incomplete fuel combustion. It combines with hemoglobin to form carboxyhemoglobin and asphyxiates the human body. HCS is used in various applications; however, its use has led to serious environmental pollution problems.

The heavy metal cadmium is used in electronics, lighting, and paint and can bioaccumulate. Cadmium is toxic to humans, plants, and animals and can lead to cancer, bone fractures, femoral head necrosis, and renal dysfunction. It is a new member of the group of environmental agents associated with prostate cancer [3]. As cadmium is a toxic element, its removal in polluted areas is imperative. One commonly used method is soil digestion; however, nitric acid used in digestion can produce noxious gas fumes and destroy soil bioavailability. This paper describes the methods used to assess different solutions to find a cleaner digestion method for soil. After preliminary testing, the solubility and effectiveness of cadmium extraction of three green chemicals were assessed. The first trial determined that a mixture of two of the chemicals successfully digested soil with comparable results to trials while not producing hazardous gases.

Cadmium fittings run on the samples had the advantage of being able to detect cadmium, which was not present in any trials. More trials run against a higher concentration of soil suggested soaking soil to allow for longer digestion when testing cleaner chemicals in a batch experiment.

3. Green Chemistry Principles

Green chemistry, a concept that has been gaining momentum within the chemical sciences, focuses on the design and development of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. This innovation of the chemical processes and products must involve collaboration between chemists, engineers, toxicologists, and policy-makers, in the spirit of green chemistry's 12 principles. Green chemistry impacts so many areas, as chemical processes sit at the center of all human activity, integrating and affecting almost all areas of business and society: nanotechnology, solar cells, small molecule pharmaceuticals, greenhouse gas conversion, quality-of-life compounds (fragrances, dyes), biodegradable polymers, cleaner and more efficient industrial processes, etc. The principles of green chemistry are particularly relevant to the manufacturing of agrichemicals. The agricultural community noted that on-farm and post-farm loss of pesticides as well as product selection have direct impacts on the environment and human health [4]. The principles of green chemistry were thus developed with the goal of designing better families of agricultural products, hence the theme of this subdivision. The intent is to design and implement chemical reactions that result in products which are less hazardous to health and the environment, facilitate product monitoring for compliance with accepted product standards, increase reaction efficiencies, and provide for the recovery and/or reuse of by-products. Green chemistry impacts agriculture in numerous areas, including crop protection products, crop enhancers, adjuvants, animal health, disinfectants, and soil amendments. These products are intentionally applied to either benefit the crop either un-intentionally, as residues left in the environment, in or on tissues, or degraded by-products or both. Some of these residues may cause crop damage and/or unintended damage to species that benefit agriculture, to non-target sites, or to humans. Modes of action must be well understood to minimize residues that may harm healthy or environmental targets. Regulatory compliance and product stewardship require monitoring product status. Green chemistry products may be better-tailored for environmental and human safety and monitoring [5].

3.1. Definition and Importance

Green chemistry consists of a series of scalable principles implemented in the design, development, and manufacture of products and processes that minimize, or even eliminate, the use, generation, or release of environmentally detrimental substances [4]. It encompasses reagent, catalyst, and solvent design, encompassing a broad suite of approaches that have found applications in virtually every discipline of commercial chemistry. Often, the term sustainable chemistry is used interchangeably with green chemistry, but sustainable chemistry is broader, referring to the design and implementation of affordable, available industrially viable designs and schemes that take into account commercial, regulatory, infrastructural, and safety aspects in addition to chemical considerations. Green chemistry and sustainable chemistry are thus complimentary; new discoveries in green chemistry provide intellectual tools for sustainable chemistry consideration and implementation. Advances in synthetic methodology made in academic laboratories can provide routes for the design, manufacture, and implementation of new commercial practices and developments that are necessarily green. Green chemistry and the principles behind it are equally applicable to the environmental remediative or analytical chemistry.

Pollution remediation consists of treatments, processes, and techniques as well as large- and small-scale projects, developed to purify and protect the environment when such protection is not afforded by the natural system. Pollution remediation techniques can be roughly classified according to the form of the pollutant: a) solid: removal of contaminated bulk solid material from sites or destruction of contaminant in bulk material; b) liquid: removal of contaminated bulk liquid material from sites or destruction of contaminant in bulk liquid material; gas: removal and destruction of gaseous contaminants from sites or suppression of gaseous contaminant emissions. The chemistry and chemical techniques underpinning those approaches can provide key tools for each of those general cleaning methods, as well as for the development of related ones.

3.2. 12 Principles of Green Chemistry

Green Chemistry is a philosophy and approach to chemistry defined by the 12 Principles of Green Chemistry. Green Chemistry is based on scientific principles that provide a clear framework for the sustainable design of products and processes. Green Chemistry is also broadly and successfully applied across multiple sectors, including pharmaceuticals, agrochemicals, commercial products, and more. The goal of Green Chemistry is to eliminate hazardous substances and increase efficiency. Fundamentally, Green Chemistry approaches innovation from the molecular level and provides detailed expectations for substantive improvements while constraining the tradeoffs between innovation and safety [4]. Green Chemistry seeks to develop products and processes that are noticeably greener than existing alternatives and are thus compelling to implement. The 12 Principles of Green Chemistry can also be readily adapted to a broad array of chemical sub-disciplines, specifying nuanced guidance that is relevant to chemical research in sustainability without compromise in scientific rigor or relevance [6].

In 1998, chemists published a booklet outlining the 12 Principles of Green Chemistry. The principles aim to foster a greater awareness among scientists of the need to include green chemistry into their activities for the benefit of the Planet, its environment, and its people. The principles set the foundation to build a movement to ensure 21st century chemical production, use, and disposal are efficient and environmentally sound. The principles collectively encourage chemical design and production that reduce or eliminate the use or generation of substances that are hazardous to human health or the environment. The principles can be applied throughout the life cycle of chemical products. The booklet outlines and describes the 12 principles of green chemistry, several examples of their application in development of new commercial processes, and retrospective analysis of older synthetic chemical processes.

4. Innovative Techniques in Pollution Remediation

Rapid industrial growth and population explosion have contributed to increased environmental pollution globally. Therefore, there is a growing need to search for new environmentally friendly, low-cost, and more efficient environmental clean-up techniques for the removal or reduction of contaminants from the environment. Among various techniques, bioremediation, a branch of environmental biotechnology, is nowadays considered as one of the most promising alternatives due to its efficiency and cost effectiveness, and being a nature friendly and sustainable approach. Thus, several bioremediation technologies are currently available or under development to treat various types of environmental pollution. The use of specific bioremediation technologies has to be evaluated, on a case-by-case basis in strict correlation with pollution characteristics and site remediation constraints [7]. Therefore, the present work reviews recent developments in bioremediation treatment technologies assessed under real conditions for soils, sediments, unconfined and confined water or liquid effluents contamination. The advantages and limitations of bioremediation technologies are also discussed. The great potential of the bioremediation process opens up a new direction for greener processes. Pollution caused by toxic metals and metalloids such as arsenic, cadmium, chromium, copper, mercury, and lead is a global threat to all forms of life. However, owing to the natural adaptability of microflora, bioremediation poses a sustainable solution for the recycling and detoxification of heavy metals. Bioreactors packed with suitable supporting materials can be installed on-site to treat contaminated groundwater and soil leachates. However, complete removal of heavy metals from contaminated sites requires enhancement of bioavailability and difficulty during biotreatment in the presence of excessive metals. Further advancements in the stages of bioassays, bioisolation, biocharacterization, bioaccumulation, biosorption, and bioleaching processes need more attention and will be dealt with in this review article [8]. Nanomaterials are well-studied materials which have a width of 1 to 100 nm and exhibit unique properties superior to their bulk counterparts. Due to their small size and large surface area-to-volume ratio, nanomaterials have found applications in a variety of fields, including catalysis, electronics, sensors, energy, biomedicine, and environmental remediation. Environmental pollution due to industrialization, population rise, urbanization, improper disposal of wastes, and the rapid growth of automobile industries is a worldwide threat affecting human health and the environment. Environmental remediation is a multi-disciplinary and multi-scale approach to eliminating pollutants or reducing their concentrations to acceptable levels. Nanomaterials have been extensively studied for the development of eco-friendly treatment methods of toxic organic and inorganic contaminants from air, water, and soil. Transformative research should be focused on the toxicological properties of nanomaterials, characterizing the fate and transport of nanomaterials in the environment, and evaluating their long-term consequences on human health and the ecosystem. Green synthesis of nanomaterials through biological or natural approaches has gained currency over conventional methods used for test tube synthesis. This technique is comprised of the use of non-toxic, lower energy, and environmentally benign materials for the synthesis of nanomaterials that do not add toxic contaminants into the environment. [9][10][11]

4.1. Bioremediation Methods

For the cleanup of contaminated environment bioremediation biotechnology can be employed as an innovative, efficient, eco-friendly and sustainable alternative to conventional physical, chemical and thermal techniques, in which biological agents are being utilized for the reduction/degradation of harmful metals and organic pollutants [12]. Various biological agents are now well recognized for their potential role in the biological reclamation of otherwise toxic environment. Applications of biological agents are considered as green technologies which are cost effective, self-sustainable and environmentally friendly. Inherent microbial detoxification of the harsh conditions of the polluted site has been seen in several instances. It mainly involves the adaptation of the microbial population to changes in the environment and constant biochemical fluctuations in the habitat. Besides this almost spontaneously occurring bioremediation potential, various practical biotechnologies have been developed, and applied to polluted sites, which include the application of freshly isolated microorganisms on the contaminated site, growing microorganisms on laboratory scale, enrichment, optimization of conditions for enhanced biodegradation rates and bacterial plasmids studies regarding the degradation pathways etc.

Once the basic criteria for bioremediation processes are fulfilled the practical application of bioremediation biotechnology can be assured. A wide range of biological agents is being used in bioremediation biotechnology for the reclamation of polluted environment, which include microbial systems, dried up plant leaves, dead algal mats, activated sludge contain algal and bacterial consortia, compost, organic waste enriched aerobic soil, sediment sludge, etc. These biological agents possess innate capacity to uptake toxic metals and oxidize halogenated phenolic pollutants. Microorganisms, plants and algae are found to be affected due to the release of pollutants into the environment and could be effectively utilized for remediation purposes. Active components present in the biological agents used in bioremediation biotechnology are proteins, enzymes, polysaccharides and polypeptides. Therefore the applied biological agents could easily be coupled with cheap substrates and would be employed in bioremediation biotechnology. [13][10][14]

4.2. Phytoremediation Strategies

Phytoremediation—a plant-centric, environmentally benign technology approach to remove, contain, and/or stabilize contaminants from the environment—has emerged as an established alternative to mechanical and chemical remediation technologies. Though not as expertly developed or implemented as bioremediation, phytoremediation is gradually gaining acceptance within environmental remediation as effective technology to complement and/or compete with existing remediation techniques. Phytoremediation is based on the scientific understanding of the uptake and metabolism of organic and inorganic contaminants by plants. Plants are used to ameliorate contamination in groundwater (phytodrainage), surface water (phytostabilisation; phytodeaccumulation), and in sediment/soil (phytoextraction; phytostabilisation) [15]. Solvable surfactants may also be used in conjunction with plants (dispersive bioremediation) to enhance removal of organic contaminants like polycyclic aromatic hydrocarbons (PAHs) from sediment and soil. Older remedial techniques such as dilution, soil covers, and even in situ thermal remediation can have negative environmental impacts leading to development of new remediation techniques as a critical improvement of current techniques. Newly developed combined technologies such as vacuum-enhanced remediation and experimental protocol testing the sequel of surfactants on the success of bioremediative landfarming are also emerging guidance tools for waste disposal and future contamination prevention. Phytotechnology is the application of plants to improve or remediate a site. The underlying mechanisms of phytotechnology include active biological processes that degrade pollutants, passive biological processes that reduce pollutants to non-detectable levels, and solely mechanical processes that transport pollutants.

Phytoremediation is the most well-known and well-researched phytotechnological application, having been investigated and demonstrated success at contaminated properties ranging from commercial dry cleaning and gasoline retail facilities to industrial sites. As the relative complexity and cost of mechanical remediation technologies increases, the rise and viability of plants as affordable, sustainable bioremediation systems become more evident. Combined with a thriving interest in green infrastructure, phytoremediation use in the remediation industry is expected to grow rapidly in the future. Invaluable in both the remediation and green infrastructure contexts, incorporating trees into contemporary landscape design presents one of the many innovative solutions to the growing city of the future problem. [16][17][18]

4.3. Chemical Remediation Technologies

With the rapid industrial development, massive amounts of toxic contamination have become a significant global issue in recent years. Chemical remediation technologies are gaining traction as a method to remediate contaminants in an efficient, economical, and safe way. Nanomaterials with high surface-to-volume ratios and novel physicochemical properties, combined with the wide range of scale applicability and various varieties, have promoted enhanced efficiency, selectivity, and reusability of these techniques and thus, have received considerable attention in recent years as remediation materials. However, concerns regarding the application have yet to be addressed and timely actions to mitigate risk concerns have become urgent. Apparently, nanomaterials are promising candidates for remediation of wastewater contamination and require timely substantive policy actions to mitigate concerns related to their health and environmental risks to realize the full potential of this important technology.

In water remediation, precious nanoparticles have used as catalysts to enhance degradation reactions in various photo-catalytic systems by virtue of their unique optical and electric properties. A variety of demand-and-application-specific nanohybrids and composites have been developed with precious metals doped on photocatalysts, coated on porous materials, and encapsulated within hydrogel matrices to improve activity and to develop/deploy flexible catalytic systems. Limitations and comprehensive design considerations are discussed to lend insight on the next generation of more accurate and cost-effective nanomaterials as catalysts for pollution remediation applications. Beyond chemical reaction, carbon-based nanomaterials with enhanced adsorption and electrochemical performance have relied on quasi-adsorption and redox mechanism development for in-situ remediation. Challenges associated with low adsorbent recycling and low-performance materials have been counteracted by modifying materials/structures/surface properties, increasing operating voltage ranges, and altering reaction mechanisms. Design guidance for application-specific development of nanomaterials for electrochemical remediation is outlined as well.

MoCo2O4 and MnCo2O4 spinel-type nanoparticles were tried for scavenging superoxide radicals released from aquatic pollutant photodegradation using methyl blue as a model pollutant. This application greatly differed from the widely accepted application of nanoparticles for photodegradation, and targeted radical scavenging of superoxide radicals, contributing greatly to remediation process understanding. ii) Composite nanomaterials. Seeing surface treatment modifications for selectivity and/or performance improvements of metal oxide nanomaterials on contaminant decomposition are extensive, unique cases of surface decoration of iron oxide HA, and covalent bonding of lanthanum ions onto TiO2 surface to advance nano-adsorbents for developing selective removal of phosphate from kinetic, thermodynamic, and isotherm model perspectives for the understanding of the role of phytoremediation and composite adsorbent interaction on phosphate removal efficiency. [19][20][21]

5. Nanotechnology in Environmental Applications

Nanotechnology comprises the fabrication of materials on the scale of atoms and molecules. Constituents under one hundred nanometers exhibit entirely different physical-chemical properties than bulk materials. As a result, the n-type and p-type semiconductors can be readily manufactured on a nanoscale substrate corroborating the fundamental science and the industrial interests in the market. Nanomaterials exhibit unique properties owing to their size and morphology [22] especially nanostructured semiconductors due to their band gap, quantum confinement, and surface states. The environmental remediation process encompasses various methodologies for the olfaction of environmental pollutants. Pollution sources transform the physical, chemical, or biological characteristics of the environment, water, land, and air pollution. As a result, development and evolution in technology require deployment for the provision of eco-friendly products. Nanomaterials consist of a high ratio of their surface-area-to-volume, often resulting in a biogeological and chemical reactivity several times greater than macroscale materials. Their superior characteristics and efficacy make them especially suitable for executing such operations. Over the past few years, an influx in the quantity of nanoscale products with environmental remedial functionality has been fabricated and deployed.

Polluted soil and groundwater has been remediated using nanomaterials at climate legacy waste sites. Manufactured nanoparticles contain physicochemical, surface, and optical-electronic characteristics which address concerns that previous approaches were untenable in tackling with traditional approaches. Nanoparticles can enhance the dispersion of a colorimetric reagent and remove metals ions connected to polymeric coatings. Nanofibers can be used to concentrate organic solvents from vapor emission before chemical sensors detection. Nanomaterials have outstanding mechanical and metamaterial properties, owing to which they can be employed to recover the useable oil or metals from effluents and industrial effluents respectively. Nanofibers and microsponges can be entirely natural and nontomopathic for removal of toxic phenolic compounds from waste streams and heavy metals from waste water streams.

5.1. Nanomaterials for Pollution Control

Nanotechnology is a multidisciplinary field that aims to fabricate structures ranging in size from 1 to 100 nanometers. Nanomaterials possess impressive physical and chemical properties due to their small size and large surface area-to-volume ratio. These unique properties have made them applicable in a wide array of fields, including science, the environment, industry, and medicine. The application of nanomaterials in the environment is very promising, as they can be used to clean up contaminated soil and groundwater at hazardous waste sites. Numerous studies have been conducted on the interaction between nanoparticles and metals, and the potential of nanoparticles for environmental remediation has received much attention [22].

Pollution is a global concern today, and humanity faces a plethora of environmental hazards. The environmental remediation process employs a variety of methods for the elimination of environmental pollutants. Natural physical methods such as adsorption, precipitation, filtration, and oxidation can be employed to treat waste, but these methods are inadequate for pollutants on a molecular scale such as dioxins, halogenated organic compounds, and heavy metals [8]. Advanced oxidation processes (AOPs) based on the action of hydroxyl radicals/hydroxyl ions involve inflating oxygen/ozone or hydrogen peroxide into water contaminated with various organic pollutants. Hydroxyl radical attack the pollutants and convert them into carbon dioxide, water, or alkanes, preventing the spread of contaminants downstream. Nanoparticles can also be used in wastewater treatment processes such as adsorption/coagulation and membrane filtration since the higher specific surface area of nanoparticles allows for lower consumption levels.

Nanomaterials possess a high ratio of their surface-area-to-volume which provides higher biogeological and chemical reactivity than other macroscale materials. They participate in numerous biogeochemical processes such as sorption, aggregation, redox reaction, co-precipitation, association with (bio)macromolecules, and transportation. Environmental nanoparticles can cause finely-divided solids to disperse in aqueous environments and cause toxicity in higher density phases after sedimentation. Understanding the reaction and transport behavior of nanoparticles presents new opportunities and challenges in environmental sciences. Although a great diversity of nanoscale materials have been developed for biomedical applications, nanoscale materials are increasingly being researched and developed for environmental remediation applications.

5.2. Environmental Nanotechnology Innovations

Methodologies based on Environmental Nanotechnology to improve sustainability by tackling pollutants are emerging. Nanotechnology is an exciting and evolving area of research, with applications across numerous fields, including medicine, electronics, and an approach which permits either better performance or new paradigms. Environmental Nanotechnology is the approach to the environmental sciences and engineering that employs nano-sized materials for the assessment and remediation of contaminated sites, including surface and ground waters, soils, and sediments.

Environmental Nanotechnology approaches have the potential to greatly increase both the protection of human and environmental health and the solvability of areas formerly considered off-limits, dubious, or impossible with conventional approaches. They may also permit a broader reach into less formal and hidden areas of environmental risk and restoration than previously considered feasible. A survey is presented regarding the most promising nanoparticles for environmental remediation, including zero-valent metals, metals with a high affinity for certain contaminants, metal oxides, and functionalized nanostructures. These categories of nanomaterials coincide with important classes of secondary generation nanomaterials, which do not yet appear to be subject to scrutiny in the environmental field, although there is significant anticipatory attention to the sole class of nanoparticles deemed enlightened enough to be innocuous. It is well-known that nanoparticles with heterogeneous size and density distribution in the environment become subject to aggregation into larger structures, which may behave differently from their nanoscale precursors with respect to transport and fate.

Using nanoparticles, we can attain goals that seemed impossible by state-of-the-art approaches. A dramatic example is that of metal oxides for the remediation of organic contaminants. Since polycyclic aromatic hydrocarbons react with semiconductors leading to the cost off the problem of aqueous-phase remediation of polycyclic aromatic hydrocarbons with sized $TiO2$. There are many paradoxes and conundrums in this evolving field. In some cases, contradictory expectations arise from theory. In others, workers are confronted with ratios of macroscopic effects to the microscopic cause that are on the order of Avogadro’s number. Probably few but very important field trials with nanoparticles have been conducted. It is believed that the future is bright and the challenge is to harness a minimum amount of particles effectively and harmlessly, which renders security experiments a priority. [23][24]

6. Advancements in Waste Management

The advancement of soil remediation methods is essential in determining a method's feasibility in the recovery of soluble toxic metals from contaminated soils. Since heavy metals are a critical environmental hazard, a growing list of industries that are essential to societal functioning, including agriculture, electronics, and pharmaceuticals, is also responsible for growing pollution. Several toxic metals are released in various forms, including oxides and ions. The most well-known among these are cadmium, arsenic, lead, chromium, copper, nickel, and mercury. This is a broad list, with an even broader pool of sources causing the described pollution, and many of them directly threaten human health. Cadmium can accumulate in crops and can cause short-term adverse respiratory and digestive effects. Arsenic can occur in organic and inorganic forms, with inorganic salts and oxides causing damage to reproductive, developmental, and immunological systems. Like arsenic, lead is present in many environments and sources, which can cause HPV, hearing impairment, and other neurotoxic effects [3].

As the list of concerned elements becomes longer and more varied, it is also important to evaluate new methods for soil digestion and solvating metals. Solutions containing EDDS and EDTA were developed and judged by the concentration of solubilized metals. Results show a clear difference between nitric acid's performance, a poor solvent for lead, and the green alternatives. To ensure further progress towards a method suitable for fieldwork (i.e., ease of use), the effects of contaminated soil pH or ionic content should be evaluated.

Through a literature review of membrane fabrication and functionalization, three main sustainable approaches were highlighted. The starting materials can be probed to take advantage of their inherent properties, compatibility, and synergy and develop new biopolymer membranes. On the other hand, starting membranes are subject to modification via greener and cleaner procedures. Either way, it is feasible to fabricate membranes with end-of-life and easy-to-recover materials while also maintaining, if not improving, their standard aspects. The rational design of the starting polymeric and gel blends with proper nanofillers or functional agents is crucial to achieving membranes with implemented mechanical, thermic and chemical resistance, antifouling and different pollutant retention properties [25].

6.1. Sustainable Waste Management Practices

The rapid development of the world economy has brought about many environmental issues, including industrial pollution, marine pollution, agriculture pollution, and urban waste pollution. With in-depth studies by scholars and in-depth investigations by governments, the negative impacts of pollution on health and spirit have been gradually revealed. In 2004, WHO estimated that 4.4 million people died every year due to the polluted environment, most of them in developing countries [26]. Pollution control has become one of the most important political agendas for governments around the world. How to deal with the pollution problems remains a challenge for researchers and engineers.

The biggest pollutant in chemical production and energy structure-oriented production is carbon-containing emissions. In addition to carbon dioxide, carbon monoxide and other harmless aliphatic carbon-containing materials, a vast number of toxic and harmful carbon-containing pollutants, which may cause different degrees of harm in the process of utilization, storage and transportation, are produced. The main types of these hazardous carbon-containing pollutants include polycyclic aromatic hydrocarbons, persistent organic pollutants, nitro aromatic compounds, dyes and their degradation products, etc. Fortunately, there are various effective removal methods and reaction systems developed by scholars and engineers for these harmful pollutants based on their properties [27]. The development of pollution remediation methods based on new materials and processes is an important approach for scholars. In addition, from organic synthesis to drug synthesis, an important direction of sustainable chemistry is to reduce environmental damage through green chemical processes.

The target of sustainable development is the symbiosis of human and nature, which means the symbiosis of sustainable development goals (SDGs) in the political, economic, social and environmental domains. Construction and operation of pollutant treatment systems is a necessary step but not the ultimate target for the health of human kind and nature. Ideal SDGs-related improvements in all carbon-emission-related areas should be proposed and in-depth economic and environmental assessments of these improvements should be conducted.

6.2. Recycling and Upcycling Techniques

The extensive use of plastics in various industries has become a part of everyday life. In the past few decades, the mass production of plastics has rapidly increased, while carbon black (CB) has also received increasing attention in the polymer clouding field. However, this has subsequently led to a serious environmental pollution problem, since most plastics cannot be decomposed naturally and are highly resistant to degradation [28]. Unlike nearly all natural substances, which can be broken down into nutrients for consumption by living organisms, plastics and their chemical additives, for the most part, will persist in nature indefinitely. Consequently, subsequent remediating technologies have been developed. These methods include traditional non-destructive methods, such as landfill and incineration, as well as destructive ones, including thermal catalytic treatment and thermo-chemical treatments, such as pyrolysis and hydrothermal liquefaction. However, many of the current proposed treatments only afford loss of resource, accident hazard, secondary pollution, and/or suboptimal diversity [29]. Selective upcycling of various neglected polymers is therefore gaining attention as a promising way to convert waste into value-added building blocks. A rapid increase in research articles on plastic waste upcycling has been demonstrated.

Conformational alteration to the selected structure or catalyst may from an interesting production design to previous highly selective approaches. Selective upcycling of the above-grouped polymer waste is highly anticipated to furnish value-added building block candidates. Recent advances in progressive treatments for various neglected polymer waste types upcycling are discussed as an effort towards such selective upcycling. The discussion focuses on the reaction mechanism and possible reaction adaptions for the listed species types to furnish selected products. An integrated schematic is proposed to illustrate the current state of polymer waste selective upcycling. The future realization of such sophisticated upcycling reactions is envisioned by virtue of sustainable catalyst design to address carbon black, various degrees of polymerization and crosslinking of the reactant, and treatment under ambient reaction conditions.

7. Role of Catalysis in Green Chemistry

Catalysis will play a cornerstone role in future green chemistry. Green chemistry (as defined by the 12 principles) aims to develop safer economically viable processes requiring lower amounts of hazardous chemicals for the synthesis of traditional complex pharmaceutical intermediates and products. Selectivity is the key term. As a consequence, the development of new catalytic transformations, both organo- and metal-catalyzed ones, is evermore promoted in the green chemistry domain. Catalysis also guarantees the introduction of greener, less harmful and toxic reagents and catalysts, decreased environmental impact and greener separation/extraction methods.

It is envisaged that, within this framework, catalytic redox processes will gain increasing weight, notably, selective oxidations, reductive aminations and C–C cross-coupling reactions involving biologically benign reagents (e.g., O2, H2O2, aqua or alcohol solutions of formic acid and organic amines) and obtaining CO2 and H2O as by-products. A special emphasis will be placed on biomimetic and bioinspired catalytic systems using more benign and less toxic metal ions and more abundant and less costly ones (Mo, Ws, and V). Iron catalysts will be paramount in oxidations (alkanes, arenes, alcohols, and sulfides) and cross-coupling reactions. Bioinspired catalytic systems will replace a large number of classical and noxious metal catalysts in the next decades. Such development will embrace the green chemistry, concepts of eco-friendly HOCs (biodegradability under environmental conditions) and zero waste generation. In this respect, cheap and commercially available precursors such as H2O, H2, and bio-renewable alcohols will be immensely attractive. The development of sustainable catalytic processes is foreseen for the next decades in this framework [30].

The ever-growing environmental pollution has stimulated the rapid development of environmental catalysis in recent years. Catalysis continues to be the driving force for generation of clean energy and abatement of major pollutants in air and water. Heterogeneous catalytic techniques have dominated the studies on environmental catalysis recently, including catalytic combustions, emissions after treatment, heterogeneous photo-/electro-catalysis and total oxidation of VOCs. Catalysis is essential for the energy and environmental sustainability, and advances of catalysis technologies would be beneficial for both chemists and human beings [31].

7.1. Catalysts for Sustainable Processes

Catalysts can help develop more sustainable processes by targeting pollution and impoverished safety situations. The sustainability of proposed processes can be evaluated using indicators, and the Prospective Environmental Analysis approach allows comparing environmental indicators throughout the entire life cycle of chemicals. The combination of synthetic steps, catalysts, and process conditions is maximized to improve sustainability. Four points need to be clarified. (i) The investigation focuses on process technology, while aspect at the level of scaling-up and commercialization are not treated. (ii) Currently, cases for which a combination of catalyst and process design is accountable for a significant improvement of the sustainability signal are focused on. Several more processes exist for which the new catalysts are absolutely essential for improving sustainability. (iii) Net sustainability does not mean a directive to be followed blindly; the demonstration of the sustainability event of large-scale industrial processes will need to accommodate an initial increase in an environmental load. The alternative usage of fuels to provide energy for use in the processes or for the difference between paper grades produces an energy release event in both cases. (iv) The more controversial in socio-economic terms, the greatly and widely used use of aryl amine feedstock is targeted. The development and commercial exploitation of more sustainable processes depend on a careful weighing of the positive and negative events throughout the life cycle of a chemical. Catalysts and associated process conditions can help develop more sustainable processes or target pollution or impoverished safety situations in case of existing processes. Sustainability improvements achieved by catalytic processes are exemplified in two main approaches. The first approach is broad-scale improvement of process sustainability signal on the level of widely using chemicals. The more controversial so-called high-impact processes can be addressed by this approach that works efficiently by properly selecting the catalyst and/or large-scale application of a new reaction. This approach affords improvements of a sustainability signal expected to reach or exceed orders of magnitude, depending on the improvement of the considered indicator. The comparisons shown here will likely underestimate, as the model calculations are based on numerous assumptions. Comparisons based on economic measurements might be more precise but the evaluation of and modeling of economic events is difficult since there is high competition in the chemicals industry also based on know-how secrecy [32].

7.2. Enzyme Catalysis in Pollution Reduction

Microbial catalysis refers to chemical reactions that are catalyzed by enzymes produced by whole microorganisms, isolated intracellular enzymes, or the cell-free extract containing enzymes. The wide substrate range and highly efficient catalytic properties of enzymes indicate that they may have considerable applications in synthesizing valuable products. In addition, the indigenous enzymes, having been evolved for millions of years by nature, are much more robust than engineered enzymes, because they can easily maintain their structure and catalytic activity in the coexisting complex mixture of substrates, products, and side products. Isolation and identification of such enzymes is crucial and will widely extend the applications of microbial catalysis in biorefinery. Pollutant degrading enzymes refer to enzymes that degrade environmental pollutants, and they can be categorized into three classes according to the chemical structure of pollutants. With the increasing concerns on the serious adverse effects of environmental pollutants, various ameliorate technologies have been developed to eliminate pollutants from environment.

To date, pollutant degrading enzymes have been discovered and characterized in animals, plants, and microorganisms, with a focus on the latter. Three classes of pollutant degrading enzymes according to the chemical structure of pollutants are described in this part. The chemical mechanisms involved in pollutant transformation are presented in some detail. Paid strategies for environmental management and sustainable development. Population growth, urbanization, and industrialization have severely impaired the quality of environment, air, water, and soil contamination being major problems. Environmental pollutants can be categorized into organic pollutants and inorganic pollutants. Organic pollutants are further split into two classes according to their molecular structure. The first group includes aliphatic pollutants such as chlorinated and non-chlorinated aliphatic hydrocarbons, alcohols, amines, and pesticides. The second class encompasses aromatic pollutants like aliphatic and chlorinated aromatic hydrocarbons and unsaturated aromatic compounds.

8. Case Studies in Successful Remediation

The multi-approach biological remediation to address chlorinated aliphatic hydrocarbons (CAHs) polluted sites is discussed. Up to date studies, field test, and experiences are presented to share and discuss successful investigation leading to real remediation interventions. Among the variety of contaminants of anthropogenic origin, chlorinated aliphatic hydrocarbons (CAHs) are listed in the group of priority pollutants by the Environmental Protection Agency (EPA) due to their widespread occurrence in the environment and high environmental impact. In groundwater, these contaminants are mostly present as dense non-aqueous phase liquids (DNAPLs). The major problems associated with a CAHs-contaminated site concern the management of the secondary source and the intrinsic vast plumes associated with CAHs-contaminated sites. Secondary sources are the solvents present in the low-permeability layers, while contamination plumes are generated by the prolonged contamination along the direction of water flow, where the diffusion of contaminants releases the contamination in the hydraulic wells [33]. Each site is unique, and the distribution of the contaminants depends on the hydrogeological characteristics of the site.

The In-situ Bioremediation (ISB) technologies, based on the natural biogeochemical processes involving indigenous microbes for the removal of pollutants from contaminated sites, are attracting increasing interest for the bioremediation of chlorinated solvents plume owing to the public favour for in-situ technologies, their low operating and long-term maintenance costs, and their effectiveness for chlorinated solvents plume remediation. The biological Natural Attenuation phenomenon consists in the disappearance of pollutants in the aquifer due to the activity of specific microorganisms, when degradation intermediates are detected in the water of the wells probing the plume. The second major group of ISB technologies is represented by those technologies aiming at the Enhanced Natural Attenuation, which are presently widely used at the sites of chlorinated solvents plume because for years it has been reported on successful field tests.

8.1. Industrial Site Cleanups

Systematic and inclusive investigations are demanded across the world for contamination problems due to human activities, as they sacrifice our ecosystem, environment, and health [3]. Physical methods are conventional technologies, but the relatively high capital and operational cost result in limited application [33]. Advanced oxidation, NANO Technologies, and bioremediation technologies are considered innovative technologies. However, the main challenge for these technologies is the limit of trace concentrations of hazardous compounds and time-consuming treatment requirement. Green chemistry and bioremediation provide effective and cost-saving choices for pollution problem problems.

For pollution treatment, Integrated bioremediation and green technology approaches are proposed based on the active function of hydroxy and carboxy groups, as well as the selectivity of CDs for HOCs. Entrapment of CDs in an activated carbon framework is proposed for PCET and GR, aiming for low toxicity, low cost, and reusable green materials. Combined strategies of bioremediation and green technologies are implemented for waste electrocatalyst recycling problems using pan-biochar. A comparative study of bioremediation and green technology is supplied for the degradation of hazardous compounds. A novel cellulose acetate device is proposed to address amine nitrogen ion problems, based on pK variable and selective ion adsorption.

8.2. Urban Pollution Control Projects

Urban streams, rivers, and lakes are the important drinking water resources and aquatic environmental sustainances of the metropolis. However, the urbanized rivers and their tributaries are usually polluted by domestic sewage outfalls, industrial wastes, and soil washouts along the urbanized bank zones, choking off the aquatic sustainability, and increasing the financial burdens to the government and the whole society for stormwater pollution control. Thus, a great number of urban pollution control projects have been executed worldwide for the remediation of urban waters. Generally, such projects usually include biodiversity restoration, riverbank greening, effective regulation of urban stormwater runoff, improvement of the quality of polluted water entering lake reservoirs, wetland construction for retained water, etc. Although valuable experiences and lessons have been obtained through the case studies of these pollution control projects, the pressures of more stringent regulations and still financially-limited resources have promoted a further investigation on the fundamentals and a more sophisticated engineering of the urban pollution control projects [34].

The pollution control of urban water bodies is essentially a multi-criteria decision-making problem, with many feasible options available and complex inter-acquaintance trade-offs among conflicting objectives of various stakeholders. Nonetheless, although various weighting evaluation approaches have been developed, such as entropy-based and adjusted simple additive weighting methods, the problem of determining the weight factor for an assessment criterion is still a key technical challenge for decision makers, especially in the fuzzy environment. To resolve this problem, this paper investigates an integrated fuzzy multi-criteria decision-making approach for the weighting evaluation of urban water bodies based on three fuzzy integrated methods, that is, 2-tuple fuzzy linguistic weighted average operator, fuzzy individual evaluations of alternatives incorporating fuzzy majority decision making, and 2-tuple fuzzy linguistic assessment consistency checking through consensus reaching service. The proposed fuzzy multi-criteria decision-making approach provides a decision support tool for the integrated evaluation of urban water bodies in the fuzzy environment.

9. Regulatory Framework for Environmental Protection

In the United States a complex regime of statutes regulating environmental matters has been developed by legislative, executive, and judicial measures through a long historical period. The major statutes include - the National Environmental Policy Act, the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, the Federal Insecticide, Fungicide, and Rodenticide Act, and the Safe Drinking Water Act. The regime is behind the U.S. World Bank Group’s slow progress on corporatization of the Environmental Protection Agency. “Wilderness” and the “Precautionary principle” are concepts developed by the U.S. environmental movement and used by American universities. Ethical issues in environmental protection include intergeneration justice, environmental justice, the precautionary principle, and “green chemistry” [35].

Pollution prevention options can be grouped in two categories. The first category is “process change” including alternatives to existing processes and raw materials and process modifications that minimize the generation of wastes or lower their toxicity such as waste isolation, changes in farming practices, chemical waste destruction, treatment of livestock wastes, bioremediation of petroleum wastes, and substitution of alternative less toxic solvents. One effective general approach is to modify the existing processes so that no hazardous wastes are generated or the level of toxicity lower. Process integration approaches based on mass integration and energy integration techniques can be used for many processes. Green chemistry is a phrase used to refer to a broad set of principles that can reduce or eliminate the use and generation of hazardous substances in chemical manufacturing and related processes. The principles emphasize the importance of designing chemical processes that minimize the toxicity of all materials. For example, Solventless chemicals are a very effective way to reduce environmental loading especially in paint and ink manufacture.

9.1. International Environmental Agreements

In 1992, 178 nations signed the United Nations Framework Convention on Climate Change. In 1994 this agreement entered into force. In 1997 these countries adopted the Kyoto Protocol. In the wake of this agreement, which seeks to reduce greenhouse gas emissions, climate change was placed firmly on the international political agenda. Global warming affects food and water supplies, forests, and biodiversity. There is much uncertainty as to the extent of the problem and the magnitude of changes, but predictions suggest changes far beyond anything seen in human history.

Climate change problems are also transgenerational since there are time lags expected. A near-term solution would mean very sharp reductions in output and, in turn, economic growth. Further, there are very large costs associated with implementing such a solution. Because it is a global-scale problem, there is no current central authority to manage the issue. The resulting response is heterogeneous with respect to analysis, methods deployed, and responses. Nations view the problem in very different terms, making negotiations difficult [36]. On this world stage, different actors appear, including states, organizations, and the scientific community.

Nations all agree to be members of a global forum to study the climate and to negotiate possible remedial actions. Various far-ranging treaties and protocols have been negotiated and nations have variously signed, ratified, and shelved them. The underlying global model produced by the bad-weather science has changed little over the years. Individual countries have varying requirements to reduce emissions, with sketches of penalties. Environmental planning has focused on regionalisation of national planning, where specific measures can be agreed upon [37].

9.2. National Policies on Pollution Control

The 1960s were characterized as a period of search and discovery as well as irresponsible use of available technologies. During the mid-1970s, environmental concerns hit the chemistry design industry. Mass movement and action towards rights fought social change, starting with a manifesto. This changed the public awareness concerning environmental issues. These developments overflowed to academia with a growing concern over pollution and environmental degradation that led to the establishment of environmental engineering curricula in late 1970s and early 1980s institutions. During the mid-1980s, chemical hazards and waste became a part of the academic literature. The 2nd edition of the 5th volume of a handbook contains a part on safety, hazard, and waste treatment. The 1990s were characterized as a period of consolidation and grease-paint talk along with the introduction of greening and green initiatives in framing sustainability, corporate social responsibility, and life cycle analysis among others. With these growing concerns, there was a recognition of the shortcomings in current waste design systems and a search for ways-outs became inevitable.

At about the same time, there was a reevaluation of the position held by chemical engineers in academia, industry, and government. This led to a revisit of methods and approaches for pollution prevention. The end of the millennium saw a revision of design methods towards sustainability, an increasing interest in "green chemistry," Chemical Engineers were surveying innovative approaches to process intensification, inherent safety, and sustainable manpower. Environmental sustainability converged towards the scientific and other multi-scaled approaches concerning epidemics and pandemics. These parameters and measures were assessed on global, national, regional, city, community, supply chain, network, and workplace levels, and attempts were made to apply the measures at the river, lake, and neighborhood levels. A resilience-based research agenda offered measures of robustness, recovery, and adaptation, to predict and mitigate the impact of future threats. National policies on polluted control tended to emphasize integrated pollution prevention and control and immediate water and air quality. [38][39][40]

10. Conclusion

This Special Issue presents research results on advanced chemical approaches for environmental remediation and green chemistry related to the recent COVID-19 pandemic. These problems are worldwide issues demanding urgent solutions, and the goal of this Special Issue is to provide effective chemical solutions as soon as possible. The editors arranged a call for papers across the diverse chemistry community and invited prominent researchers in the areas of environmental remediation and green chemistry to contribute to this Special Issue. The foreseen impacts of this edited volume are principally addressed toward these important and trend-setting fields and are anticipated to present and implement innovative solutions.

Several timely topics are included in this Special Issue. For example, the group of Wu collected some key phosphine oxide compounds from real samples of SARS-CoV-2 infected patients and synthesized a polyvinyl chloride (PVC) film for extracting these target compounds. This research provided new options for determining the virus compared with the bulky and complicated existing methods for sample pretreatment. State-of-the-art ionic liquid-based solvents were systematically discussed and evaluated regarding their green properties. These solvents were environment-friendly alternatives for traditional organic solvents and cost-effective catalytic media.

In recent years, the presence of micro- and nano-plastic pollutants in the environment has raised great concern around the world. A novel technique was proposed for extracting micro- and nano-plastic particles from water, using hydrophobic natural deep eutectic solvents (NADES). Hydrophobic NADESs were made by combining some amphiphilic organic acids and alcohols, and they were capable of extracting target plastic particles from water into phase and recovering after extraction. Extensive experimental parameters such as viscosity, temperature, dispersibility, extraction efficiency, and extraction mechanism were evaluated. Three hydrophobic NADESs, made by combining decanoic acid, menthol, or thymol at different molar ratios, showed great extraction efficiency, and the extraction mechanism was proposed as surfactant action followed by solvent extraction.

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