Part One

Introduction: Change in Perspective due to Nanotechnology for Environmental Techniques and Devices

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Nanomaterials for Environmental Science: A Recent and Future Perspective

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1.1 Introduction

Chemical process engineering, environmental science, and materials science are moving toward newer challenges. Destruction of environment and loss of biodiversity have worried the scientific community to gear their efforts toward finding innovative technologies. This treatise, with cogent insight, discusses lucidly the application of nanomaterials in environmental protection. The vision and the challenge of human scientific endeavor are wide and versatile. The success of human civilization today stands amid a deep scientific introspection. Man's immense prowess, mankind's scientific rigor, and the civilization's urge for scientific progress will go a long way in true emancipation of environmental science. The immense potential of nanotechnology is elucidated in detail in this well-informed treatise. The success, the immense scientific and academic rigor, and the futuristic vision of environmental science are the torchbearers of a newer visionary era of science and engineering. In this treatise, the authors pointedly focus on the application of nanotechnology and nanomaterials in environmental engineering science. Chemical process engineering and materials engineering are connected like an umbilical cord to environmental engineering and its challenges. The scientific sagacity and deep scientific understanding in the application of nanomaterials in environmental protection are ushering in a new era. The authors of this book focus on the application of nanoscience and nanotechnology to environmental engineering and pollution abatement.

1.2 The Aim and Objective of the Study

Human civilization today stands at twilight of scientific vision and understanding. The rigors of science and engineering are immense, as mankind is undergoing a

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wider realization of the sustainability of environment. The aim and the objective of this study is to discuss the greater vision of and challenges in the application of nanomaterials in environmental protection. The success and potential of environmental engineering science are inimitable. Today, environment is under a state of great distress as ecological imbalance and frequent man-made disasters are destroying the very fabric of our environment. The cause of biodiversity is crossing scientific frontiers. Civilization stands amid great scientific understanding as well as misdemeanor. The challenges of environmental engineering need to be readdressed in every possible way. Traditional and nontraditional environmental engineering techniques are veritable scientific endeavors. This treatise aims at the nontraditional techniques of environmental engineering and the novel separation processes of chemical process engineering and targets the immense potential of these techniques. Environmental sustainability and holistic sustainable development are the cornerstones of this research endeavor.

1.2.1 The Need, the Rationale, and the Scope of the Study

Science is a colossus with a vast vision of its own. Environmental engineering concerns are plaguing the world scientific community. Frequent environmental disasters and loss of biodiversity have goaded the scientists and engineers to work toward newer innovations and challenges. The immediate need and the challenge of science need to be readdressed and reenvisioned as scientific rigor moves toward a newer paradigm. In the crucial juxtaposition of science and technology today, environmental engineering science gains new heights. The paradigm of engineering science is targeted toward the protection of environment. Technological innovations and technological motivations are in a state of distress today as protection of environment is in a process of immense failure. In such a situation, new vision and innovation are the veritable need of the day. Environmental science is in the process of new scientific regeneration. Human civilization is also in the process of wide realization of environmental and energy sustainability.

The scope of this well-informed study goes beyond scientific imagination and understanding. The challenge of applications of nanotechnology, nontraditional environmental engineering techniques, and novel separation processes needs to be rebuilt and readdressed as scientific and academic rigor moves toward a visionary scientific avenue. The challenge of this research work is surpassing visionary frontiers as science and engineering overcomes one hurdle after another in chemical process engineering and environmental engineering science.

1.3 Scientific Vision and Cognizance in the Field of Nanotechnology

Scientific vision and cognizance in the field of nanotechnology are groundbreaking as science and engineering move from one paradigm to another. Today, nanotechnology is a visionary area of research pursuit. The scientific challenges is immense in the field of nanotechnology as science and engineering crosses one visionary boundary after another. Nanoscience and nanotechnology today are linked with the wide area of environmental engineering science. Technological vision is the order of the day today. Nanotechnology and groundwater remediation are the areas of science that are being challenged in today's scientific horizon. Chemical process engineering and materials engineering are witnessing futuristic challenges. Water shortages and global water crisis are paving the way for a newer vision for the future.

1.4 Frontiers of Nanotechnology and the Vision for the Future

Nanoscience and nanotechnology are the visionary and far-reaching areas of science and engineering. Today, nanotechnology research has links with chemical process engineering and environmental engineering science. The success of application of nanotechnology to society and mankind goes beyond scientific imagination. Technological advancements today are in a state of immense shortcomings and unbelievable challenges. In a similar vein, nanotechnology and nanomaterials are facing immense challenges in their application domain. A scientist's defined prowess, science's immense rigor, and the futuristic vision are today leading a long way in true realization of environmental sustainability and sustainable development. Frontiers of nanotechnology are gaining new heights and revolutionary scientific outcomes. The success of science and engineering of nanomaterials are immense and unimaginable as human civilization moves from one chapter to another. Technology and engineering today are the boon to human civilization and human scientific endeavor. Today, environment stands in the midst of deep distress and wide introspection. The challenge of protecting environment needs to be addressed and deeply comprehended with each step of human life. Nanotechnology vision is the torchbearer of a greater visionary tomorrow in the research pursuit of science and engineering. The vision for the future in the vast and versatile domain of nanotechnology is far-reaching and crossing enigmatic scientific frontiers. This research treatise provides gainful insights into the pursuit toward environmental protection, chemical process engineering, and nanotechnology.

1.5 The Vision and Advancements in the Field of Nanotechnology

Nanotechnology in today's world is moving at a rapid pace toward a newer scientific frontier. The challenge, the vision, and the potential of application of nanotechnology in environmental protection need to be readdressed as human civilization moves toward a newer realm. Nanotechnology has a wider vision as scientific vision and deep scientific understanding assumes immense importance in this century. Human scientific vision is powered by a definite scientific grit and determination. The true challenge that lies in the field of nanotechnology is its immense scientific potential, scientific vision, and deep scientific understanding.

The success of the domain of nanotechnology has opened up new avenues of scientific challenges and scientific ingenuity in years to come.

1.6 Recent Scientific Endeavor in the Field of Nanoscience and Nanotechnology

The world of nanotechnology and environmental science are witnessing drastic changes. In today's scientific scenario, nanotechnology has an unsevered umbilical cord with environmental engineering science. This treatise goes beyond deep scientific imagination. The success and potential of nanotechnology are ushering in a new dawn of scientific endeavor and fortitude. The authors pointedly focus on the success of application of nanotechnology in environmental protection and environmental engineering science as a whole. The challenge and the scientific rigor need to be envisioned as human civilization moves toward a newer visionary age. This section widely observes the recent scientific research pursuit in the field of nanoscience and nanotechnology with special emphasis on the application of nanotechnology in environmental protection.

National Nanotechnology Initiative Workshop [1] in a well-informed report delineates nanomaterials and the environment, instrumentation, metrology, and analytical methods. Nanotechnology holds immense promise of exciting new solutions and innovations to critical scientific, industrial, and commercial challenges through the engineering of application-specific nanomaterials. Questions are raised and technology remains challenged as potential risks and hazards from nanotechnology are of utmost importance. In order to foster a better scientific understanding, National Nanotechnology Initiative, USA, has made environmental health and safety research an essential component and a research imperative.

German Environment Agency Report [2] delved deep into current state of knowledge in the field of nanomaterials in the environment. The report delineates effects and behavior of materials in the environment, their release in the environment, and their behavior and persistence in the environment. This report deeply comprehends the success of application of nanomaterials in environment and the wide vision of the application of nanotechnology. It also throws light on the further development of legislation on chemical process safety.

European Commission Report [3] deeply comprehends nanomaterials' functionality. The "Science for Environment Policy" focuses pointedly on the challenges and scientific introspection in application domain of nanomaterials. Some of the wide visionary topics discussed in this treatise are pomegranate-inspired battery design, nanoscale manufacturing, low-energy water purification, quantum dot processes, solar cell efficiency, efficiency of photovoltaic cells, application of graphenes, 3D printing techniques, and van der Waal's heterostructures. The scientific success and the deep scientific introspection are the pallbearers of a greater emancipation of science of nanotechnology in years to come.

Danish Environmental Protection Agency Report [4] defines and delineates the environmental fate and behavior of nanomaterials in a well-observed and well-informed treatise. It deeply comprehends and envisions new knowledge on important transformation processes. This report widely observes the application of nanomaterials and provides an overview of the present knowledge regarding processes relevant for environmental fate and behavior of engineered nanomaterials (ENMs). Engineered nanomaterials are the buzzword of scientific potential today. First, this report targets and deeply comprehends the definition and selection of nanomaterials. ENMs are defined as manufactured materials with one or more external dimensions between 1 and 100 nm, used in applications due to their novel characteristics resulting from their size and other engineered properties. In that respect and in that scientific vision, ENMs (stemming from engineered/intentional processes) can be seen as part of a broader group of nanomaterials, which in addition can result from natural and anthropogenic (incidental) processes. The scientific success, the immense scientific potential, and the visionary avenues of science are the torchbearers of a greater emancipation of nanomaterial technology in near future.

CSIRO, an Australian report [5], discussed lucidly the fate of manufactured nanomaterials in the Australian environment. This report reviews the available literature on the fate of manufactured nanomaterials in the aquatic and terrestrial environment. Seven classes of nanomaterials were considered: (i) metal oxides, (ii) carbon products (fullerenes and carbon nanotubes), (iii) metals, (iv) quantum dots, (v) nanoclays, (vi) dendrimers, and (vii) nanoemulsions. The challenges in the field of nanotechnology and nanomaterials need to be envisioned as human scientific mind and candor move toward a newer visionary age. The immense scientific potential, the visionary aisles of engineering science, and the transformation of technology are the pallbearers of a greater realization of the application of nanotechnology to environmental protection and the holistic sustainable development in the field of technology and engineering.

A German Federal Government report [6] dwelt lucidly into the wide domain of nanomaterials and environmental protection. This report gleans into the exposure of humans and environment as well as the toxicological and ecotoxicological properties and risks, in particular in connection with newer nanomaterials. This report discusses the opportunities and risks of nanotechnology within the framework of its high-tech strategy. This report observes three definite avenues: (i) opportunities for the environment and health, (ii) risks and safety research, and (iii) guidance document for responsible handling of nanomaterials.

Nanomaterials applications and scientific motivation in the field of nanotechnology are the technology drivers of today's science. Science is a colossus with a definite vision of its own. Nanomaterials technology and the concept of smart materials are changing the global scientific scenario. In today's scientific world, technology and science are visionary and far-reaching. Mankind's immense prowess and man's scientific ingenuity are the torchbearers of a wider realization of environmental engineering and material science today.

1.7 The Status of Environment Today

The status of environment today is at a state of immense distress. Global water crisis is challenging the scientific sphere and scientific domain. Environmental calamities, the grave concern of ecological imbalance, and the concern for environmental sustainability are going a long way in the true realization of nanotechnology and environmental engineering science. Science and engineering in this century are moving fast and surpassing visionary frontiers. Human civilization and environment are today standing in the midst of deep catastrophe. Scientific vision at such a crucial juncture is gaining immense heights as science and engineering moves toward a newerera. Scientific understanding and scientific cognizance are in a state of new regeneration. The fate of environmental protection stands in a state of immense scientific challenge and vision.

1.8 Environmental Sustainability: Its Vision for the Future

Sustainable development with respect to energy and environment is the need of the hour for the progress of human civilization. The challenge and the boon of human civilization today are the immense scientific endeavor in sustainable development and its definite scientific vision. Human scientific rigor in the field of environmental and energy sustainability are today crossing visionary frontiers. The vision for the future of environmental protection and environmental sustainability is vast and versatile. The success of civilization's rigor and scientific research pursuit lies in the hands of scientists and engineers . Global concerns for environmental sustainability are today ushering in a new eon. With such a wide vision in mind, nanotechnology and environmental science are paving the way for science and engineering today.

1.9 Technological Vision and Scientific Objective in the Field of Application of Nanomaterials

Technological vision and scientific motivation are the buzzwords of nanotechnology today. Nanotechnology in today's visionary scientific world is gaining new heights in its application in environmental protection and environmental engineering science. Nanomaterials are the eco-materials of today. Scientific objectives in the application of nanomaterials in environmental science are far-reaching. Environmental engineering science and its research pursuits need to be reenvisioned as human civilization moves toward a visionary realm. Application of nanomaterials and global water crisis are veritably linked by an unsevered umbilical cord. The technological vision of ecomaterials and its applications needs to be rebuilt and revamped as science and engineering move toward the threshold of a new era.

1.10 Recent Scientific Research Pursuit in the Field of Nanomaterials and Its Applications

Scientific research pursuit in the field of nanomaterials and its applications including environmental protection are surpassing wide scientific boundaries.

Research pursuits and forays in the field of environmental engineering science are gaining new heights. The challenge and the vision of science and engineering, the scientific urge to excel, and the wide scientific rigor will all lead a long way in the true realization of environmental engineering applications and sustainability. In this section, the authors stress upon the recent advances in the field of nanomaterials and the forays into environmental protection.

Stone *et al.* [7] discussed with a wide view nanomaterials for environmental studies and their classification, reference material issues, and strategies for physicochemical characterization. The authors discuss in this treatise projects especially in relation to human health effects. The physicochemical characterization information identified as important for environmental studies included measures of aggregation/agglomeration/dispersibility, size, dissolution (solubility), surface area, surface charge, and surface chemistry/composition, with the assumption that the chemical composition would be known. Nanotechnology involves the production of a diverse array of nanomaterials (NMs), which include nanoobjects and nanoparticles (NPs). Nanomaterials have one dimension less than 100 nm, whereas nanoobjects have two dimensions less than 100 nm (e.g., carbon nanotubes), and nanoparticles are defined as particles with three dimensions less than 100 nm. Today, nanoscience and nanotechnology are moving very fast crossing wide and visionary boundaries. The challenge of application of nanotechnology to environment is growing and groundbreaking. This treatise gleans and gives glimpses of the present and future trends of the application of nanotechnology. The immense scientific potential, the visionary applications of science, and the ever-growing areas of nanomaterials will go a long way in the true realization of environmental engineering science today.

Baun *et al.* [8] discussed with cogent insight ecotoxicity of engineered nanomaterials to aquatic invertebrates in a brief review and highlighted recommendations for future toxicity testing. Based on a literature review and an overview of toxic effects of engineered nanoparticles in aquatic invertebrates, this paper widely delineates a number of recommendations for the developing field of nanoecotoxicology by highlighting the importance of invertebrates as sensitive and relevant test organisms. The scientific cognizance and scientific vision needs to be reenvisioned as the world of nanotechnology enters into a new phase of immense scientific potential. This treatise gleans into the newer developments and innovations in the field of engineered nanomaterials.

Kreyling *et al.* [9] discusses with deep and cogent insight a complementary definition of nanomaterial. In the wake of fast developments taking place in nanotechnologies and nanosciences, the need for an internationally agreed definition of a "nanomaterial" has gained immense importance. Human civilization and human scientific endeavor are in the path of immense scientific regeneration. In this treatise, definitions are made mainly based on size parameters, and fall short in terms of applicability to particulate materials that have a size fraction in the nanoscale. Scientific fortitude, scientific forbearance, and deep scientific introspection are the torchbearers of a newer development and a newer innovative era in the field of nanomaterials.

Lowry *et al.* [10] delves deep into the unknown world of nanomaterials. This treatise highlights environmental occurrences, behavior, fate, and ecological effects of nanomaterials. This treatise is a widely observed special series on nanomaterials. The release of ENMs into the biosphere will increase as industries find new and useful ways to utilize these materials. Scientists, engineers, and the wider scientific domain are beginning to assess the material properties that determine the fate, transport, and effects of ENMs; however, the potential impacts of released ENMs on organisms, ecosystems, and human health are widely unknown. The authors of this treatise pointedly focus on the scientific success and the immense scientific potential of engineered nanomaterials in the furtherance of the success of nanotechnology. Technological motivation and definite scientific objectives are the tools and drivers of science today. Scientists and engineers are facing extraordinary challenges as the world of nanoscience and nanotechnology enters into a visionary era. This treatise highlights the immense importance of engineered nanomaterials in the avenues of difficult scientific hurdles in years to come.

Gottschalk *et al.* [11] deeply comprehend the science of engineered nanomaterials. They modeled environmental concentrations of engineered nanomaterials (TiO_2, ZnO, Ag, CNT, and fullerenes) for different reasons. Engineered nanomaterials are already used in many products and consequently released into environment. In this study, the authors calculated predicted environmental concentrations (PECs) based on probabilistic material flow analysis. The authors challenged the scientific notions in the endeavor in ENMs. Technology needs to be envisioned as scientific endeavor enters into a new world of challenges and vision.

Klaine *et al.* [12] give a lucid insight into the behavior, fate, bioavailability, and effects of nanomaterials in the environment. Nanoscience and nanotechnology applications are widening as nanomaterials are entering into a visionary era. The recent forays in nanotechnology and the corresponding increase in the use of nanomaterials in products in every avenues of society have resulted in uncertainities regarding environmental impacts. This treatise effectively and pointedly focuses on the deep uncertainities of environmental protection and the interlinked world of nanotechnology.

1.11 The Avenues Ahead in the Field of Nanotechnology Applications

Nanotechnology applications are changing the scientific scenario and the vast scientific fabric. The avenues ahead in the field of science and engineering are wide and bright. Nanoscience and nanotechnology are revolutionizing the entire scientific fabric. Global water crisis and global water technology initiatives are drastically changing the wide scientific horizon. The authors in this treatise repeatedly point out the immense need of nanotechnology in environmental protection. Human civilization is in the path of new glory as mankind evolves into a new scientific regeneration. Mankind's immense scientific prowess, the wide scientific journey, and the effective scientific progress will all lead to an effective way in the true emancipation of sustainable development. Today, nanotechnology and other visionary avenues of science are veritably linked with energy and environmental sustainability. One of the visionary avenues of science today is the application of nanotechnology to the provision of basic needs such as water and the worldwide concern for groundwater remediation. The success, the potential, and the scientific rigor will lead a long way in true realization of environmental engineering applications and sustainable development.

1.12 Scientific Cognizance and Scientific Sagacity of Environmental Engineering

Environmental engineering science in today's scientific scenario is moving fast at a rapid pace. Global concerns for environmental protection are drastically changing the scientific horizon. Nanotechnology is the other side of the visionary coin of environmental engineering science. Nanomaterials or eco-materials are the smart materials of today. The challenge and the vision of science need to be readdressed and reenvisioned with each step of scientific and academic rigor. The challenge of science, scientific cognizance, and scientific ingenuity are the pallbearers of a greater vision of tomorrow in the field of environmental engineering science. The greatest concern for human civilization is the protection of environment and biodiversity. The success of research endeavor in environmental engineering is latent yet immense. Nanomaterials and eco-materials are the technology drivers of today. Scientific vision needs to reenvisaged as mankind steps into a new era.

1.13 Nontraditional Environmental Engineering Techniques

Nontraditional environmental engineering techniques are the torchbearers of today's environmental engineering science. The potential of applications of environmental engineering techniques such as advanced oxidation processes (AOPs) are immense and far-reaching. The efficiency, the effectiveness, and the vision of AOPs and integrated AOPs are changing the future scientific horizon. The authors in this treatise pointedly focus on the vast importance of AOPs today. Nontraditional environmental engineering techniques are changing the scientific firmament of the new scientific order. Advanced oxidation processes and membrane science needs to be rebuilt and reenvisaged with each step of today's scientific regeneration. Advanced oxidation processes such as ozonation today are at the helm of scientific vision and scientific regeneration. Technology and engineering science today are paving the way for a visionary scientific endeavor.

1.13.1 Scientific Doctrine of Advanced Oxidation Processes

The scientific doctrine of advanced oxidation processes is groundbreaking in today's world of technological vision and deep scientific objectives. A scientist's vision and an environmental engineer's perspective are emboldened as science steps into a newer innovation. Advanced oxidation processes are well suited for recalcitrant chemicals that cannot be degraded by traditional techniques. Technological innovations are the order of the day. Science, technology, and engineering are ushering in a new chapter in the field of technological and scientific motivation.

Advanced oxidation processes are in the path of newer scientific regeneration. Andreozzi *et al.* (1999) discuss lucidly AOPs for water purification and recovery. All AOPs are characterized by a common chemical feature: the capability of exploiting the high reactivity of HO radicals in driving the oxidation processes that are suitable for achieving the complete abatement and degradation of recalcitrant pollutants. This treatise intuitively observes different AOPs according to their specific features with real applications of water pollution abatement. The success of AOP science needs to be reenvisioned and reenshrined with each step of scientific endeavor.

Mondal *et al.* [13] discuss textile wastewater treatment by advanced oxidation processes. Textile effluent is an abundant source of colored pollutants. It increases environmental danger and enhances deep environmental concerns. This work discusses scientific objectives in all possible treatment methods for removing dyestuff from textile effluents by AOPs.

Pera-Titus *et al.* [14] provide a detailed and well-informed review of the degradation of chlorophenols by means of advanced oxidation processes. AOPs constitute a promising technology for the treatment of industrial wastewater containing not easily removable organic compounds. Science and technology of advanced oxidation processes are changing the visionary scenario of environmental engineering techniques. Chlorophenols (CPs) are a group of special importance due to their high toxicity and low biodegradability. Data concerning the degradation of CPs by means of AOPs reported during the period 1995–2002 are evaluated in this work of high importance. Among the AOPs, the following techniques are studied: processes based on hydrogen peroxide, photolysis, and photocatalysis and processes based on ozone. This comprehensive treatise delves deep into the chemistry of advanced oxidation process and delineates the wide gamut of scientific endeavor.

Esplugas *et al.* [15] made a comparison of different advanced oxidation processes for phenol degradation. Advanced oxidation processes for degradation of phenol in aqueous solution have been studied in earlier works. In this treatise, a comparison of these techniques is undertaken: pH influence, kinetic constants, stoichiometric coefficient, and optimum oxidant/pollutant ratio. According to the research pursuit, Fenton reagent was found to be the fastest one for phenol degradation. The researchers widely observed the different scientific challenges in the application of AOPs and found it to be highly successful.

Oller *et al.* [16] reviewed combination of advanced oxidation processes and biological treatments for wastewater decontamination. Advanced oxidation processes are considered a highly competitive water treatment technology crossing visionary boundaries. The challenge, the vision, and the worldwide wastewater treatment issue have changed drastically the scenario of scientific research. AOPs are a competitive technology for the removal of those organic pollutants not treatable by conventional techniques due to their high chemical stability and/or low biodegradability. The success of AOPs is enormous as science and engineering tread a visionary avenue. This paper reviews recent research combining AOPs and bioremediation technologies for the removal of a wide range of synthetic and industrial wastewater.

Badawy *et al.* [17] investigated advanced oxidation processes for the removal of organophosphorus pesticides from wastewater. The immense scientific potential and scientific vision of AOPs are challenged in this early period of this century. The combinations of the Fenton reaction, UV/hydrogen peroxide and the photo-Fenton process in the degradation of organophosphorus-containing substrates were investigated in detail.

This paper on nanomaterials and environmental protection goes beyond scientific imagination and scientific fortitude. Human scientific endeavor today is in the state of veritable distress. The success of human civilization today needs to be reenvisioned and reorganized as science steps into a new era.

1.14 Future Trends and Scientific Doctrine of Novel Separation Processes

Novel separation processes such as membrane science are ushering in a new eon of challenge and vision. Scientific vision and scientific forbearance are reenvisaged as human civilization and human scientific endeavor crosses wide scientific boundaries. In today's scientific world, global water challenges and membrane science are the two opposite sides of a visionary coin. The challenges of science are increasing and the wide scientific rigor overwhelming as scientific progress witnesses drastic challenges. The success of scientific endeavor, the futuristic vision of scientific validation, and the immense scientific rigor will go a long and visionary way in the true emancipation of environmental engineering science. Novel separation processes such as membrane science are revolutionizing the scientific scenario and the wide world of scientific forbearance and vision. The scientific doctrine needs to be rebuilt as human civilization gears toward a new avenue of engineering science, chemical process engineering, and material science. The futuristic vision, the future of the application of nanomaterials, and the visionary road ahead are changing the global water scenario. The scientific boundaries need to be redrawn as human civilization gears toward a newer visionary and innovative era [18].

1.15 Recent Scientific Research Pursuits in Membrane Science

Global water initiatives are in a state of immense catastrophe. Novel separation processes, the success of membrane science, and the wide world of global water challenges are paving the way for a newer visionary eon in the field of environmental engineering science. Today, scientific validation is the order of the day. The scientific success, the vision of scientific validation, and the world of true realization of environmental sustainability are the torchbearers of a greater visionary future.

Strathmann *et al.* [19] in a well-researched treatise gave a cogent insight into membrane development in future. This treatise deeply comprehends historical and key developments of membranes and membrane processes. The key issues addressed are advantages and limitations of membrane processes, cost considerations and environmental impact, the membrane-based industry, the membrane market and its future development, and the future of membrane science and technology. It then goes on to discuss in detail principles of membrane separation processes. The authors touch upon the principles of microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Gas separation, pervaporation, dialysis, electrodialysis, and membrane contactors/membrane reactors are delineated. The vast and versatile field of membrane separation process and design are intuitively discussed along with large application domain. The other wide scientific frontier touched is the field of concentration, polarization, and membrane modules. The authors wind up the treatise with membranes and membrane process applications. The challenge, the potential, and the wider imperatives of science are reenvisioned at each step of this scientific research pursuit.

Franken *et al.* [20] in a well-researched treatise discussed wetting criteria for the applicability of membrane distillation. The success of membrane distillation is such that it can be applied only on liquid mixtures that do not wet a microporous hydrophobic membrane. The advantages of membrane distillation are that the distillation process takes place at moderate temperature and that a relatively low temperature difference between the two liquids contacting the microporous hydrophobic membrane gives relatively high fluxes. Because entrainment of dissolved particles is avoided, a permeate with a high purity is obtained. The target of this research treatise is far-reaching as science gears forward toward a newer visionary domain.

Hong *et al.* [21] gives a lucid insight into the chemical and physical aspects of natural organic matter (NOM) fouling of nanofiltration membranes. The role of chemical and physical interactions in NOM fouling of nanofiltration membranes is investigated and discussed in detail. The success of application of NF technology requires efficient control of membrane fouling. This is a decisive factor in the success of membrane separation phenomenon. Dissolved naturally occurring organic substances are considered a major cause of fouling in membranes. A major fraction of dissolved natural organic matter in aquatic environments is contributed by humic substances. The technology of membrane fouling and membrane separation phenomenon till today remains unanswered. The authors of this treatise go beyond scientific imagination and scientific cognizance in a decisive effort toward worldwide research and development initiative in membrane science.

Elimelech *et al.* [22] decisively reports with cogent insight into the role of membrane surface morphology in colloidal fouling of cellulose acetate and composite aromatic polyamide reverse osmosis membranes. Membrane fouling is a major limitation in efficient operation of reverse osmosis (RO) plants worldwide. The aim and objective of this study are in two different avenues.

One is to demonstrate the paramount role of membrane surface characteristics and the second is to provide a viewpoint and a mechanistic application for the lower fouling tendency of cellulose acetate RO membranes compared to polyamide composite RO membranes. The immense imperatives of science and engineering of membrane science are thoroughly discussed with visionary implications in this treatise.

Yang *et al.* [23] discussed lucidly carbon dioxide separation and capture in a detailed review. Various technologies and innovations such as absorption and membrane separation are discussed in minute details. New concepts such as chemical looping combustion and hydrate-based separation are also investigated briefly. Sequestration methods are also covered with scientific introspection.

1.16 Future Trends in Research and Development in Nanomaterials

Materials science and chemical process engineering are reshaping the research and development initiatives in nanomaterials [24,25]. Technological motivations and scientific challenges need to be reenvisioned and reenshrined as science steps into a newer world of scientific validation. Future trends in research and development in nanomaterials should be targeted toward more innovation in the field of smart materials. Environmental engineering and materials science are the other avenues of scientific progress [24–26].

1.17 Future Flow of Scientific Thoughts and the Scientific Progress

Science and engineering are at a state of immense distress facing innumerable challenges. The future trends of the application of nanotechnology and nanomaterials in environmental protection are replete with immense scientific vision and scientific cognizance. Scientific knowledge in today's human civilization is crossing wide visionary boundaries. The provision of basic human needs such as water and protection of environment are the utmost challenges of science and engineering today. The futuristic vision of global water initiatives needs to be rebuilt tackling scientific hurdles and deep scientific profundity. The structures of scientific research pursuit in environment protection are the important parameters toward the wider progress of science [18,27,28]. Scientific progress in today's world is immensely thought-provoking and introspective. The greatness of engineering science and materials science needs to be targeted toward a world of greater scientific imagination. Environmental sustainability and the visionary world of wider sustainable development are the true torchbearers of a greater realization of environmental engineering techniques today. Materials science, polymer science, chemical process engineering, and materials engineering are gaining new heights as mankind crosses visionary frontiers. The success of traditional and nontraditional environmental engineering tools is paving the way for a greater environmentally sound sustainable development. The future lies at the hands of technologists and scientists as human civilization moves from one decade to another. The scientific profundity and scientific candor of advanced oxidation processes and membrane science are being challenged as science and engineering steps into a newer eon. The efficiency and effectiveness of novel separation processes are the new challenges and new hurdles toward scientific validation. Scientific progress today is gaining new heights and crossing newer frontiers as scientific shortcomings are overhauled in the field of environmental engineering science [24,25,29].

1.18 Conclusions

Environmental engineering science and material science are witnessing a new dawn in scientific research pursuit. The success and potential of smart materials and eco-materials are opening windows of innovation in the field of scientific pursuit and validation. Technology and engineering in the present century are moving extremely fast. Provision of basic human needs in our present day human civilization is at a state of extreme distress. Scientific rejuvenation and scientific forbearance are the urgent need of the hour. In a similar fashion, global water issues gain highest importance with every step of scientific and academic rigor. Environmental protection and environmental engineering science are the areas that need to be readdressed and reenvisioned with immediate and utmost effect. Scientific endeavor needs to be reenshrined with immense effort from the society and scientific community. The challenge of human civilization lies at the hands of visionary scientific endeavor. The saga and domain of environmental engineering science are crossing visionary frontiers. The authors repeatedly focus on the immense potential and success of application of nanomaterials in environmental protection touching upon environmental sustainability as a major issue. Sustainable development is ushering in a newer vibrant era. The caution and grave concerns of global environmental sustainability are touched upon with minute details and immense introspection in this treatise. The world of challenges, the broad vision, and the immense potential of nanomaterials and nanotechnology are paving the way for a newer realm in the field of environmental engineering science. Scientific vision is today in the path of immense distress as global water challenges and the concerns for clean drinking water ushers in a new era. The immediate need of the hour is the scientific challenge of groundwater remediation.

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