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Environmental Degradation: Challenges and Strategies for Mitigation

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Environmental Degradation: Challenges and Strategies for Mitigation

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Preface

The motivation of this volume titled *Environmental Degradation: Challenges and Strategies for Mitigation* is mainly to present techniques for protecting the environment by identifying the causes of degradation, impact of degradation on socioeconomic health, identifying suitable treatment or remediation technologies for mitigation, and strategies for value-added product recovery from waste.

The book contains 24 chapters covering causes of degradation, various technologies, and methodologies for treatment/remediation, and strategies for mitigation. The chapters are divided into five parts. Part I is an Introduction to the book and gives an overview on environmental degradation and mitigation. Part II, consisting of three chapters, deals with Causes of Degradation, while Part III consists of seven chapters under the title Treatment or Remediation Technologies. On the other hand, Part IV deals with Impacts of Degradation and consists of seven chapters; Part V is devoted to Socio-economic Framework which consists of six chapters. These 24 chapters are now briefly introduced.

Chapter 1 entitled "**An Overview on Environmental Degradation and Mitigation**" discusses injudicious use of fossil fuel, exploitation of water resources, enhanced soil pollution, and emission of harmful gases caused by many undesirable changes that severely affect the ecosystem, ecological habitat, wildlife, plants, animals, and humans, including necessary actions, and policy initiatives have been born worldwide to regulate and counteract environmental degradation for sustainable management of social, economic, and environmental benefits along with the increase in green economy.

Chapter 2 entitled "**Deforestation and Forests Degradation Impacts on the Environment**" details the appropriate political, judicial, institutional framework, and competent market mechanisms to minimize the rate of deforestation, including multi-sectoral market and public policy along with the enhancement of property rights, the firm formulation of user rights, and land occupancy, and privatization of forests may play pivotal roles in minimizing forest degradation and deforestation.

Chapter 3 entitled "**Measuring Environmental Impact of Agricultural, Manufacturing, and Energy Sectors in Bangladesh Through Life Cycle Assessment**" deals with identifying the key contributing factors to environmental degradation in

Bangladesh by conducting a comprehensive review on the available literature on LCA studies on agricultural, manufacturing, and energy sectors; a compilation of relevant studies provides a comparative picture of the prime environmental impacts inflicted by these sectors, highlighting the hotspots responsible for environmental degradation. Finally, the study also exhibits ways to implement sustainable resource management for the mentioned sectors and ultimately addresses the knowledge gaps in these sectors.

Chapter 4 entitled "**Chemical Fertilizers and Pesticides: Impacts on Soil Degradation, Groundwater, and Human Health in Bangladesh**" focuses on the impacts of chemical fertilizers and pesticides on soil degradation and effects of chemical fertilizers and pesticides on groundwater pollution with reference to Bangladesh situation, delineates the harmful effects of chemical fertilizers and pesticides on human health, and suggests that organic amendments and biocontrol agents should be prioritized as environmentally benign alternatives to reclaim the productivity of soil and for a robust sustainable agriculture, including protection of groundwater quality and human health.

Chapter 5 entitled "**Environmental Impacts and Necessity of Removal of Emerging Contaminants to Facilitate Safe Reuse of Treated Municipal Wastewaters**" describes the fate of micropollutants in the environment and the redundancy of conventional treatments toward their effective removal, identifies the effect of released micropollutants on the environment, and provides suggestive information on advanced oxidation processes used for the remediation of contaminated wastewater. It further suggests that the reuse of treated water must be preceeded by the removal of xenobiotic compounds from wastewater as confirmed by the detrimental effect of these released pollutants to the environment. The presence and persistence of such xenobiotic compounds in the treated water from the wastewater treatment plants beget the need for advanced treatment technologies for the removal of these compounds.

Chapter 6 entitled "**Emerging Biotechnological Processes in Controlling Nitrogen Pollution to Minimize Eutrophication of Surface Waters in Asia**" investigates to identify appropriate process alternatives to conventional nitrification–denitrification for the removal of ammonia from wastewaters and learn the emerging biotechnological processes in controlling nitrogen pollution with associated merits and demerits including the selection of the appropriate process for the removal of nitrogen pollution from wastewaters for environmental protection.

Chapter 7 entitled "**Hybrid Anaerobic Baffled Reactor and Upflow Anaerobic Filter for Domestic Wastewater Purification**" focuses on the hybrid system that has good performance in treating domestic wastewater with removal efficiencies of 88, 78, 90, 70, 34, and 75% for parameters of BOD, COD, TSS, NH_3, PO_4, and total coliform, respectively. The removal can be achieved within a detention time of 24 hours. However, tertiary treatment for phosphorus removal is required to meet the discharge regulation. The low-cost hybrid system of ABR and UAF has effectively treated domestic wastewater and has met the effluent discharge regulation.

The system can be implemented widely in developing countries to reduce water pollution and support SDG 6 related to water and sanitation.

Chapter 8 entitled "**Remediation of Heavy Metal Pollutants of Industrial Effluents and Environmental Impacts**" emphasizes nano-calcium silicate precipitation tubes (CaSPT) as HMsl (Zn(II), Cd(II), Cu(II), Pb(II), and Cr(III)) adsorbents in an aqueous medium to identify its application as water purifier after thorough physicochemical characterization.

Chapter 9 entitled "**Textile Dye Removal from Industrial Wastewater by Biological Methods and Impact on Environment**" discusses impacts of textile dyes on aquatic environment, vegetation, and human health and investigates the dye decolourization potential of already available chemical and physical treatment methods including evaluation of positive outcomes of biological treatment methods on removing textile dyes from industry effluents. It further suggests that biological decolouriation techniques can be used to remove textile dyes from effluents. Various types of biological reactors operated in batch and continuous modes have been tested for decolourization of textile dyes and have shown positive results. The level of color reduction depends on the type of dye, microbial species used, type of reactor used, operating conditions of the reactor, and the mode of operation.

Chapter 10 entitled "**Environmental Remediation Technologies**" attempts to summarize a variety of remediation technologies, including their theories, current status and advanced development, applicability and suitability of a technology as well as their limitations. Among all the existing technologies, remediation through nano-technology has emerged as one of the promising technologies because nanomaterials have a higher surface-to-volume ratio, which increases reactivity, adsorption, and effectiveness of contaminant removal. In addition, compared to traditional approaches, nano-materials have the ability to exploit unique surface chemistry, allowing them to be functionalized or grafted with more than one functional group that can be used to target specific contaminants, resulting in an effective remediation.

Chapter 11 entitled "**Wastewater Remediation: Emerging Technologies and Future Prospects**" critically evaluates different conventional and emerging physicochemical and biological effluent treatment techniques for waste water remediation.

Chapter 12 entitled "**Microbial Diversity and Physio-Chemical Characterization and Treatment of Textiles Effluents**" emphasizes the issue of dilution and biological treatment of textile effluents, which is very much essential before it is discharged to the ecosystem. Finally, it concludes that bioremediation and treatment of effluents by microbial community help neutralize pollutants and minimize their effect in the aquatic environments.

Chapter 13 entitled "**A Sustainable Solution for the Rehabilitation of Surface Water Quality Degradation**" focuses on the application of vegetated ditch in treating diffuse pollution, the effectiveness of the system as well as the mechanisms of contaminant removal. Furthermore, it critically evaluates the challenges faced by vegetated ditch implementation as well as for the enhancement of the system. The nature-based water quality treatment system, such as VD, has been shown to be able to serve as a sustainable solution in mitigating diffuse pollution occurring in agricultural areas. Apart from its acknowledged ability to remove the most common contaminants of agricultural runoff, which are nutrient and pesticides, VD system has also been demonstrated to be able to remove organic matters, pathogen, heavy metals, and contaminant of emerging concerns (CECs).

Chapter 14 entitled "**Recovery from Natural Disasters and Environmental Destruction in East Japan**" examines the transformation of resources in the Tohoku region as a result of the Great East Japan Earthquake (GEJE), including the characteristics of the East Japan Area, its impact, effects of earthquake on the physical, economic, and social environment, and disaster prevention and infrastructure strengthening.

Chapter 15 entitled "**Biodiesel and Its Environmental Impact and Sustainability**" focuses on producing biodiesel fuel from waste/used cooking oil through the process of transesterification. A few important physical parameters are analyzed, such as density, viscosity, flash, fire point, caloric value, and cetane number. Biodiesel blends at various concentrations 10%, 20%, 30%, 40%, and 50% are prepared and tested in 5HP Kirloskar diesel engine to assess the fuel suitability. The present investigation shows that the cooking oil wastages could be a prominent candidate for biodiesel production. The lower blend up to 20% can be used as a substitute fuel to diesel engines.

Chapter 16 entitled "**A Case Study on Practices and Acute Toxicity Symptoms Associated with Pesticide Use Among the Farmers of Mid Brahmaputra Valley of Assam**" discusses the assessment of knowledge, attitude, practices regarding pesticide handling, and acute toxicity symptoms of pesticide use among the farmers of mid-Brahmaputra Valley of Assam. This study indicates that there is an inadequate level of knowledge among farmers which influence their practices. Personal experiences are more important than abstract knowledge.

Chapter 17 entitled "**Laccase Enzyme in Nanoparticle for Pesticide Degradation: A Special Emphasis on Chlorpyrifos Degradation**" focuses on laccase enzyme, their sources of generation, characteristics, and application, including the application of nanoparticles in pesticide degradation and their role as a carrier for enzyme immobilization, and discusses the mechanism of action of laccase-immobilized nanoparticles in pesticide degradation.

Chapter 18 entitled "**Deforestation and Forests Degradation Impacts on Livelihood Security and Climate Change: Indian Initiatives Towards Its Mitigation**" discusses the deforestation, forest degradation, habitat loss, and forest fragmentation, which directly or indirectly affect the livelihood security. Deforestation and forest degradation are aggravating with the increase of human population and their rising dependency on forests, thus necessitating management strategies to sustain biodiversity and its sustainability.

Chapter 19 entitled "**Sustainable Technologies for Value Added Product Recovery from Wastewater**" evaluates different technology options that can be utilized for sustainable by-product recovery from effluent streams, the applicability of techniques vis-à-vis the scale-up potential for large-scale applications, and waste valorization technique like acid leaching is studied from the perspective of industrial application.

Chapter 20 entitled "**Socio-economic Environmental Sustainability and Indian Mining Industry—A Perspective**" elaborates the issues concerning the socioeconomic dimension of the environment with a focus on the Indian mining industry, including the methodology of socioeconomic impact assessment, and the framework for environmental sustainability to tackle the environmental degradation menace, industry–community relation, etc., emphasizing that mining enterprises are useful for the societal development of rural areas, where mines are generally located.

Chapter 21 entitled "**Trade and Gas Emission in Mauritius: Impact on Socioeconomic Health and Environmental Degradation**" discusses an investigation of the potential association between international trade and environment in the small island economy of Mauritius from 1980 to 2018, and also examines the extent to which economic growth, education level, and population size affect the environment of the island.

Chapter 22 entitled "**Plastic Waste Management: Current Overview and Future Prospects**" describes the plastic production, consumption, and waste generation, including assessment of waste disposal and treatment techniques, recent approach and technological advancements as well as strategies and scopes for sustainable management plastic solid waste.

Chapter 23 entitled "**Transboundary River Management of the Ganges–Brahmaputra–Meghna (GBM) Delta: Environmental Challenges and Strategies**" emphasizes identifying the environmental challenges associated with the Ganges, Brahmaputra, and Meghna rivers and the effects that they have on the GBM delta. It also analyzes ways to improve the transboundary river management of this region to overcome the anthropogenic and natural environmental challenges that are posed on the delta system. It is suggested that proper management strategies can reduce the environmental uncertainty of this region. Compliance, enforcement, and dispute settlement can resolve long-standing issues in the Ganges, Brahmaputra, and Meghna river management.

Chapter 24 entitled "**Achieving Sustainability by Retrofitting Circular Economy Models in Food Waste Flow of Bangladesh**" focuses on quantification of the household food waste generation of Bangladesh for the first time. The food waste has been measured and analyzed throughout urban and rural households of the country. Different recycling methods from across the world have been explored, and this study suggests suitable opportunities for recycling and circularity of the food waste in Bangladesh.

Special thanks to all who contributed in making this volume a source of knowledge and reporting the latest findings in their areas. The authors put a lot of efforts during all phases of the book production starting from writing, revising based on reviewers' comments and Springer evaluation reports, and finally checking the proofs of chapters. Acknowledgements are extended to all members of the Springer team who have worked long and hard to produce this volume.

The editors would be happy to receive any comments to further improve future editions. Comments, feedback, suggestions for further improvement, or proposal for new chapters for next editions is welcome and should be sent directly to the volume editors.

College Station, USA — Vijay P. Singh
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For his seminal contributions, he has been honored with more than 105national/international awards from professional organizations. As a sample, he is a recipient of the Arid Land Hydraulic Engineering Award, Ven Te Chow Award, Torrens Award, Norma Medal, Lifetime Achievement Award, and OPAL Award, all given by ASCE. He was awarded the Ray K. Linsley Award for outstanding contributions to surface water hydrology and the Founders Award of AIH. He has been awarded three honorary doctorates. He is a fellow of ASCE, AWRA, IE, ISAE, IWRS, IASWC, and IAH; a member of AGU, IAHR, IAHS, and WASER. He is a member/fellow of 12 engineering/science academies. He is licensed as Professional Engineer (PE), Professional Hydrologist (PH), and Honorary Diplomate, AAWRE.

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He has published more than 80 journal articles and technical reports. He is a member of the organizing and scientific committee of several conferences and reviewer of Journal of Cleaner Production, Journal of Hazardous Materials, Energy; and Section Editor of International Journal of Environmental Chemistry. Also, he has published a number of edited books.

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He has adequate experience in establishing institutes/organizations. In addition, he has adequate experience in planning, formulating, executing, and managing of R&D programs including organizing seminars/symposia/conferences at national and international levels. He has got to his credit guiding a number of M.Tech. and Ph.D.

students in the areas of mathematical sciences and earth sciences. He has visited and delivered invited lectures at different institutes/universities in India as well as in abroad in the various countries such as USA, Canada, UK, France, Thailand, Germany, South Korea, Malaysia, Singapore, South Africa, Costa Rica, The Netherlands, France, China, and Australia. He is Recipient of Raman Research Fellowship and other awards.

He has been recognized for four decades of leadership in research and service to the hydrologic, environment, and water resources profession. His contribution to the state of the art has been significant in many different specialty areas, including water resources management, environmental sciences, irrigation science, soil and water conservation engineering, and mathematical modeling. He has published more than 100 journal articles; four text books; and fourteen edited reference books. He is the reviewer of scientific journals and member of the scientific committee of international conferences. He also holds position of Vice President of International Association of Water, Environment, Energy and Society.

Part I
Introduction

Chapter 1
An Overview on Environmental Degradation and Mitigation

Vijay P. Singh, Shalini Yadav, Krishna Kumar Yadav, and Ram Narayan Yadava

Abstract Environmental degradation is directly linked with environmental quality deterioration and depletion of resources. It is the world's most pressing problem and has created many challenges to humans, plants, animals, wildlife, and their habitats due to injudicious use of natural resources like unlimited burning of fossil fuel, water and soil pollution, and emission of harmful gases. The environmental degradation may be caused due to the several factors including pollution, climate, climate change, waste disposal, deforestation, desertification, and overpopulation. Worldwide, many policy initiatives have been born to develop strategies for mitigating and adapting to regulate and minimize restoring environmental degradation. The present chapter aims at (1) presenting an overview of environmental degradation to better understand this global issue, (2) describing different types of environmental degradation, (3) explaining several causes of environmental degradation in detail, and (4) discussing the impacts of environmental degradation and their mitigation measures briefly.

Keywords Degradation · Pollution · Climate · Remediation · Environment-friendly · Strategies

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1.1 Introduction

Environment is the aggregate of all the extrinsic forces, influences, and conditions, which affect the life, nature, behaviour, growth, development, and maturation of living organisms (Douglas and Holland 1947). The "environment" holds land, water, air, and the interrelationship which exists between these elements and human beings, other living creatures, micro-organisms, and plants (EPA 1986). When the evolution of human beings started, they were afraid of nature and the natural changes. However, these natural resources began to deplete due to population growth, urban sprawl, increasing technology, and developmental activities resulting in environmental deterioration. Environmental degradation is the deterioration of the environment through exhaustion of natural resources, including all the biotic and abiotic components, including air, water, soil, plant, animals, and all other living and non-living elements on the earth (Bourque et al. 2005). The availability of resources such as water and land will be reduced due to the degradation process (Barman et al. 2013). The continued rapid degradation of land and water resources due to water quality degradation may result in hydrocide for future populations (Lundqvist 1998).

Environmental degradation (ED) is the outcome of past and present generations destroying natural resources faster and injudiciously than nature can restore them and being unable to sustain them for future generations. The effects of ED can be visible through several ways, including the devastation of forests resulting in soil erosion and threatening agricultural livelihoods, construction of big dams or diverting river water causing water shortages, removal of coastal protection such as mangroves species leading to waterlogging of soils, air pollution from industries and coal-based thermal power plants causing environmental pollution, and increased ill-health effects on living beings. All these factors can lead to increased poverty and environmental degradation (CEDRA 2009). Environmental degradation is one of the ten threats officially cautioned by the United Nations. The United Nations International Strategy for Disaster Reduction defines environmental degradation as "The reduction of the capacity of the environment to meet social and ecological objectives, and needs". The central cause of environmental degradation is human interference (Tyagi et al. 2014).

1.2 Types of Environmental Degradation

Environmental degradation refers to the loss of the natural environment in some way for present or future use (McMahon 2021). It is mainly of three types: (a) land/soil degradation; (b) water degradation; and (c) atmospheric/air degradation (Ansumant 2019). Land degradation refers to the deterioration or total loss of the productive capacity of the soil for present or future use (FAO 1981). The major factors for land degradation are deforestation, desertification, soil erosion, soil salinity, and water logging. According to UN studies, 23% of all usable land, excluding mountains, deserts, Polar Regions, etc., has been degraded to such an extent that its productivity has been affected. The per capita land resource is showing a marked decrease in many thickly populated countries. In India, it may go down from 0.33 ha to 0.25 ha in the near future (FAO 2011). Land degradation indicates complicated ecological processes where soil fertility is progressively decreased. Without remedial measures, such processes may lead to a constant situation of desertification and loss of agricultural and forest productivity (Laguna et al. 2019). Extreme weather phenomena are especially significant natural forces of change since prolonged drought and heavy rainfalls cause land quality depletion.

Water degradation refers to the deterioration of water quality in any form. The process of water degradation may alter the physical, chemical, and biological properties of water. The quality of water plays a significant role in human life as it directly affects their welfare. The indiscriminate use of chemical fertilizers, insecticides, and pesticides, the improper disposal of waste, and chemical spills from the industry have caused a deterioration in the water quality (Yadav et al. 2018). The major water quality issues resulting in degradation include waterborne pathogens and noxious and toxic pollutants (Peters and Meybeck 2000). Despite efforts of United Nations organizations, international banks, and some national governments over the past several decades, human health is still a substantial risk due to water quality problems in many areas of the world (WRI 1996). In 1990, 1.2 billion people, or 20% of the world's population, did not have access to a safe water supply, and about 50% of the world's population had inadequate sanitation services (UNCSD 1997).

Atmospheric degradation is caused by air pollution, and it is the main contributor to the environmental issues that are leading to global warming and greenhouse gas emission. The increasing air pollution has led to health effects and environmental problems all over the planet. The impact of air pollution has a chain reaction causing the breakdown of other ecosystems as well. The main contributor to air pollution is vehicular and industrial emission. The smoke released from the burning of fossil fuels in vehicles and industries consists primarily of carbon monoxide, carbon dioxide, sulphur dioxide, nitrogen oxides, and hydrocarbons. All these gases are detrimental to the environment. A high concentration of sulphur dioxides in the air can lead to respiratory diseases in man and animals and can cause the formation of sulphur smog when it is exposed to sunlight. Sulphurous smog is also referred to as London smog. Sulphur dioxide gases are released upon the burning of fossil fuels containing sulphur like coal and gasoline. The release of particulate matter into the air like dust, sand, and gravel from construction and mining industries is another way that degrades the atmosphere. The presence of particulate matter often makes breathing difficult and contributes to the formation of smog in cities. Deforestation has led to the reduction of vegetation on the earth's surface to a great extent. The clearing of land makes it more prone to soil erosion and loss of fertility. However, one of the significant impacts of the reduced number of trees is the reduction of photosynthesis, the natural process of converting the harmful carbon dioxide to oxygen. This means a greater amount of carbon dioxide now remains trapped within the environment.

1.3 Causes of Environmental Degradation

Environmental degradation is a consequence of socio-economical, technological, and institutional activities. It can take place in several ways. Pollutions of soil, water, and air are undoubtedly the leading causes (Chopra et al. 2016). Environmental degradation is caused due to anthropogenic and natural activities. The natural causes include earthquakes, tsunamis, droughts, avalanches, landslides, volcanic eruptions, floods, tornadoes, and wildfires. However, the anthropogenic environmental degradation results from commercial/industrial development, overpopulation, deforestation, pollution, hunting, surface mining, urban sprawl, overgrazing, and improper management of industrial effluents and wastes (Bhattacharya et al. 2015). Mainly, anthropogenic activities affect the natural ecological balance through overexploitation and pollution. After a certain limit of resilience, ecological balance cannot be sustainable for a long time. For example, industrial discharge of contaminated wastewater pollutes the water bodies and degrades resources' quality, visibility, and biodiversity (Olorode et al. 2015). Natural and anthropogenic factors of environmental degradation are shown in Fig. 1.1.

Overutilization or mismanagement of groundwater creates a dark zone in many areas, and water scarcity persists there. Increased population is also a cause of environmental degradation due to unbalanced demand and supply. That needs more land

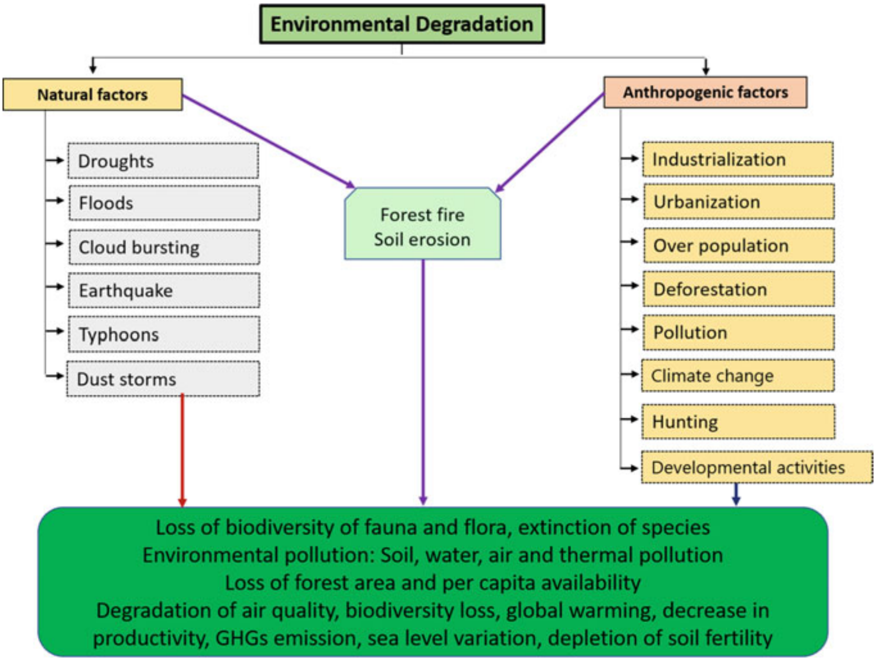

Fig. 1.1 Natural and anthropogenic factors of environmental degradation

for settlement and farming, resulting in deforestation, which leads to environmental degradation. Reduced forest cover results in an elevated level of carbon in the atmosphere and causes global warming. Solid waste generation is directly related to human health, economy, and environment and problematic issue of concern everywhere globally, particularly in urban centres. Landfills are disposal points for solid waste, especially in urban areas. Sewage and waste from industries and the municipality also increase pollution of the sources of water. They pollute the environment and deteriorate the surroundings. Sometimes, natural calamities like earthquakes, tsunami, storms, tidal waves, and wildfires also play a role in environmental degradation and cause substantial loss of resources, living beings, and other animals and plant life (Bhattacharya et al. 2015). Some of the crucial examples that cause environmental degradation are described below.

Pollution: Air, water, soil, or noise pollution resulting from human activities is harmful to the environment and living being's health. Water pollution has increased due to various organic and inorganic substances, illegal dumping, disposal of large amounts of industrial waste into nearby rivers or lakes, etc., and severely degraded water quality (Yadav et al. 2012). The usage of chemical fertilizers and pesticides for agriculture practices often contaminates groundwater or nearby water bodies through seepage or runoff, respectively (Gupta et al. 2013). These chemicals are extremely harmful to the aquatic ecosystem as well as for human consumption. The eutrophication of water bodies, biomagnification of marine organisms, stratification of nutrients, temperature variation, yield of fishes and changes in the acidity of water, and exhaustive use of groundwater are primarily induced by anthropogenic activities and affecting the environmental sustainability for future generations (Yadav et al. 2019). Natural, e.g. volcanic eruption, windstorm dust, or human-induced sources, e.g. toxic gases from industries, vehicles, burning coal, biomass, and landfill garbage in the open area, can degrade air quality. Human-induced air pollution is a major environmental concern worldwide as it is responsible for approximately 9 million deaths per year (Manisalidis et al. 2020). Vehicular emission accounts for the elevated levels of heavy metals in the atmosphere (Gupta et al. 2021a). The emission of toxic gases from the industries and coal-based thermal power plants produced several environmental problems such as acid rain, smog, decline in air quality, reduction in the yield of agricultural crops, and harmful effect on humans and animals. The contamination of soil and relevant crops is presently a severe environmental health concern worldwide (Gupta et al. 2021b). The discharge of toxic pollutants from wastewater treatment facilities and industries pollutes the soils with heavy metals and emerging pollutants (Malik and Maurya 2014). Heavy metals enter into the food chain through food consumption and ultimately accumulate in consumers resulting in an increased frequency of chronic diseases (Tembo et al. 2006).

Climate: Climate has a significant impact on dryland soil, vegetation, water resources, and land use. The drier the climate, the greater the rainfall variability and higher the drought risk. Such fluctuations are expressed geographically in expansions and contractions of the dryland belts such that a semiarid region may experience arid conditions at one time and sub-humid conditions at another.

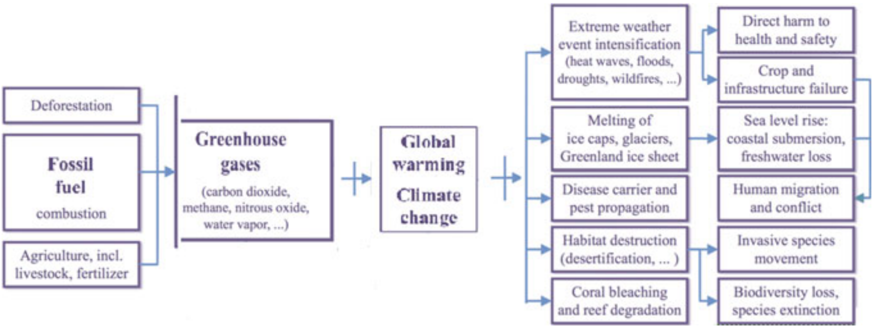

Fig. 1.2 Major impact of climate change on the environment and human and biodiversity

Climate Change: Climate change and global warming have global effects on the yield of crops, sea level, the acidity of oceans, melting of glaciers, migration of species, invasion of species, extinction of species, and greenhouse gas emission. The major impact of climate change on the environment and humans, and biodiversity is shown in Fig. 1.2.

Waste Disposal: The waste is created by human activities. The handling of this waste can pose risks to the environment and human health (Gupta et al. 2015). A total of 2.01 billion tonne/year of municipal solid waste generation was reported in 2016, which is expected to reach 3.40 billion tonne/year by 2050 (World Bank 2018). Open dumping of untreated municipal solid waste emits gaseous and particulate matter into the atmosphere (Malav et al. 2020). The municipal solid waste also attracts viruses, bacteria, and several other pathogens, resulting in severe or long-lasting illnesses for living beings (Fan et al. 2018). Municipal solid waste is the third-largest source of man-made methane (CH_4) emission after fossil fuel burning and enteric fermentation (Annepu 2012). The methane gas is 21 times more potent than $CO_2$for global warming. The enormous amount of plastic waste is one of the alarming concerns for the environment.

An approximate 335 million tonnes of plastic waste was generated in 2016 (PlasticsEurope 2017). Millions of tonnes of plastic are dumped directly into the ocean resulting in marine pollution. The sunlight and the physical stresses can breakdown the plastic into smaller particles. The particles less than 1 mm in diameter are called microplastics (Schweitzer and Noblet 2018). Marine organisms can ingest these microplastics, resulting in severe physical and toxicological changes in their bodies and entering into the food chain (Rezania et al. 2018).

Deforestation: Deforestation is the permanent removal of forest cover by people and land conversion for other uses, such as agriculture or infrastructure. Lindsay et al. (2018) reported that the forest cover of more than 2 km^2 was lost from 2000 to 2012. Extensive deforestation for developmental projects, recreational purposes, and timber declines the biodiversity of flora and fauna. Deforestation makes up about one-sixth of global CO_2 emissions (Hannah 2015). Deforestation and forest fire are also responsible for the destruction of natural habitats of wild fauna and flora.

Desertification: The degradation of productive land into arid, semiarid, and dry sub-humid regions is called desertification (Anonymous 1992). It is a slow process that exacerbates land quality, leading to a decline in its productivity. There are three major desertification processes: degradation of the vegetation, soil erosion by water and wind, and salinization and alkalization and waterlogging (Dregne 1991). Rangeland desertification is primarily a matter of degradation of vegetation cover through overgrazing, lopping, and cutting woody vegetation. Desertification has inevitable consequences on local communities and economic exercises (Ferrara et al. 2016).

Overpopulation: Speedy population growth places pressure on natural resources and demand for food, clothes, and shelter, resulting in deforestation and environmental degradation. Due to overpopulation, noise pollution, metals, and hazardous material pollution, mainly their use and habit containing these substances may cause severe environmental degradation.

1.4 Impacts of Environmental Degradation

Environmental degradation is the deterioration of quality resources due to their injudicious use. Pollution of water, soil, and the air is causing undesirable changes and is harmful to the ecosystem, ecological habitat, wildlife, plants, animals, humans, and micro-organisms (Choudhary et al. 2015). Besides this, substantially expanding the human population and expanding economic growth has played an indispensable role in these degradations. The United Nations International Strategy for Disaster Reduction characterizes environmental degradation as the lessening of the limit of the earth to meet social and environmental destinations and needs. Environmental degradation is one of the most significant threats that are being looked at in the world today. It has attracted global attention, and worldwide necessary actions and policies have been established to regulate and counteract these menaces state of affairs. Environmental degradation has led to several adverse impacts on humans and other natural resources and creates a risk to society, pollution, biodiversity loss, climate change, and many economic losses. The world is making impressive strides in minimizing damage to the environment, although a lot needs to be considered (population growth and urban development). Effects of environmental degradation on humans and other resources with suitable examples are presented in Table 1.1.

Table 1.1 Impacts of environmental degradation

S. No.	Impact on	Suitable examples
1	Human health	Human health might be at the receiving end as a result of environmental degradation. Areas exposed to toxic air pollutants can cause respiratory problems like pneumonia and asthma. Millions of people are known to have died due to the indirect effects of air pollution
2	Climate change	Climate change will have wide-ranging effects on the environment and socio-economic and related sectors, including water resources, agriculture and food security, human health, terrestrial ecosystems, biodiversity, and coastal zones. For example, changes in rainfall patterns are likely to lead to severe water shortages and flooding
3	Air pollution	Air pollution can have a severe health impact on humans. For example, if you are exposed to very high air pollutants, you may experience irritation of the eyes, nose, throat, wheezing, coughing, and breathing problems and have a greater risk of heart attacks. Air pollution can also exacerbate existing lung and heart conditions, like asthma
4	Soil pollutants	Soil pollutants harbour many negative consequences that affect flora, animals, humans, and the ecosystem. For example, since youngsters are more susceptible to illnesses, polluted soil creates greater danger. In addition, these chemical substances pose severe health dangers to human beings
5	Water pollution	According to the Environmental Protection Agency (EPA), 46% of US streams, 21% of lakes, 18% of coastal waters, and 32% of the nation's wetlands are contaminated by water pollution. Water pollution has many impacts on the environment, and its effects are most readily visible in the lakes and streams where pollution kills fish and other aquatic life
6	Biodiversity loss	Biodiversity is essential for maintaining the balance of the ecosystem in combating pollution, restoring nutrients, protecting water sources, and stabilizing the climate. Unfortunately, deforestation, global warming, overpopulation, and corruption are significant causes of biodiversity loss
7	Ozone layer depletion	The ozone layer is responsible for protecting the earth from harmful ultraviolet rays. Unfortunately, the presence of chlorofluorocarbons and hydrochlorofluorocarbons in the atmosphere is causing the ozone layer to deplete. As it finishes, it will emit harmful radiation back to the earth

(continued)

Table 1.1 (continued)

S. No.	Impact on	Suitable examples
8	Tourism industry	The deterioration of the environment can be a massive setback for the tourism industry that relies on tourists for their daily livelihood. Environmental damage in the form of loss of green cover, loss of biodiversity, massive landfills, increased air, and water pollution can be a big turn-off for most tourists
9	Economic impact	The enormous cost that a country may have to bear due to environmental degradation can have a significant economic impact on the restoration of green cover, cleaning up landfills, and protecting endangered species. The economic impact can also be in terms of the loss of the tourism industry
10	Reduced land productivity	The land degradation may affect the availability of valuable nutrients in soil and hence the soil fertility gradually decreases
11	Food insecurity	Land degradation will lead to reduction in productivity or turn the land into non-productive land
12	Adaptation	The person needs to adapt into the new environment as consequence of environmental degradation

1.5 Treatment or Remediation Technologies

1.5.1 Prevention of Deforestation

In order to mitigate the adverse effects of environmental degradation, deforestation prevention is a crucial step. We are aware and cannot afford to cut or burn trees down as trees store greenhouse gases, produce oxygen, and are the natural habitat for many animals and plants, which may become endangered if these forests are destroyed. An extensive afforestation campaign should be launched in the interest of environmental protection. We can further make a positive impact through reforestation or afforestation.

1.5.2 Governmental Regulations

Governments require intervening and setting a framework whenever there are problems that lead to significant eco-degradation. Governments set high taxes for activities that harm our planet and support environmentally friendly behaviour with financial subsidies. These will also force industries and private people to avoid activities that lead to environmental degradation. There should also be high fines for illegal dumping to reduce the adverse ecological consequences. People and industries will continue to dump their trash illegally as they know that penalties are pretty low even if they get caught. Therefore, raising fines for illegal dumping would increase the incentive to dispose of trash at official waste disposal sites.

1.5.3 Sustainable Consumption and Production Regulations

In the last few decades, the productions of various commodities and their consumption and waste generation have become worldwide concerns under different environmental perspectives. The rapid change in consumption patterns has increased the adverse effects on the environment and all living creatures. Developing strategies to reduce consumption levels and move towards sustainable consumption and production regulations have become essential. Developed society always strives to use the latest electronics, smartphones, trendiest, and other commodities. This behaviour leads to massive resource depletion and excessive waste production that must be reduced significantly to avoid adverse environmental degradation.

1.5.4 Adoption of the Principle of Reduce, Reuse, and Recycle (3R)

Reduce, reuse, and recycle (3R) principles are pertinent in current scenarios because they decrease and help manage vast amounts of waste on the planet and preserve natural resources by maintaining space and cutting down landfills. 3R principle of management of waste for restoring the environment is presented in Fig. 1.3. We can

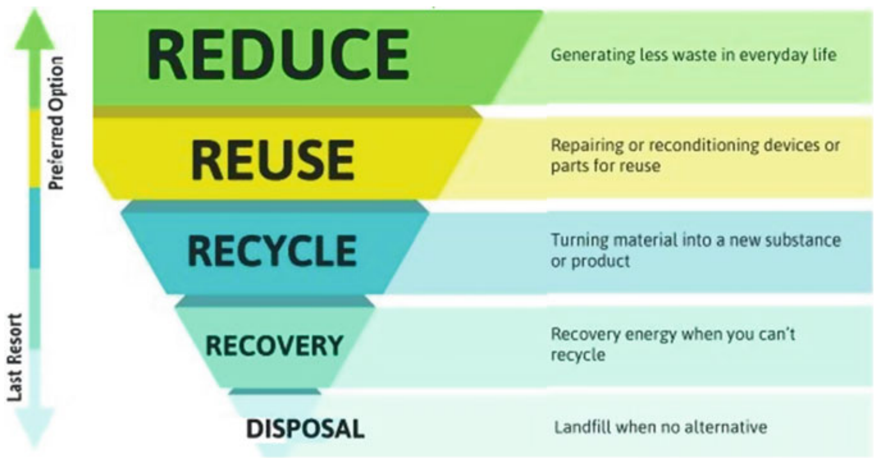

Fig. 1.3 3R principle of management of waste for restoring the environment

reduce waste production by using this waste to produce various usable commodities, chemicals, energy, and nutrient-rich manures. By doing so, waste will be utilized more effectively. For example, plastic waste is a big problem that leads to significant pollution and the degradation of the environment. However, it is reusable stuff, which can be recycled several times.

1.5.5 Adoption of Environment-Friendly Education

In today's scenario, the adoption of environment-friendly education is significant to society. Proper education can change our daily lifestyle and behaviour, significantly reducing adverse environmental consequences and improving our ecological footprint. Ecological education can make us more responsive towards nature and encourage us to act environmentally friendly. Furthermore, it may enhance positive impact by convincing other people regarding the importance of behaving environmentally and make them aware of environmental degradation to prevent its adverse effects.

1.6 Conclusion

Environmental degradation has created many challenges to human society, animal, and their habitats. Everyone is suffering from disturbances in the ecological system and deteriorated natural resources quality. Injudicious use of fossil fuel, exploitation of water resources, enhanced soil pollution, and emission of harmful gases caused many undesirable changes that severely affected the ecosystem, ecological habitat, wildlife, plants, animals, and humans. This issue has been taken seriously, and necessary actions and policy initiative have been born worldwide to regulate and counteract environmental degradation. There is also a need to minimize environmental degradation and develop strategies for mitigation and adaptation to cope with these problems by restoring natural resources, encouraging afforestation, and following strictly (3R) principles to reduce, reuse, and recycle the waste.

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Part II
Causes of Degradation

Chapter 2
Deforestation and Forests Degradation Impacts on the Environment

Rahul Kumar, Amit Kumar, and Purabi Saikia

Abstract Forests are important terrestrial carbon sinks and help in mitigating the emissions of CO_2, and other greenhouse gases (GHGs). Besides, it provides multiple ecosystem goods and services including livelihood security, socio-economic development, ecosystem functioning, biodiversity maintenance, carbon dynamics, nutrient cycling, and climate regulation. Population explosion, land-use change for agriculture, industry, urbanization, and improper forest management are considered as the major reasons responsible for the acceleration of forest degradation. Shifting cultivation, the traditional land-use technique is another leading cause of global tropical forests degradation. Deforestation and forest degradation set off a series of environmental changes that significantly reduce the valuable provisioning services and also affect locally to global biodiversity. It is responsible for *ca.* 15% of all GHGs emissions contribute to rising global temperatures, changes in weather patterns, and an increased frequency of extreme weather events. Climate changes can alter wildlife habitats and decrease the availability of food and water. Besides, it is responsible for increased soil erosion, disruption of nutrients and water cycle, disrupted livelihood. Investment in natural ecosystems, through reduced carbon emissions from deforestation and forest Degradation (REDD), and reducing emissions from deforestation, forest degradation, and other forest-related activities (REDD +) related strategies, contributes significantly to GHGs emissions reduction and forest carbon stocks enhancement. It also generates possible sources of livelihood security for the poor tribal communities that provide financial incentives to prevent deforestation and additional benefits for the conservation, management, and restoration of forests. However, forest landscape restoration (FLR) enhances the ecological integrity of deforested or degraded landscapes and also improves human well-being using nature-based

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solutions (NbS) such as plantation, agroforestry, erosion control, and natural forest regeneration. In this chapter, major ecological disturbances that cause forest degradation and deforestation have been discussed in detail along with FLR to enhance the ecological integrity of deforested landscapes and some policy interventions.

Keywords Deforestation · Climate change · Forest degradation · Nature-based solution · Forest landscape restoration (FLR)

2.1 Introduction

Forests are inherently endowed with a range of ecosystem goods and services that are beneficial to humankind (FAO 2003) in terms of livelihood, health, income, custom, tradition, religion, and culture (Adebisi 2007). There is ~ 9.4% of the earth's surface and31% of the total land surface has been covered by forests (FAO 2020). It plays many significant ecological and economic services including more than a quarter of modern medicines with an estimated worth of US$108 billion, pollination services to agriculture with the worth of US$12 billion Yr^{-1} that originate from tropical forests (FRA 2010). Besides, forests help in protecting watersheds that supply water to rivers and other aquatic bodies (Gartner et al. 2017) and maintain the balance of O_2, CO_2, and atmospheric humidity. ~ 289 Gt of carbon is stored in the biomass alone by the world's forests (FRA 2010) with global trade of wood and wood-based products worth US$ 235 billion, > 40% of the oxygen in the rainforests, which releases 8–10 times more water vapour through the process of transpiration into the atmosphere as compared to the corresponding ocean areas, and are habitat to more than 80% of terrestrial biodiversity (FAO 2020).

Deforestation is the large-scale conversion of forested lands to non-forested ones for a variety of industrial, urbanization, agricultural, commercial, and municipal purposes but replantation has never been done (Aina and Salau 1992; Fiset 2011). Forest destruction is a mechanism that leads to a transient or irreversible deterioration in the forest structure, composition, and its inherent capacity to provide various ecosystem goods and services (FAO 2007). Deforestation leads to soil erosion, siltation in rivers that reduces clean water access, and also affects rainfall patterns globally (Ellison et al. 2017). Forest area decreased from 32.5 to 30.8% of the total land area in the last three decades from 1990 to 2020 (FAO 2020). ~ 420 Mha of forest have been transformed to other land uses and the size of the primary forest has reduced globally by over 8.0 Mha in the last three decades (FAO 2020). However, the average net forest degradation decreased by nearly 40% (from 7.84 to 4.74 Mha Yr^{-1}) between 1990 to 2000 and 2010 to 2020 due to diminished forest area in some countries and an increase in some others (Table 2.1) (FAO 2020). Forest destruction leads to the reduced ability of forests to provide essential products and services to people and other lifeforms (IUCN 2020). Southeast Asian forests are facing the highest exploitation rate and are considered as one of the world's hotspots for deforestation (Hansen et al. 2013). ~ 50% of the world's forest areas have disappeared in the last 60 years

Table 2.1 Annual rate of forest area change

Period	Net change (Mha Yr^{-1})	Net change rate (% Yr^{-1})
1990–2000	−7.84	−0.19
2000–2010	−5.17	−0.13
2010–2020	−4.74	0.12

Source FAO 2020

and more than 1.0 ha of tropical forests are destroyed every second (IUCN 2021). The deforestation rate between 2015 and 2020 was estimated at about 10 Mha Yr^{-1}, down from 16 Mha Yr^{-1} in the 1990s (FAO 2020). This extreme and destructive force on forests is not restricted to tropical forests as *ca.* 3.7 Mha of woodland in Europe destroyed by animals, rodents, pests, forest fires, and other human-related activities (IUCN 2021). The gross global value addition in the forestry sector is US$ 468 billion (Patari et al. 2011) that supports ~1.6 billion global forest-dependent populations by providing daily sustenance needs (UN 2011).

The construction of large dams, power plants, urbanization, increasing irrigation systems, and energy demands were the major causes of deforestation, which ultimately influenced climate change, the hydrologic cycle, and atmospheric recycling in the Amazon region (Lettau et al. 1979). The most significant negative consequences of deforestation are temperature rise, habitats depletion, extreme weather events, soil degradation, infectious diseases, rising GHGs, and environmental pollution (Shafik and Bandyopadhyay 1992; Rustad et al. 2000; Dickinson 2003; Jones et al. 2013; Rossati 2017; Wolff et al. 2018; de França et al. 2020). Agricultural expansion, mainly commercial agriculture, is one of the major causes of deforestation related forest biodiversity loss, accounting for a total of 40% of forest cover loss between 2000 and 2010, while local subsistence agriculture accounted for another 33% loss (FAO 2020). Selective logging of commercially valuable timber tree species causes severe damage to many of the world's forests, especially in Southeast Asia where the density of commercially valuable timber species is very high (Vasquez-Grandón et al. 2018). Other causes of forest degradation include forest fires, excessive removal of non-timber forest products (NTFPs), and pollution (Kumari et al. 2019). Almost 17.4% of global GHGs emissions resulted from deforestation and forest degradation (Ravindranath and Ostwald 2007) and excessive deforestation destabilizes the ecosystem, affect the environment, contribute to global warming, and ultimately to climate change by releasing millions of tons of GHGs into the atmosphere that are trapped in wood in the form of carbon (Zurbrigg 2019). While mangrove forests act as a barrier against tsunamis, cyclones, and hurricanes (Marois and Mitsch 2015), *ca.* 330 Mha of global forest are providing soil and water management, landslide management, sand dunes stability, desertification prevention, and coastal defense (FRA 2010). The European and the African Unions are initiating a scheme to create a green wall of trees around the Sahara to minimize desertification, protect crops, and improve livelihoods in the Sahel-Saharan region (Chen 2019). More than one billion ha of degraded areas throughout the world are suitable for FLR that can be woven into other existing rural economic activities through community-based forest management (Laestadius et al. 2015). The Bonn Challenge (2011) along with the New York Declaration on Forests (2014) sets the goal of halting tropical deforestation and aimed to restore 350 Mha of degraded forests by 2030 and convert it to productive, functional, and biodiversity-rich forested landscapes (Pendrill et al. 2019), while the United Nations' Sustainable Development Goals (SDGs) aimed at a complete halt of deforestation.

2.2 Factors Responsible for Deforestation and Forests Degradation

Forests have been deeply influenced by changes in climates and natural and anthropogenic influences (Popoola 2014). Illegal deforestation in the form of over-extraction of fuelwood, NTFPs, forage removal, illegal timber felling, and forest fires partly damage forests without recovery within a fair timeframe (DeFries et al. 2007). Unprecedented population rise and poor enforcement of forest protection laws have led to an expansion of human habitation and agricultural farming into the existing forests thereby intensifying the deforestation rate mainly in areas with a high density of forest-dependent populations (Acheampong et al. 2019). Degradation is considered as a precursor to deforestation as timber felling and other logging activities reduce the perceived conservation value and increase access to the forest (Asner et al. 2006; DeFries et al. 2007). Demographic, technological, economic, policy and institutional, and cultural development in the form of agricultural intensification, timber logging for commercial purposes, and infrastructure development are the five underlying driving forces of tropical deforestation (Geist and Lambin 2002). The causes of deforestation may be natural, or anthropogenic, and it may be direct or underlying or indirect (Herold and De Sy 2012). Human interferences and natural factors responsible for deforestation and forest deforestation are the largest direct causes, while the underlying causes may be of global, national, and local levels (Mbow et al. 2017) (Fig. 2.1).

2.2.1 Direct Cause

2.2.1.1 Agricultural Expansion and Intensification

Agricultural intensification is the major cause of ~ 80% of global forest destruction and loss (Kissinger et al. 2012). Large-scale commercial agriculture is the most widespread cause of forest destruction and loss in ~ 78% of the forest area in forty-six tropical and subtropical countries around the world (Hosonuma et al. 2012) and

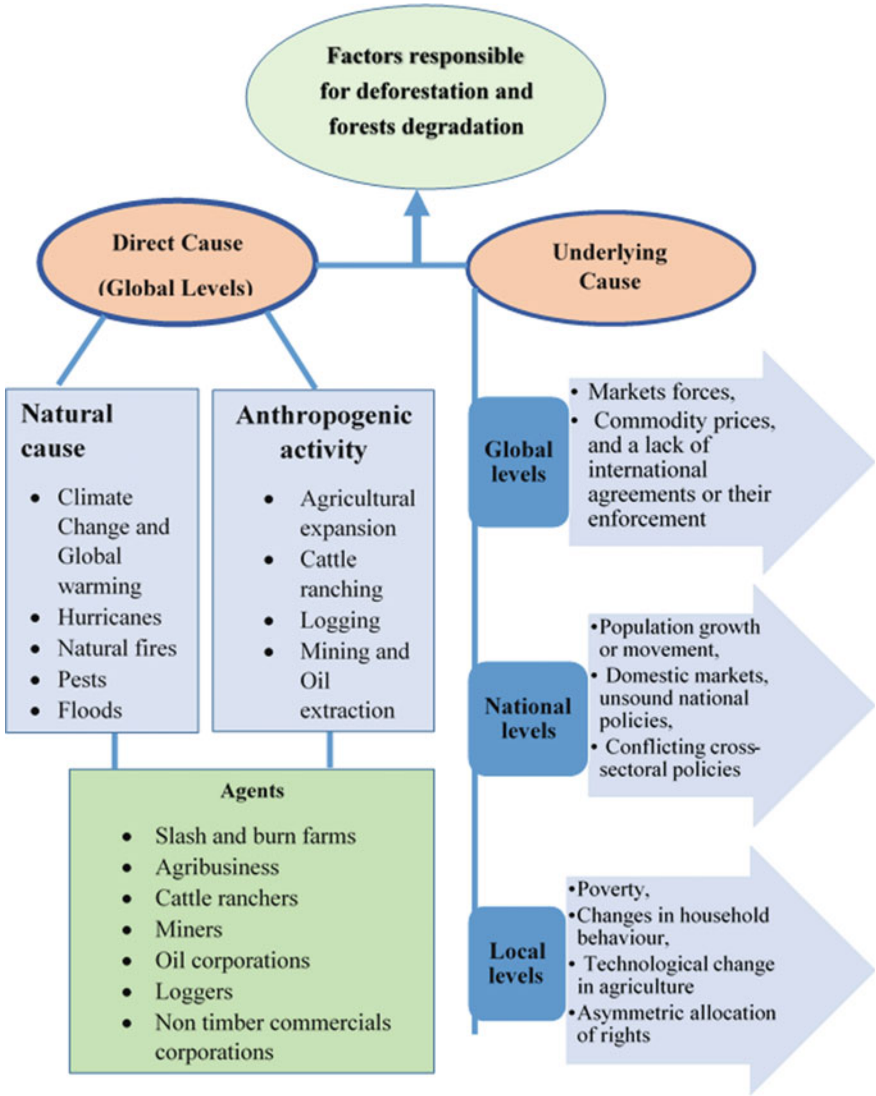

Fig. 2.1 Factors responsible for deforestation and forest deforestation (*Source* Herold and De Sy 2012)

is responsible for almost 70% of the deforestation in Latin America during 2000–2010 (FAO 2016a). While commercial agriculture is responsible for 40% of global deforestation, local small-scale traditional farming, urban expansion, infrastructure development, and mining activities account for an estimated 33, 10, 10, and 7% of deforestation, respectively (Fasona et al. 2018). Growing international demand for agricultural products is also an important driver of deforestation (DeFries et al. 2010) and in the Amazon, cattle ranching, soybean farming, and oil palm plantations for international markets have been identified as the main drivers of post-1990s deforestation (Rudel et al. 2009; Boucher et al. 2011). The area of oil palm plantations in Indonesia increased from 1.7 to 6.1 Mha from 1990 to 2000, replacing an estimated 1.7 to 3.0 Mha of forests (Fitzherbert et al. 2008). The net forest loss and gain in the agricultural area from 2000 to 2010 in Africa, South and Central America, and South and Southeast Asia are shown in Table 2.2 (FAO 2015, 2016a). Expansion of smallholder agriculture was the dominant cause of ~ 41% forest cover loss in Peru (De Sy et al. 2015). Agricultural intensification further helps to expand the crop frontier including the soy production in Brazil and oil palm in Indonesia at the cost of pasture lands or natural forests (Angelsen and Kaimowitz 2001). Agricultural intensification is an alternative to increasing agricultural productivity without expanding farms with better economic and ecological benefits using high-yielding varieties, crop rotation, proper spacing for planting, integrated approach of pests and diseases control, and the right quality and quantity of inorganic fertilizers along with organic and biofertilizer to enhance the crops yield (Sayer et al. 2015). Although agricultural intensification saves land, it may induce several environmental impacts, including impacts of agrochemicals on natural ecosystems (Cunningham et al. 2013). Therefore, agricultural intensification using sustainable measures including landscape approaches is needed to minimize its various environmental impacts.

Table 2.2 Nations with net gains in agricultural land and net losses in forest land between 2000 to 2010

Region	Country	Net forests loss (000 ha)	Net agricultural gain (000 ha)
Africa	Angola, Benin, Burkina Faso, Cameroon, Chad, Ethiopia, Guinea, Liberia, Madagascar, Malawi, Mali, Niger, Senegal, Sierra Leone, Uganda, United Republic of Tanzania, Zambia, Zimbabwe	−19,821	31,190
Asia	Cambodia, Indonesia, Myanmar, Philippines, Sri Lanka, Thailand	−10,562	13,484
Europe	Finland*	−227	74
Central America	El Salvador, Haiti, Honduras, Panama	−1421	545
South America	Argentina, Brazil, Paraguay, Peru	−29,834	32,068
Total		**−61,865**	**77,287**

*Most of this loss may be understood by sampling error, the true loss was due to urbanization
Sources FAO 2015, 2016b

2.2.1.2 Pasture Expansion and Overgrazing

The increasing need for grazing lands rapidly accelerated ~ 33% of the forest cover loss in Argentina, Bolivia, Brazil, Paraguay, Venezuela, and Colombia (De Sy et al. 2015). The pastoral practices and livestock grazing in the Western Himalaya, are leading to a reduction in the forest cover by the invasion of various invasive weeds, grasses, and forbs in the canopy openings that encourages grazing activities and decline in survival of oak seedlings which has ultimately influenced vegetation structure, composition, and biodiversity (Ives and Masserli 1996). On the other hand, overgrazing reduces the productive capacity of forested lands. When the vegetation biomass is consumed by livestock and other wildlife (stocking rates) exceeds the vegetation's ability to recover in a timely manner (carrying capacity), resulting in overgrazing (Holechek et al. 2004). Grazing animals and wildlife mainly feed on palatable grasses, herbaceous growth, and small regenerating plants which ultimately eliminate the ground vegetation of the forest by impacting the natural regeneration potential (Thakur et al. 2011). Complete barrenness used to be the result of continuous overgrazing for several successive years, which took several years to build up the soil and restore its original forage yield (Sampson 1923). Overgrazing by livestock in summer cattle camps has caused the loss of 299.81 ha (~7.85%) of forest around the transition zones of the Kedarnath Wildlife Sanctuary, Western Himalaya during a period of 29 years (Thakur et al. 2011).

2.2.1.3 Illegal Logging

Illegal logging refers to a set of activities such as logging, shipping, purchasing, and trading logged timbers neglecting the national legislation with the potential to harm national revenue, environment, and sustainable forest management (Roe 2015). Some tropical countries, such as India, China, South Korea, Japan, Vietnam, and Thailand needed a comprehensive legal framework to avoid illegal timber smuggling and trading, which made it difficult to distinguish the legal source from the illegal one during timber and timber-based products importing and exporting (Hoare 2015). India, China, Japan, and South Korea are the leading consumers of wood in Asia and also the major wood importers in the global market having ~ 91.8% of the total imports of tropical timbers in Asia in the year 2018 (Guan et al. 2020). Logging can severely deteriorate forest cover (Putz et al. 2001), although it is not responsible for large-scale deforestation, but catalyzes deforestation (Chomitz et al. 2007). Rosewood, a CITES Appendix II included plant species, exports to China have surged 14-folds during 2009 and 2014 (Bolognesi et al. 2015; Ong and Carver 2019). Illegal rosewood extraction and trade resulted in severe forest degradation and loss of biodiversity in Madagascar (Ong and Carver 2019). Across Ghana, logging activities have had detrimental impacts on the collection of NTFPs at the local community level (Acheampong et al. 2019). The illegal logging activities in Africa are very high, varying from 50% (Equatorial Guinea and Cameroon) to 80% (Liberia) (Khan et al.

2018) and ~ 80% of logging activities in the Amazon Forest are illegal (Toyne et al. 2002).

2.2.1.4 Fuelwood Collection

Fuelwood extraction is not a primary cause of forest destruction and degradation in the humid tropics, but it is a major cause of deforestation in the drier tropics (Pearson et al. 2017) and often responsible for the degradation of tropical dry forests (Olagunju 2015). It is a paramount cause of deforestation and forest deterioration in El Salvador (Abdulkareem et al. 2017). Fuelwoods are used in most of the African countries for heating and cooking purposes by the majority of households which leads to a higher rate of forest degradation in African countries (Yvonne 1998). Out of the Indian States, Maharashtra is the biggest consumer of fuelwood in quantity, followed by Odisha and Rajasthan, while Nagaland has the largest dependency on fuelwood per capita per year, followed by Himachal Pradesh and Tripura (ISFR 2019). Deforestation caused by a strong reliance on trees for fuelwood resulted in a rise in CO_2 levels in the atmosphere and the deforestation of 26,602 ha Yr^{-1} in 1999 is estimated to have released 7.77 MT of carbon into the atmosphere (Ramesh 2015).

2.2.1.5 Mining

Mining is one of the major factors that accelerated forest degradation and deforestation (Ahmed and Aliyu 2019). The rate of deforestation raised 2.77 times in Guyana during 2000–2008 (Biswas and Biswas 2018), while 82% of forest cover in the Philippines was degraded due to mining and logging during 1934 (17 Mha) which decreased to 3 Mha in 2003 (Docena 2010). Similarly, massive mining of coal, iron ore and bauxite led to large-scale deforestation in Jharkhand (East India), which accelerated huge water scarcity in the region (Kumar and Saikia 2020). Infrastructural development initiatives such as highways allowing approach to mining and extraction sites, and major hydroelectric reservoirs were part of Brazil's Amazon development strategies in the forest core region (Carvalho et al. 2004). Similarly, the highlands of Nyamagari, Odisha, India have been threatened by Bauxite mining that degraded ~ 750 ha of protected forest in the region (Griffiths and Hirvela 2008). Mining is a labour-intensive activity that diverts resources from forest clearing (Chakravarty et al. 2012) as woods are utilized as fuel for mining operations. The forests cover of The United Republic of Tanzania is ~ 48.1 Mha (nearly 55% of the total land area), however, human settlements, illegal logging, charcoal manufacturing, forest fires, mineral extraction, mining, and infrastructural expansion are clearing an estimated 372,816 ha of forests annually (FAO 2020).

2.2.2 Natural Causes

The devastating earthquake in April 2015, in Nepal, demolished large tracts of native forests affecting its resistance and resilience capacity coupled with the severe devastation in inhabited areas and in croplands (Bhagat et al. 2018; Kumar and Pandey 2017). The series of earthquakes and its aftershocks affected around 41% of all forest areas, primarily sub-temperate forest (70%) and pine forest (30%) (REA 2015). The impact on the forestry sector was assessed around US$ 284 million (NPC 2015). The satellite-based observation supports concurrent monitoring of landscape alteration including infestation, forest fire impact, biomass, deforestation, and degradation (van Marle et al. 2017). The incident of landslides, floods, and degradation of soil, has become common phenomena over the monsoon in most of the hilly terrains and deforestation may exacerbate some of these natural disasters that lead to degradation of the land and loss of human lives and assets (UNEP 2005). Deforestation accelerated soil erosion, reduced agricultural productivity, groundwater recharge, and increased downstream sedimentation, and surface runoff (Rasul 2014; Ahmad et al. 2021).

2.2.3 Underlying Causes

Underlying causes that impact forest conversion are population increase, changing patterns of food consumption, and expansion of agriculture, including market change, technical advances and active policy involvement, land tenure safety, and land-use change management. Alterations in market and farming strategies that boost the requirement of farmland and thus accelerated the clearing of forests (FAO 2016a). The forests in coastal regions having an influential maritime transport network are particularly susceptible to land transformation to farmland due to its advantageous site and suitability, accessibility, and high fertility. People seeking economic possibilities on the forest frontier might exert pressure on forests due to high levels of poverty and inadequate agriculture production techniques. Where intersectoral connections are limited, actions in higher-priority sectors like agriculture, mining, infrastructure development, and energy may have a bigger influence on forests (FAO 2016a). Unplanned and haphazard land-use transformation, insufficient capacity for implementation of forest management plans, illegal logging and poaching, insufficient local participation in decision-making processes, lack of legal frameworks, and research funding are all potential aspects of poor governance lead to deforestation and forest degradation (Rademaekers et al. 2010).

2.2.3.1 Corruption in Forest Sector

Corruption is one other major cause of deforestation and forest degradation thus necessitating immediate measures to prevent these unlawful actions around the global forests (Chakravarty et al. 2012). Unlawful and unsustainable deals by forest officers with private firms, illegal selling of harvest authorizations, under-declaration of volumes cut into public woodlands, concessional underpricing of wood, commercialization of forests, cross-border smuggling of forest products, illegal logging and trading of timbers are the major practices affecting forest conservation (Koyuncu and Yilmaz 2009).

2.2.3.2 Urbanization, and Infrastructure Development

The haphazard urbanization, population increase, and infrastructural development often led to irreversible loss of neighbouring natural forests, which are a prominent cause in the Indian scenario (Mather 1991; Sands 2005; Diksha and Kumar 2017). Tropical forests are significant targets for mining, or hydropower, which demand the growth of the transportation system and construction of highways in the pristine forest regions (Chakravarty et al. 2012). People usually encroach in the forest through new routes to fulfil their sustenance needs (Amor and Pfaff 2008). The expansion of infrastructure facilities in the majority of tropical forests is a global problem, contribute to over 20% of anthropogenic carbon emissions that are harmful to global carbon sinks (Sahana et al. 2018) and ~ 21% of forests in the tropical regions vanished globally since 1980 (Bawa et al. 2004).

2.3 Environmental Implications of Deforestation and Forests Degradation

Forest degradation is an action that tends to a short-term to long-term deterioration of vegetation cover or its species composition (FAO 2007). The decrease in forest canopy cover is caused by logging, fire, timber felling, and other natural and anthropogenic consequences that lead to terrestrial biodiversity loss which is the most severe and short-sighted result of deforestation (Butler 2019). Decreases in rainfall pattern, higher atmospheric and land surface temperatures, and changes in local hydrology are the major impacts of deforestation at the local and regional levels (Salati and Vose 1983). Tropical deforestation leads to heavy floods, sedimentation, water scarcity, reduced production of hydropower, landslides, and losses of productivity in some unique ecosystems like mangrove and coral reefs across the world (Adedire 2002).

2.3.1 Deforestation Impacts on Climate Change

Deforestation is the 2nd major cause of atmospheric CO_2 emissions after burning of petrochemical fuels (57%) and *ca.* 25% of the global GHGs is solely linked with deforestation (Bennett 2017). However, the world's forests can store more than double the amount of CO_2 found in the atmosphere (Landry and Matthews 2016). Deforestation and habitat depletion have a major effect on net forest carbon impacts (Mandal et al. 2012) as tropical forests can store *ca.*, 55% CO_2 (Okojie 1991). Clearing of forest alters typical weather patterns, resulting in increased drought and desertification, food shortages, polar ice cap melting, coastal floods, and the relocation of key vegetation regimes (Dregne 1983). It clearly influences local and global climate by affecting the wind speed, hydrological cycle, and solar insolation (Chomitz et al. 2007). Deforestation can change the global energy demand through changes in micro-meteorological processes and increasing atmospheric CO_2 concentration (Pinker 1980).

2.3.2 Deforestation Impacts on Soil Erosion

Tropical forest soils provide nutrient flux and recycling (Cusack et al. 2018), carbon storage and sink, GHGs emissions (Powers et al. 2011), erosion resistance (Chaves et al. 2008), water storage, drainage, and filtration (Markewitz et al. 2004). It is to note that ~ 60% of forest cover is pertinent to avoid erosion of soil in the forested landscape (Pimentel and Burgess 2013). The substantial reduction in the number of essential plant nutrients in the upper layers of soil after forest fires as most of the surface nutrients are blown away by strong winds along with ashes and volatilization of essential macronutrients like carbon and nitrogen during the combustion (Eldiabani et al. 2018). Erosion-induced transfer and loss of soil organic carbon (SOC) and major essential nutrients can be considerable in tropical forests (Haileslassie et al. 2005). It induced continental nutrient fluxes in the tropics just like the same magnitude of fertilizer applications, i.e. ~ 15 Tg N Yr^{-1} and ~ 10 Tg P Yr^{-1} (Quinton et al. 2010). Presently, the rates of soil erosion largely exceed the rate of soil formation (Amundson et al. 2015). The loss of tree covers due to deforestation, and alteration in land-use practices may exacerbate the rate of soil erosion. In some cases, after clear-cutting, the agricultural practices like monoculture of cash crops further contribute to large erosion due to lack of soil anchorage capacity of such shallow-rooted crops (Bennett 2017).

2.3.3 Deforestation Impacts on Disrupted Livelihood

Most of the forest fringe communities are mainly dependent on agriculture for livelihood and economic security, while some small-scale trade of timber and other forest goods, small-scale cultivation, food processing, and harvesting and processing of MFPscontribute significantly to the socio-economic upliftment of the community

(Abane 2009). Major NTFPs include snails, fishes, mushrooms, canes, raffia, herbaceous medicines, edible roots, tubers, honey, and leafy vegetables. Half of degradation and deforestation in tropical areas is caused by shifting agricultural practices and other forms of traditional farming of resource-poor populations and smallholders (UN-REDD 2012). The prevalent subsistence practices include traditional farming for agricultural crops and animal husbandry, forest goods gathering, hunting, wildlife trading, and crafting. Deforestation contributes to the drying of important water bodies that buffer water supplies to forest-dependent communities (Agyemang 1996). It disrupts regular weather cycles, causing erratic changes in weather patterns, thereby raising the chances of drought. The cropping in woodland ecosystems is vulnerable as it easily is non-viable by minor changes in their composition (Amisah et al. 2009). Thus, long-term deforestation could lead to detrimental effects on plant growth, rural poverty exacerbation, limited contributions of forest-dependent populations to the national economy, and more importantly, undermined the livelihoods of forest-dependent people throughout the world (Acheampong and Marfo 2011). With the decline in major forest resources, NTFPs, and other forest goods and services, they have to move more distances to maintain their food security and socio-economic well-being (Pandey et al. 2010). Forest-dwelling populations seldom benefited from the timber extraction process as concessions are reserved solely for commercial use and insufficient compensation used to be provided to the forest-dwellers' farming operations that were destroyed in the timber harvesting process (ITTO 2005).

2.3.4 Deforestation Impacts on Water Cycles

Evapotranspiration and cloud formation are important processes involved in the water cycle that swells the water vapour and then returns it back to the earth's surface in various forms of precipitation (Butler 2019). When forests are cleared, the rate of transpiration is hampered, which ultimately affects the amount of rainfall ultimately, leading to drought. Although Haiti and the Dominican Republic share the same island, Haiti's forest cover is considerably smaller than the Dominican Republic's, accounting for less than 1% of the overall land area (Hedges et al. 2018) has undergone more severe surface erosion, floods, and landslides. More than 50% of areas of Haiti will be at risk of desertification in 2050 as per the IPCC climate change projections (Hedges et al. 2018). The combination of increased temperatures and reduced rainfall increases the possibility of drought.

2.3.5 Deforestation Impacts on Social Consequences

Deforestation induces inequality and numerous socio-economic consequences (Colchester and Lohmann 1993) due to the lack of ecosystem goods offered by forests. By damaging forests, we are compromising our quality of life (Butler 2019) as forests offer important ecosystem services including flood control, fisheries, and pollination roles that are of special significance to the marginalized populations dependent on natural resources for their sustenance needs. Majority of global marginalized people are relying on forests for subsistence and they gather raw products for their small-scale agriculture-based processing units (UN 2011). Forests provide the livelihoods to ~ 1.6 billion marginalized global population (Lewis-Jones 2016).

2.3.6 Deforestation Impacts on Food Security

Deforestation directly impacts food security as removal of trees limits the supply of edible products like vegetables, fruits, and a range of edible wild animals (Fig. 2.2), while it indirectly affects food security by degrading soil quality and altering the local climate as agricultural productivity depends significantly on soil health and local weather patterns. Haiti was ~ 80% self-sufficient in food and fully self-sufficient in rice during the 1980s, but it produces less than 40% of what it consumes today due to ongoing deforestation (World Bank 2014). Haiti's vulnerability to climate change is extreme as per the Global Climate Risk Index 2018 and ranks 3rd out of 198 countries (Eckstein et al. 2019). The global climate change has also significantly impacted Haiti and raised the vulnerability to a range of consequences including sea level rises, higher sea temperatures, flooding, erosion, infestation by invasive, salinization of freshwater estuaries, and increased intensity and frequency of hurricanes.

2.3.7 Health Associated with Forest Threats

The change in land-use and climate together, boost the forest degradation that has generated and made ways for transmission of "never-seen-before" pathogenic viruses to humans, including the Kyasanur forest disease in India, Ebola in West Africa, Zika in North America, SARS in Asia, and SARS-CoV2 caused COVID-19 globally (Paul 2020). Forest-related diseases include malaria, African trypanosomiasis, leishmaniasis, HIV, and Lyme disease of which HIV, Ebola, lesser-recognized pathogens of forest origin include Henipaviruses and SARS-CoV2 are of zoonotic origin (WHO 2020).

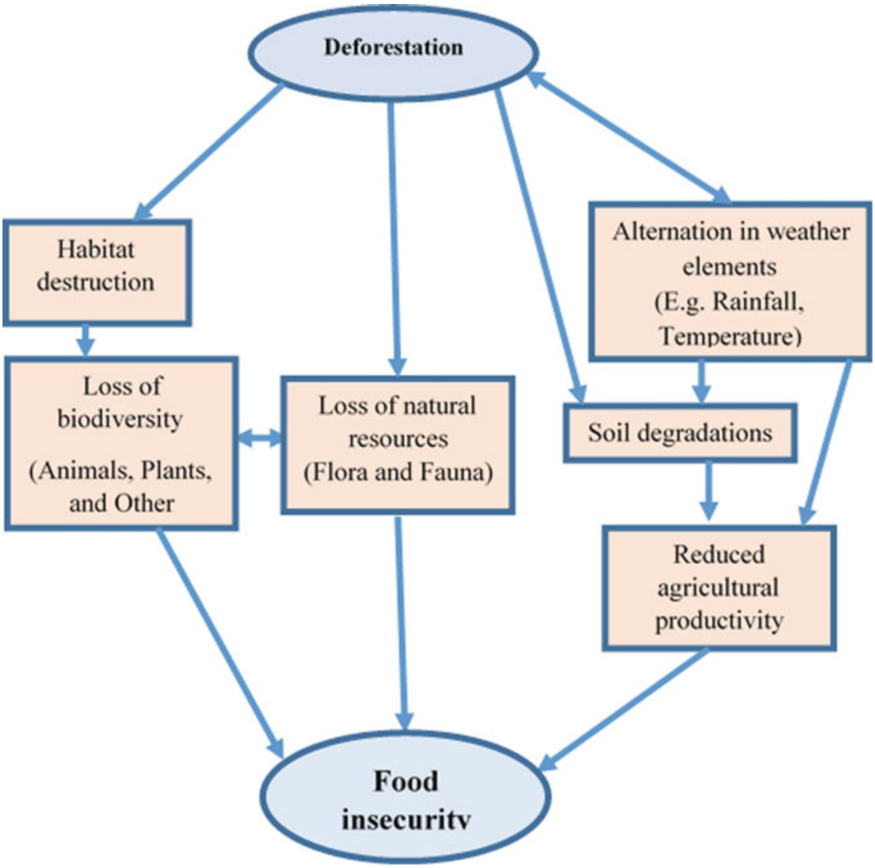

Fig. 2.2 Diagram showing the relationship between human-induced deforestation and food insecurity (*Source* Olagunju 2015)

2.4 Forest Landscape Restoration (FLR): An Initiative Towards Degradation Prevention

The SDGs Report (2019) confirmed approximately 20% of the total land surface was degraded during 2000–2015 (UN 2019).While the GPFLR reported ~ 2 billion ha of the degraded forest landscapes of the globe with the potential for restoration (FAO 2020). Around 13 Mha of the forest was transformed to non-forest cover annually during 2000–2010 that led to severe difficulties in eradicating inequality, preserving biodiversity, and challenged climate change adaptation (FAO 2020). FLR involves stakeholders at various levels comprising marginalized community groups in decision-making and implementation to enhance the ecological integrity of the degraded landscapes and also to improve human health by applying nature-based solutions (NbS). Various ecological, social, and economic aspects can be taken into account at a landscape level so that different requirements and expectations for landscape use can be balanced (Aretano et al. 2013). FLR encompasses various interventions outside and inside forests, including agroforestry, natural regeneration, planted forests, silviculture, enhanced fallows, watershed protection, and erosion management (Chazdon et al. 2015). The New Generation Plantation Platform (2007) was designed for complementing forest degradation by effective ecosystem support and improvement along with contributing towards social and economic growth and mitigation of climate change impacts (Silva et al. 2019). Integration in the plantation program of invasive commercial trees with native tree species can intensify biodiversity and local economies (Lof et al. 2019). Forest and landscape restoration not only takes place in isolated locations but in and over entire landscapes improves the overall forest health and assists in recovery, conservation, and sustainable management by combining a range of land uses and ecosystem management practices. Many plant species play significant keystone roles in a forest as ~ 13% of the total tree species of forest can contribute to ~ 90% of the total carbon storage (Balvanera et al. 2006). Selection of plant species in different plantation schemes must consider these tree species as one of the significant components along with other locally available trees. Investment in natural ecosystems, through reduced carbon emissions from deforestation and forest Degradation (REDD), and reducing emissions from deforestation, forest degradation, and other forest management activities (REDD +) related strategies, contributes significantly to a reduction in GHGs emissions, enhancement of forest carbon stocks. It also generates alternative income sources for the poor tribal that provide financial incentives to prevent forest destruction and also to provide additional benefits in terms of livelihood support from the protection and reclamation of forests.

FLR is a process of regaining ecological integrity, ecosystem productivity, and health to enhance economic valuation for human well-being throughout the destroyed or degraded forests. It tries to restore the entire landscape to meet the needs of present and future generations in terms of multiple benefits (Newton and Tejedor 2011). Article 5 of the Paris Agreement (2015) made it compulsory for all partner countries to minimize the activities related to forest destruction and degradation for intensifying the terrestrial sinks and reservoirs of GHGs. The Government of Germany and IUCN launched Bonn Challenge (2011) with the target of restore 350 Mha of degraded and deforested landscapes by 2030. India's nationally determined contributions targeted to create an additional carbon sink of 2.5–3.0 billion tonnes of CO_2 equivalent from supplementary forest cover by 2030. Approximately 96.4 Mha of India's geographical area is undergoing the process of desertification/ land degradation (SAC 2016), whereas 63 Mha of potential areas identified for restoration (ISFR 2019). India has launched a pilot project in collaboration with the IUCN to enhance the capacity of forests to restore degraded forests in Haryana, Madhya Pradesh, Maharashtra, Nagaland, and Karnataka in the first phase under the FLR project which is part of the India's Bonn Challenge commitments (2015) also to combat desertification.

2.4.1 FLR Principles

Effective FLR is forward-looking, dynamic, focused on improving environmental sustainability, and providing potential opportunities for adapting and further optimizing ecosystem goods and services. It implements a variety of guiding principles (Fig. 2.3), involving landowners and managers, local community members, civil society, governments, and the private sectors (Mansourian 2005). Focus on landscapes principle, depicts the restoration of entire landscapes that necessitate balance across the landscape with a range of interdependent land uses. It helps in restoring the ecological integrity of the landscape, including its species richness, its ability to contain erosion and floods, and its resilience to climate change and a range of ecological disturbances (IUCN and WRI 2014). Restoration techniques leverage constant tracking and learning to make changes as the mechanism of restoration progress (Gann et al. 2019).

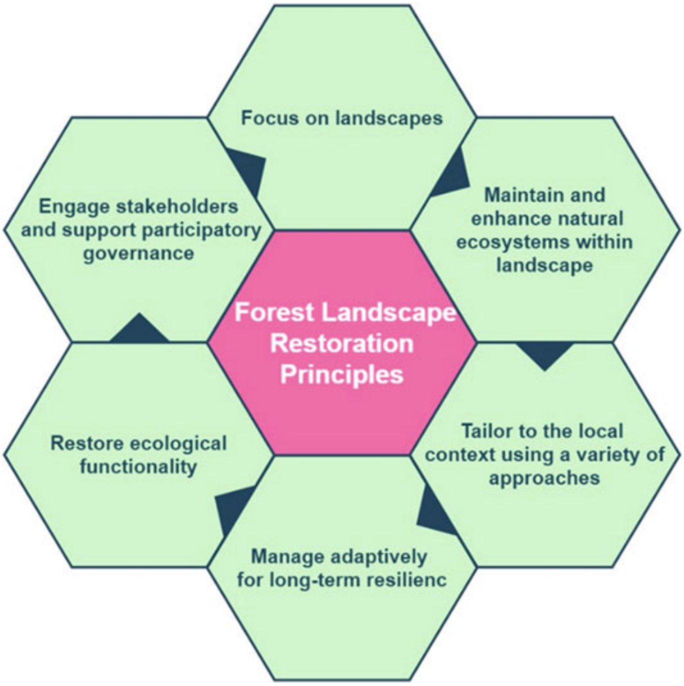

Fig. 2.3 Forest landscape restoration (FLR) principle (*Source* Mansourian 2005)

2.4.2 *Characteristics of FLR Initiatives (Maginnis et al. 2007)*

(a) The site-level restoration assessments need to harbour landscape-level priorities and consider possible landscape-level impacts.
(b) Restoration initiatives would cause both increased ecosystem integrity and improved landscape for human well-being.
(c) It includes a variety of stakeholders mutually agreeing on the most scientifically suitable and socially and economically viable restoration solutions.
(d) It is a progressive initiative to improve the durability of forests including primary forests, secondary forests, pasture land, and cropland to leave potential possibilities available for improving the distribution of forest-related products and services at the landscape level.

2.4.3 *Few Best Practices for Forest Landscape Restoration (FLR)*

The degraded land was selected for large-scale forest restoration to serve as a resource base for local communities. IUCN and WRI proposed a set of best practices to ensure restoration, long-lasting, and beneficial (IUCN 2020):

(a) Plantation tree species and other woody plants in appropriate landscapes
(b) Expand the accomplishments from individual sites
(c) Restore ecosystem integrity, health, functions, productivity, goods and services
(d) Prioritize local needs in conformity with national and global preferences
(e) Implement different restoration strategies including active, passive, and rehabilitation
(f) Adapt to the prevailing situations over time
(g) Escape those strategies which lead to the change in natural ecosystems.

However, the successful implementation of these FLR measures is necessary for a shared awareness and organized implementation in India. The concept and recognition of FLR, including the development of a benchmark, surveillance, and stakeholders and institutional structures, are required to tackle in India for fulfilling its obligations.

2.5 Policy Interventions

National and international efforts are helpful to some extent to reduce forest loss and such policies may mobilize new funds for forest conservation, in addition to addressing factors responsible for forest destruction in the developing world (Pfaff et al. 2010). Conventions and policies on the conservation and mitigation of biodiversity and climate change highlight the requirement for enhanced forest conservation, restoration, and adaptation to climate change (Secretariat 2009). Unfortunately, deforestation impacts the sustainability of the environment worldwide with more deleterious effects on developing countries. Exertions to save forests have attracted prodigious international attention. The UN-SDGs and UNFCCC have stressed conservation of forest to fulfil SDGs (UN 2000).

2.5.1 UN Sustainable Development Goals (SDGs)

The restoration was acknowledged as the key contribution to the UN Convention to Combat Desertification on Zero Net Land Degradation, the UNCCCon climate mitigation, the Ramsar Convention on Wetland (Aronson and Alexander 2013), the Convention on Migratory Species, and the SDG (UN 2015). SDG 15 aims to conserve and encourage feasible use of terrestrial ecosystems, maintain forests, combat desertification, and restrict biodiversity loss. The adoption of sustainable forest management helps in minimizing deforestation and restoring damaged forests and significantly increasing global afforestation and reforestation (Gigliotti et al. 2019).

2.5.2 Aichi Targets

Ecosystems continue to be destroyed quicker than its restoration, while the living beings relied on ecosystems (Leadley et al. 2014). The restoration of the architectural, functional, and constitutional aspects of profligate ecosystems (Tittensor et al. 2014) made a fundamental element of Aichi Biodiversity Targets 14 and 15 (Leadley et al. 2014) intended by the Convention on Biological Diversity (CBD) to fulfill the human needs and conserve biodiversity. Target 14 is vital for living beings, while target 15 intends to restore deteriorated ecological communities to assist climate change mitigation and adaptation (Gann et al. 2019). Aichi Biodiversity Targets and the conservation of ecosystems from the stubborn adverse consequences induced by REDD + compels the development of spatio-temporal study, sensitive signs of ecosystem wellness and biodiversity (Fujiki et al. 2016).

2.5.3 Bonn Challenge

The Bonn Challenge (2011) is an international initiative of the Government of Germany and IUCN to bring 150 Mha of global damaged and deforested land into its original state by 2020, and an additional 200 Mha with a total of 350 Mha by 2030 (Verdone and Seidl 2017). Restoring 150 Mha of depraved and bare land in biomes around the world following the FLR strategy would produce an economic advantage of *ca.*, US$ 84 billion Yr^{-1} that could provide directly increased income and employment opportunities in rural families (IUCN 2020). Accomplishing the 350 Mha goal would produce around US$ 170 billion Yr^{-1} in net watershed conservation benefits, increased crop yields, forest products, and sequester up to 1.7 Gt of CO_2 eq. Yr^{-1} (Stanturf et al. 2019). The Bonn Challenge later accepted and extended by the New York Declaration on Forests at the UN Climate Summit (2014) is an effective means of accomplishing many already existing international commitments like the UNFCCC REDD + goal, CBD Aichi Target 15, and the Rio + 20 land degradation neutrality goal.

2.5.4 REDD and REDD + strategies

An international policy for decreasing emissions from REDD + activities is aimed to diminish impacts of climate change and also promotes sustainable development using a range of activities related to forestry sectors (UNFCCC 2007). The clearing of forest and its degradation result in reduced ability of forests to supply a range of valuable ecosystem goods and services in most of the developing nations (Lawson et al. 2014). The REDD + was meant to financially incentivize nations to reduce emissions from deforestation and forest loss that substantially reduce global total GHGs emissions (Shukla et al. 2019) that will help to accomplish sustainable development goals through forestry-related activities (UNFCCC 2007). REDD + activities also promote sustainable management of woodlands and enhance the forest carbon stocks (Pachauri and Reisinger 2007). Total avoidance of deforestation renders a very cost-effective option to minimize the emissions of GHGs (Griscom et al. 2017). Forest reference level (FRL) or forest reference emission level (FREL) is considered as a standard norm to define the level of GHGs emissions in absence of REDD + interventions (Pirker et al. 2019). Minimizing the rate of deforestation may be a cost-effective way towards sustainable forest management and also to mitigate the impacts of climate change (Angelsen 2008). A systematic understanding of the circumstances of forest destruction is required to identify the strategic interventions of such transformative policies (Duguma and Minang 2015). Therefore, it is very much essential to recognize key drivers of forest destruction and degradation to effectively address deforestation through REDD + . The focus of REDD + in developing countries is to support the livelihoods of poor communities and contribute towards socio-economic development of most of the tropical forests (Lawson et al. 2014).

2.5.5 Recommendations and Future Research Prospects

Integrating ecosystem-based approaches and nature-based solutions with forest management will prevent habitat fragmentation and habitat loss. Hence, successful enforcement of existing forest use and management laws and regulations, as well as community participation in the policymaking process from the grassroot level, allows the government to arrest rapid forest decline by instilling a sense of ownership among communities. However, it is recommended to combat deforestation through adopting structured strategies, *i.e.* environmental awareness, agroforestry practices, increasing the protected areas (PAs), developing livelihood alternatives, proper policy formulation and enforcement, reforestation, afforestation, and by avoiding deforestation. Additionally, forest managers can also play a major role by raising consciousness regarding the significance of forests and forest resources and also the detrimental consequences of deforestation. To address the deforestation further actions can be taken as follows-

- Reinforcing and expanding the IUCN category I–VI PAs (Schmitt et al. 2009) as the rates of forest degrading activities within PAs are less as compared to non-protected ones, as most of the PAs are often situated in remote and inaccessible areas with minimum pressure on forests for economic activities (DeFries et al. 2005).
- Agroforestry, tree plantations, reforestation, and sustainably managing existing planted forests may minimize the existing pressure on the natural woodlands to fulfil the need for woods and wood-based products.
- Also clear, uniform, and up-to-date data on forest cover, and real-time data on forest destruction activities, would aid in forest conservation in accordance with laws, regulations, and objectives.

2.6 Conclusions

Deforestation can be avoided if alternative livelihood options are provided to the forest-dependent communities to minimize their dependency on the forest for different sustenance needs. Awareness about the scientific harvesting of NTFPs can be a better solution to check deforestation. In particular, Global Forest Watch has witnessed tremendous development as online forest surveillance and alerting system. Detailed deforestation information is also necessary to ensure adequate risk assessments on the basis of up-to-date information. Appropriate political, judicial, institutional framework and competent market mechanisms are needed to minimize the rate of deforestation. Multi-sectoral market and public policy along with enhancement of property rights, the firm formulation of user rights, land occupancy, and privatization of forests may play pivotal roles in minimizing forest degradation and deforestation. Besides, the amount and impact of any payment should not be too much and should be determined appropriately in the case of various forest resources based on the wider socio-economic perspectives. Advancement of forecasting the rate of forest destruction, soil erosion, and land transformation over a certain period provides crucial information for policy making. The grounds for implementation of new legislation on forest use and management should thoroughly provide solutions to deal with the challenge of forest destruction. Besides, an enduring think tank other than the government is required on a regular manner as reflected in the Forest Policy (2001) for formulating and implementing the policies to save the forests and their biodiversity. Steps should be undertaken by the government on the improvement of forest management practices. Proper implementation of the forest management policies will help to curb the ongoing problem of forest destruction and degradation to minimize the problem of global climate change and biodiversity loss.

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Chapter 3
Measuring Environmental Impact of Agricultural, Manufacturing, and Energy Sectors in Bangladesh Through Life Cycle Assessment

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Abstract As one of the fastest-growing economies in the world, Bangladesh is dependent on its agricultural, manufacturing, and energy sectors. Fertile land driving agricultural growth, rapid population growth, low labor cost, and burgeoning local consumption are some of the key factors that are pushing for rapid industrialization in the country. The deeply embedded inertia of the economy to move away from the business as usual scenario is driving more pollution and exhaustion of scarce resources. To act on these challenges necessitates measuring the environmental impact of these economically productive activities. As such, life cycle assessment (LCA) is a globally well-recognized method for evaluating the environmental burden of any product, process, and/or industry. It enables us to discern the hotspots of the environmental impact along the value chain. This chapter presents an in-depth and methodical review of all the LCA studies published to date on the economically and environmentally significant sectors (i.e., agricultural, manufacturing, and energy) of Bangladesh to capture the typology and magnitude of the major environmental impacts caused by these sectors. Subsequently, it presents a comparative picture of all the key environmental impacts caused by these industries/sectors and accordingly attempts to identify the hotspots of harmful anthropogenic activities leading to major environmental degradation in Bangladesh. The investigation unearths several trends in these three sectors. Intensification of agricultural production and its dependency on chemical fertilizers and pesticides are the main causes of exorbitant nitrogen and phosphorus discharge, resulting in eutrophication, biomass devastation, and soil health deterioration. The manufacturing sector is responsible for ecotoxicity, metal

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depletion, freshwater eutrophication as well as freshwater ecotoxicity. In the energy sector, natural gas power plants were found to be half as harmful as the petroleum and heavy fuel oil-based power plants. The most harmful stage of the power plants' life cycle is the operational phase where combustion takes place. Among energy technologies using renewable sources, small scale biogas plants were found less polluting than firewood or kerosene-powered stoves and diesel generators. Apart from these, textile and leather tanning industries of Bangladesh were identified for causing significant GHG emissions, acidification, and contamination of the aquatic ecosystem. The recommendations provided in this chapter would guide policy retrofitting for these sectors to ensure sustainable management of natural resources and the environment; therefore, initiating a shift toward responsible production and consumption. This chapter also outlines the knowledge gaps associated with LCA studies relating to these vital sectors of Bangladesh and suggest future research directions for filling those gaps.

Keywords Life cycle assessment · Environmental degradation · Industrial pollution · Sustainability · Industrial ecology · Circular economy · Environmental management

3.1 The State of Bangladesh's Economically Important Sectors and Environmental Footprint

The country with a population of 163 million people (World Bank 2019) has grown to become one of the fastest growing economies in the world. Although an annual GDP growth rate of 8.2% (World Bank 2019) is appreciable, the pathway to this development can be deemed sacrilegious in the current era of sustainable development. Over the last few decades, Bangladesh has gone through massive land use changes facilitated by the industrial and agricultural revolutions (Mahbub et al. 2019). Owing to the rapid economic growth and to support such a large population, the country had to increase its food production—a development made possible due to the advancements and steady growth of the agricultural sector. The manufacturing sector of the country has grown substantially to the point where this sector alone contributes 19% to the national GDP (Ministry of Finance 2019). Just as significant as these two sectors are for the country's economy, the infrastructural input required to facilitate their functioning is likewise demanding. For example, statistics indicate that about 32.36% of the countrywide electricity production was consumed by the agricultural and industrial sectors (Bangladesh Power Development Board 2019).

Figure 3.1 visually represents the growth rates of GDP, agricultural, and manufacturing sectors, along with the trend in population and electricity use from 1994 to 2014 (World Bank 2014). Electricity consumption depicts an exponential growth in this period which is supported by positive growth rates in agriculture, manufacturing, and GDP. Agriculture and manufacturing are energy-intensive industries. This means, to support the sectoral growth rates and population, the energy sector in

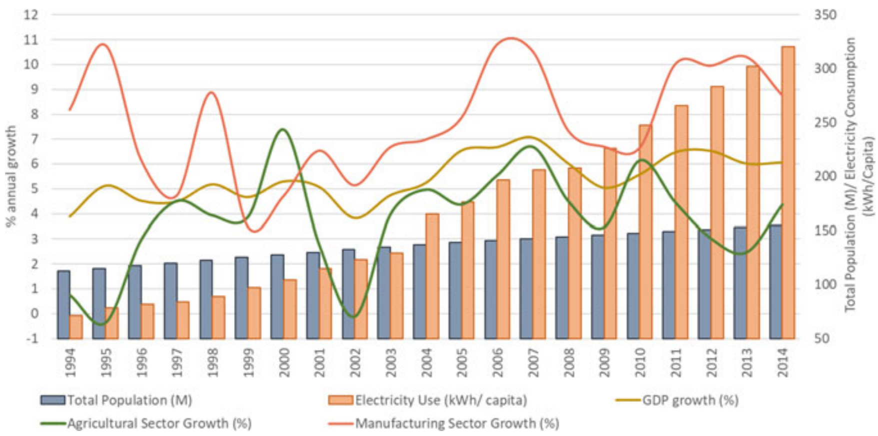

Fig. 3.1 Growth trend of GDP, agricultural and manufacturing sectors, electricity use, and population in Bangladesh

Bangladesh has had to undergo exponential capacity increase to meet the burgeoning demand.

There are severe repercussions of this relentless unsustainable growth in the agricultural and industrial sectors, as well as their associated infrastructural inputs, such as electricity. The claws of industrialization and urbanization have left lacerations on the air, water, soil, and the overall natural environment of the once verdant Bangladesh. The forest lands with healthy soil of the country have been converted to crop lands, the scale of which is now known to a quantitative extent (Mahbub et al. 2019). The lost forest cover has resulted in decreased species population as well as receding ecological services. The land which once was dominated by Bengal Tiger pugmarks is now etched with concrete roads and pavements. The roaring rivers of the country are now loaded with pollutants (Hasan et al. 2019) and shrinking by the day (Ummai et al. 2011). The resource pool of the country has also been severely impacted. Evidently, the next challenge for Bangladesh is to maintain the stark growth but ensure that the footprint it leaves is minimal. To that end, the country is under an urgent need of adopting sustainable development practices.

The first step of this transition toward sustainable consumption and production would be to identify the very root of the ongoing environmental degradation and then find ways to decouple economic growth from environmental degradation. One measure in this regard could be employing the life cycle assessment (LCA) tool. A tool of industrial ecology, LCA allows us to measure the environmental footprint of a product or process, thereby helping us identify the particular process that contributes the most to degradation. The discussion above stands as evidence that the agricultural, manufacturing, and energy sectors contribute most to environmental degradation of the country. Therefore, the primary focus of this chapter is to conduct a comprehensive review on the available literature on LCA studies on these sectors. A compilation of relevant studies will provide us with a comparative picture of the prime environmental impacts inflicted by these sectors, highlighting the hotspots responsible for environmental degradation. Hence, this review will suggest ways to implement sustainable resource management for the mentioned sectors and ultimately help identify the knowledge gaps in these sectors.

The chapter begins with a description of the methodological approach and its rationale in Sect. 3.2. Section 3.3 then presents the findings from the literature review of agricultural, manufacturing, and energy sectors' LCA studies. Based on the results, Sect. 3.4 outlines the discussion of the potential policy interventions to balance the environmental tradeoffs of the economic activities. Lastly, the review concludes with Sect. 3.5.

3.2 Approach for Identifying Literature

The main objective of this review was to attain a comprehensive prospect of the environmental impacts caused by the three sectors—agricultural, manufacturing, and energy through the lens of LCA. Therefore, to carry out a systematic review, the available LCA studies in Bangladesh were at first selected. Subsequently, the resultant studies were sorted sector wise. Sector-focused literature were extracted employing the following criteria:

- Studies that focused exclusively on environmental impacts of processes or products considering Bangladesh as their spatial boundary
- Studies were selected based on different economic sectors of Bangladesh as it is stated as the scope of this review
- Studies which are published in the reliable peer reviewed journals in English language

A detailed information regarding the selected literature has been provided in Table 3.1. Studies found under agricultural sector were focused on aquaculture (Henriksson et al. 2018; Suravi (2018), rice paddy (Jimmy et al. 2017), and rice (Roy et al. 2007). While Henriksson et al. (2018) considered 1 ton of wet weight live animal at farm gate as their functional unit (FU), the study by Suravi (2018) considered 1 kg of fish produced. The FU for rice was 1 ton of rice produced (Roy et al. 2007), whereas the study on rice paddy carried out the assessment using 1 kg of rice as their FU (Jimmy et al. 2017). In case of manufacturing sector, studies were focused on bicycle (Roy et al. 2019a), rebar from ship recycling (Rahman et al. 2016) and on leather manufacturing (Chowdhury et al. 2018). Roy et al. (2007) used one regular bicycle which weighs 18.4 kg as their FU. On the other hand, the FU for the study on leather was 1 m^2 of crust leather, and for steel production, it was 1 ton of rebar. Studies under energy sector focused on electricity production (Huq et al. 2019; Tarannum and Mohammedy 2019), small-scale biogas (Rahman et al. 2017), and on PV system (Rahman et al. 2019). The study by Huq et al. (2019) scrutinized the electricity produced using reciprocating engine, whereas the study by Tarannum and Mohammedy (2019) was chiefly a comparative study between electricity produced

Table 3.1 Methodical review of selected literature

Sector	Study	Product/process	System boundary	Functional unit (FU)
Agriculture	Henriksson et al. (2018)	Aquaculture	C to G[a]	1 ton of wet-weight live animal at farm gate
	Roy et al. (2007)	Rice	G to G[b]	1 ton of rice
	Jimmy et al. (2017)	Rice paddy	G to G	1 kg of rice paddy
	Suravi (2018)	Aquaculture	G to G	1 kg of fish production
Manufacturing	Roy et al. (2019a)	Bicycle	C to Gr.[c]	Regular bicycle—18.4 kg
	Rahman et al. (2016)	Steel in ship recycling	G to G	1 ton of rebar produced
	Chowdhury et al. (2018)	Leather	C to G	1 m^2 of crust leather
Energy	Huq et al. (2019)	Power plant	C to Gr	1 kWh electricity produced
	Tarannum and Mohammedy (2019)	Power plant	C to G	1 kWh electricity produced
	Rahman et al. (2017)	Small scale biogas plants	C to Gr	Methane produced from 1 kg cow dung
	Rahman et al. (2019)	PV system	C to G	1 kWh AC electricity produced

[a]C to G: cradle to gate; [b]G to G: gate to gate; [c]C to Gr.: cradle to grave

using natural gas in contrast to electricity produced using heavy fuel oil. Both the studies concerned with the electricity production adopted 1 kWh electricity produced as their FU. Besides, in case of the biogas plant, the FU was the amount of methane produced from 1 kg of cow dung. The study showed that the PV systems used 1 kWh AC electricity produced as their FU.

3.3 Assessment of Environmental Impact/Degradation Based on the Findings of Available LCA Studies for Bangladesh

3.3.1 Agricultural Sector

The agricultural sector can primarily be divided into four sub-sectors, namely crops, animal farming, fisheries, and forest (Ministry of Finance 2017). However, in this section, only two of the sub-sectors, crops and fisheries, will be the main focus. These studies assessed the environmental footprint of aquaculture and agricultural crops such as rice and rice paddy. All the identified impact categories and related detailed information have been presented in Table 3.2.

The studies conducted by Henriksson et al. (2018) and Suravi (2018) focused on the environmental impact of aquaculture. The impact categories reported by both studies were global warming potential, eutrophication, freshwater ecotoxicity, and acidification. The investigation by Henriksson et al. (2018) reported that the global warming potential (GWP) from shrimp farming was 8200–186,000 kg CO_2-eq t^{-1}, whereas according to Suravi (2018), it was 6.96 kg CO_2 eq. In case of acidification, Henriksson et al. (2018) stated that pollutants emitted from agricultural fields such as NO_x and NH_3 were the main culprit. On the other hand, eutrophication was attributed to the large amount of feed and fertilizer present in farm runoff water due to intensive *koi* (*Anabas testudineus*) farming. The main source of freshwater ecotoxicity was pesticide use found in *koi* farming. Both the studies were in agreement regarding the fact that fish feeds played an important role in increasing the overall environmental footprint of aquaculture.

The LCA research on rice by Roy et al. (2007) focused on identifying the global warming potential of the different production processes. The findings of the study point out that untreated processes had a significantly lower CO_2 emission compared to other processes adopted for the same purpose. In the case of the LCA done on rice paddy, main identified environmental impacts were GWP, photochemical oxidant formation, terrestrial acidification, water depletion, ozone depletion, and marine and freshwater eutrophication. Jimmy et al. (2017) also reported that the paddy field emission accounted for the GWP and marine eutrophication which were found to be 3.15 kg CO_{2eq} and 0.0158 kg N_{eq}, respectively. Irrigation system was responsible for 3 m^3 water depletion and 0.00126 kg $P_{eq.}$ Pesticide and fertilizer use contributed to the 0.02827 kg SO_{2eq} terrestrial acidification and 0.159 mg CFC-11$_{eq}$ ozone depletion. Fuel combustion due to operation and transportation was responsible for the 0.0123 kg photochemical oxidant formation as well as the previously mentioned ozone depletion. According to the study, irrigation played an important role in case of most impact categories.

Table 3.2 Magnitude of environmental degradation for agricultural sector

Impact category	Aquaculture		Rice paddy
	Henriksson et al. (2018)	Suravi (2018)	Jimmy et al. (2017)
	FU—1 ton of wet-weight live animal at farm gate	FU—1 kg of fish production	FU—1 kg of rice paddy
Global warming potential	8200–186,000 kg CO_2-eq t^{-1} (shrimp farming)	6.968079449 kg CO_2 eq	3.15433 kg CO_2 eq
	3800–111,000 kg (*koi* farming) CO_2-eq t^{-1}		
Acidification	106–666 kg SO_2-eq t^{-1} (*koi* farming)	0.050811994 molc H+ eq	0.0273 kg SO_2 eq (terrestrial acidification)
	1.7–11 kg SO_2-eq t^{-1} (shrimp and rice farms)		
	1.7–47 kg SO_2-eq t^{-1} (shrimp farming)		
Eutrophication	80–1869 kg PO_4-eq t^{-1} (*koi* farming)	0.001859145 kg P eq (freshwater eutrophication)	0.00122 kg P eq (freshwater eutrophication)
		0.024718555 kg N eq (marine eutrophication)	0.01545 kg N eq (marine eutrophication)
		0.114664207 molc N eq (terrestrial eutrophication)	
Freshwater ecotoxicity	45,000–1,356,000 PAF m^3 d t^{-1} fish (*koi* farming)	223.1521879 CTUe	0.04642 kg 1, 4—DCB eq
Ozone depletion	–	1.09671E−07 kg CFC-11 eq	1.39E−07 kg CFC-11 eq
Water depletion	–	2.96767 m^3	0.028746111 m^3 water eq
Photochemical oxidant formation	–	0.01533411 kg NMVOC eq	0.01088 kg NMVOC

3.3.2 Manufacturing Sectors

The LCA studies belonging to the manufacturing sectors of Bangladesh were bicycle production, steel in ship recycling, and leather industry. Detailed information regarding the environmental impact metric have been shown in Table 3.3.

Roy et al. (2019a) conducted LCA on bicycle production in Bangladesh to uncover its environmental hotspot and to estimate the emission compared to the motorized

Table 3.3 Magnitude of environmental degradation for manufacturing sector

Impact category	Bicycle	Steel in ship recycling		Leather	
	Roy et al. (2019a)	Rahman et al. (2016)		Chowdhury et al. (2018)	
	FU—1 bicycle (18.4 kg)	FU—1 ton of rebar produced		FU—1 m^2 of crust leather	
		Primary rebar	Secondary rebar	FCL	CRL
Global warming potential	197.78 kg CO_2 eq	2248 kg CO_2 eq	283 kg CO_2 eq	0.7 kg CO_2 eq	0.7 kg CO_2 eq
Freshwater eutrophication	0.0154 kg P eq	–	–	0.022 kg P eq	0.024 kg P eq
Acidification	–	–	–	0.042 kg SO_2 eq	0.035 kg SO_2 eq
Ecotoxicity	0.1251 kg 1,4- DB eq	–	–	27,000 kg TEG water	6000 kg TEG water
Ozone depletion	–	–	–	3.5 E−09 kg CFC-11 eq	3.5 E−09 kg CFC-11 eq
Metal depletion	29.4352 kg Fe eq	–	–	–	–
Fossil depletion	53.4626 kg oil eq	–	–	–	–
Human toxicity/impact on human health	28.92 kg 1,4-DB eq	2.5×10^{-3} DALY	1.86×10^{-4} DALY	–	–

vehicles. The identified impact categories were climate change, eutrophication, freshwater ecotoxicity, metal and fossil depletion, marine ecotoxicity, and particulate matter formation. Among them, marine ecotoxicity (17%), metal depletion (16.1%), and freshwater eutrophication (13%) have higher impact on environment and have been identified as hotspots for bicycle production.

Rahman et al. (2016) conducted LCA on steel production from secondary rebar (extracted from dismantled ship) and has drawn a comparison with the environmental impact of steel production from primary rebar (extracted from ore). This comparative study has shown a significant improvement of eradicating GHG emission if secondary rebar (283 kg CO_2 eq) is used instead of primary rebar (2248 kg CO_2 eq). Besides, primary resource use has been cut down to 16,510 MJ if secondary rebar (4760 MJ) is used instead of primary rebar (21,760 MJ) for steel production.

Chowdhury et al. (2018) conducted an LCA on leather manufacturing where they proposed an environmental footprint comparison between two different qualities of leather, namely full chrome leather (FCL) and chrome retanned leather (CRL). This study shows that, FCL and CRL are on par for impact categories such as eutrophication, climate change, ozone depletion, and acidification. However, the impact on freshwater ecotoxicity is three times higher in FCL than CRL as FCL production releases triethylene glycol (TEG) contaminated effluent.

3.3.3 Energy Sector

We have identified four studies related to life cycle assessment of energy production technologies in Bangladesh. A common trend noticed in all four studies was that the most used environmental impact category metric was GWP.

Huq et al. (2019) conducted LCA of reciprocating engine power plants, and Tarannum and Mohammedy (2019) conducted LCA of combined cycle natural gas power plants and heavy fuel oil power plants, respectively. Huq et al.'s (2019) findings revealed that reciprocating engine power plants lead to 672.22 g CO_2 eq/kWh electricity production. The main polluting component here is carbon dioxide. Natural gas fired combined cycle power plants lead to 464 g CO_2e/kWh in comparison to the 830 g CO_2e/kWh from heavy fuel oil dependent power plants (Tarannum and Mohammedy 2019). The main greenhouse gases emitted in this case are carbon dioxide and methane. Methane's impact on the environment is understood to be 28 times as much as carbon dioxide (Tarannum and Mohammedy 2019). Both studies concluded that natural gas-powered power plants are about half as harmful as their petroleum-based counterparts. Both studies also posited that the majority (from 71 to 91%) of the emissions are attributed to the operational phase of the plants where fuel combustion takes place.

Rahman et al. (2017) and (2019) conducted LCA of renewable energy technologies—small-scale biogas plants and solar photovoltaic systems in Bangladesh, respectively. They compared these technologies to traditional alternatives such as wood biomass cooking stoves, kerosene-fueled stoves, diesel generators as well as oil, gas, and coal power plants. Rahman et al.'s (2017) investigation uncovered that biogas generated from anaerobic digester plants emit 11 t of CO_2 annually. 40% of emission occurs from methane leakage due to poor maintenance of the plants. This is still less polluting than other cooking gas sources in rural areas such as firewood or kerosene-powered stoves. Rahman et al.'s (2019) investigation of small-scale 3.6 kWp solar PV systems posits that it releases 150 g CO_2/kWh of electricity generated. Battery and PV panel manufacturing are the most GHG and energy-intensive components of this system. Solar PV's use phase has negligible emissions.

3.4 Environmental Policy Recommendations for Impact Decoupling

As presented in the previous sections, the assessment of the nature and magnitude of environmental impacts caused by the key sectors of Bangladesh through the review of available LCA studies allowed identifying the key systems, processes, and areas of these sectors that are main contributors to the environmental degradation in Bangladesh. Considering these findings, several policy recommendations could be provided for minimizing the harmful environmental impacts associated with these sectors, which are presented as follows:

3.4.1 Policy Interventions for Agricultural Sector

The empirical evidences of the environmental impact induced by the agricultural sector as presented in this chapter clearly indicate the need for Bangladesh to adopt sustainable agricultural practices. As mentioned earlier, eutrophication, climate change, and water depletion are the major environmental impacts caused by the agricultural sector. In this section, recommendations suitable for Bangladesh for transitioning into a more sustainable agricultural production has been provided (Table 3.4).

Eutrophication is widely known to be injurious to aquatic systems. The reviewed studies have concluded that the use of phosphorous and nitrogen-based fertilizers contributes to both freshwater and marine eutrophication. The surface runoff from fertilizers have high potential of causing eutrophication; the ultimate consequence of which can be algal bloom in freshwater bodies and hypoxia in coastal waters (Atapattu and Kodituwakku 2009). Improper use of both nitrogen and phosphorus fertilizers in agricultural systems has been found to be the main reason behind nitrogen and phosphorus losses (Roy et al. 2019b; Bowles et al. 2018). One way to prevent excess flow of phosphorus into aquatic systems would be to prevent losses by identifying the optimum fertilizer requirement of particular crop and soil type (Roy et al. 2019b). Besides, intercepting fertilizer runoff, for example, by using field buffer strips can play a significant role in preventing the movement of excess nutrient into water bodies (Bowles et al. 2018). In addition to that, measures to improve the water quality of aquaculture wastewater can be adopted. One such example can be the use of water spinach floating bed in China (Zhang et al. 2014). There is an urgent

Table 3.4 Sustainable agricultural production approaches

Sustainable agricultural production approaches	Impact category	Responsible process
Water spinach floating bed	Eutrophication	Fertilizer use and feed production
Prevention of fertilizer misuse		
Incorporation nutrient recycling		
Employing field buffer strips		
Rice straw derived biochar	GHG emission	Paddy field emission (NH_3 and NO_x emission)
Optimized irrigation	Water depletion GHG emission	Irrigation

need for formulating national policies and regulations toward sustainable management of phosphorus and nitrogen fertilizers in agricultural lands, and the agricultural department could play vital role in properly implementing these policies for minimizing nutrient loss and associated environmental impact. In this regard, there should be coordinated efforts among various stakeholders and departments involved in fertilizer production, supply, use, crop production, agricultural extension, waste management, and environmental protection.

Another important factor to be considered in case of Bangladesh is the mangrove forests located in the southwestern region since costal aquaculture is a widely practiced process of fish production (FAO 2021). Shrimp aquaculture has been identified as one of the chief sources of mangrove forest destruction in Bangladesh (Islam and Wahab 2005). Therefore, while designing a sustainability solution, this unique mangrove ecosystem should be of utmost importance. The fisheries department and forest department need to work in coordination to take necessary initiatives and actions for minimizing pollution caused by shrimp farming and associated adverse impact on the mangrove forest.

The main source of greenhouse gas emitted from agricultural sector is the volatilized of ammonia from paddy field. An effective way to reduce the paddy field emission would be using rice straw derived biochar an alternative to synthetic nitrogen fertilizer (Sun et al. 2019). Since rice straw is a common by-product of the rice production systems in Bangladesh, using derived biochar from this particular source can prove to be a sustainable substitute. Lastly, water depletion can be attributed to the commonly practiced irrigation within the agricultural systems. A way to reduce pressure on the already depleting aquifer of the country would be to employ optimized irrigation practices (He et al. 2020). The study also reported that optimized irrigation reduced greenhouse gas emission. Therefore, necessary actions should be taken for sustainable irrigation practice particularly in the arid regions of Bangladesh.

3.4.2 Policy Interventions for Manufacturing Sector

Manufacturing sector has been identified as another key sector leading to environmental degradation in Bangladesh as assessed in this chapter. Therefore, considering the key findings of the current assessment as presented in the previous sections, necessary policy and management interventions are required to minimize the adverse environmental impact of this sector which will be discussed in this section (Table 3.5).

Under the manufacturing sector, material preparation and assembly of bicycle production spike the potentiality of freshwater eutrophication, ecotoxicity since the effluent discharge rate (7.1 m^3) is high. Effluent treatment plant (ETP) can be effective in reducing the pollutant to the standard discharge level by decreasing the amount of nutrients and other toxic chemicals (can increase BOD and COD levels) from the wastewater coming out of the bicycle industry. In leather production, processes

Table 3.5 Overview of sustainable manufacturing approaches

Production	Impact	Responsible process	Sustainable manufacturing approaches
Bicycle	Freshwater eutrophication, freshwater ecotoxicity	Material preparation	ETP installation
Leather	Aquatic ecotoxicity, eutrophication	Deliming process	Use of nitrogen free deliming agent
			Scrubbing bio filtration
			Fleshing skin in green or soaked state
		Unhairing	Add enzymes and amines
		Tanning	Use aromatic sulfonic acid
			Chromium uptake with nanocomposite assisted chrome tanning
Steel from secondary rebar	GHG emission	Electricity production and natural gas production	Lowering leakage percentage of methane in natural gas production
			Use decarbonized energy through energy transition

namely trimming, soaking, fleshing, dehairing, bating, pickling, tanning, splitting, shaving, and retanning trigger chromium, sulfide, and ammonia discharge to the wastewater and other animal impurities like blood, dirt, and hair which pollutes surface water nearby leather and tanning industry. Leather and tanning industry usually use nearby surface water as a sink to open dump their wastewater in an untreated manner. In order to reduce ammonia and COD load, nitrogen-free deliming agent can be used to lower the pH and deswelling of the fibers (Sui et al. 2012). In addition to that, instead of using ammonium salt in this process, sulfonated phthalic magnesium salt can be used as well (Qiang et al. 2012). During dehairing process, enzymes and amines can be introduced to partially minimize the consumption of sulfides (Clonfero 1999). In tanning process, the partial substitute of chlorine can be used by using aromatic sulfonic acid and reduces the amount of chlorine and sulfate in discharged effluent (Chowdhury et al. 2018). In liming process, scrubbing bio filtration can reduce hydrogen sulfide and fleshing skin in green and soaked state allows more rapid and uniform penetration to the skin for which residues carry low concentration of chemical and thereby volume of wastewater reduces (Black et al.

2013). Since chromium uptake can be boosted 90% by using synthetic tanning materials in tanning process (Lofrano et al. 2013), recovery or reuse of chromium can be a plausible way to reduce the level of chromium in effluent discharge. Stricter regulations and emission standards are required for heavily polluting tannery industries, and Department of Environment should regularly monitor the emission level against these standards. Relocation of tannery industries from highly populated and environmentally sensitive areas is necessary, and the government has already taken some initiatives in this regard. The government should also provide incentives and necessary logistic support to tannery industries to establish modern effluent and waste treatment plants.

According to Rahman et al. (2016), steel production from secondary rebar is more sustainable than primary rebar in terms of environmental impact. However, on the final stage of of steel production from secondary rebar mentioned in the said study, the GHG emission is higher compared to the other production stages because of two important processes, namely electricity production and natural gas production by combusting methane. Lowering the leakage percentage of methane (9% of the methane production) during natural gas production can overall reduce the GHG emission and hence aid to decouple the overall impact of steel production (Cathles 2012). Modernizing the existing steel industries through replacing old process and technologies with sophisticated and environment friendly technologies could help to minimize environmental footprint of this sector. Introduction of carbon tax could also drive these industries toward sustainable practice.

3.4.3 Policy Interventions for Energy Sector

As it is evident from the discussion on the adverse environmental impacts of the energy sector from Sect. 3.3, it is high time for Bangladesh to adopt cleaner mechanisms of energy production. Considering the findings of the current assessment, a number of initiatives could be undertaken to minimize the environmental footprint of the energy sector.

The reviewed literature indicate that solar power-based energy could be a viable option for Bangladesh. The country needs to upgrade its existing infrastructure to make these compatible with green and clean energy technologies. Future town/urban and industrial planning should consider installation of solar panels in every new household, community infrastructure, and industries. Considering the burgeoning population, Bangladesh naturally has a higher content of organic waste. In this case, a waste to energy scenario could be adopted. The option for energy recovery in the existing waste management policies and strategies needs to be incorporated.

The findings from energy sector tell us that even the eco-friendliest technologies are not emission free. This implies that to accelerate efforts to curb climate change and other anthropogenic environmental pressures, we must take bigger strides toward creating an enabling ground for clean technologies. We believe that multiple stakeholders need to align their visions and steward this much-needed transition. Government agents are a major player in this energy ecosystem that, firstly, need to create a congenial environment in the regime for entrepreneurs and businesses to introduce new clean technology or proliferate the adoption of existing climate mitigating technologies. This can be done through policies that encourage open innovation, knowledge building, industrial transition to clean technologies, enabling access to market and finances, and encouraging social practice change toward reducing individual ecological footprint.

It is understood that lock-in effect is a major hurdle in the way of phasing out fossil fuel-dependent technologies (Kalkuhl et al. 2019), which plays a major role in preventing positive change. Thus, next to building the enabling clean energy ecosystem, it is necessary to implement market-based approaches such as carbon taxation and removal of subsidies to fizzle out old and polluting technologies such as coal and heavy fuel oil power plants. Secondly, research and development friendly policies should be developed such that Bangladeshi context-specific research can lead to domestic and home-grown inventions and adoption. Collection and access to reliable data on energy technology and pollution can be a good starting point.

Apart from these three major sectors, there are several other sectors (i.e., textile, waste management, household, and commercial) which might also have significant adverse impact on the environment. Often these sectors are linked to the others, and therefore, policy initiatives should consider the synergies among these sectors to provide a holistic solution rather than treating each sector in isolation.

3.5 Conclusion

This review has been a preliminary attempt at collating and assessing the environmental impact of agricultural, manufacturing, and energy sectors of Bangladesh through the lens of LCA tool. In fact, nearly all of the LCA studies done in Bangladesh belong to these three sectors; therefore, future LCA studies should focus on other sectors that are also likely to contribute to environmental degradation in Bangladesh. The LCA studies on agricultural sector showed that the most harmful environmental impacts are caused by increased use of fertilizer and pesticides in order to support the rising yield. Manufacturing sector is responsible for discharge of harmful pollutants to the water system, emission of GHG, and high amounts of energy consumption. The footprint of energy sector is characterized by high levels of emissions from heavy fuel and petroleum-dependent power plants, diesel run generators, and use of kerosene for household use. On the other hand, small biogas digesters and solar PV systems promise a cleaner future through reduced GHG emissions and energy use.

From a methodological point of view, the most common hurdle encountered by all of the authors in conducting energy LCA is the lack of data. Information on natural gas well, operational data of power plants, infrastructure, transportation, pipelines, decommission, waste disposal, and infrastructure maintenance were difficult to acquire. This either undermined the accuracy of the results or led to inevitable cut-offs in both up-stream and down-stream processes in the value chain.

A noticeable knowledge gap in almost all of the papers is the lack of consideration of all impact categories in LCA, some of which may be due to data insufficiency. LCA sheds light on impact categories such as GWP, land use change, acidification, eutrophication, ozone layer depletion, and human toxicity (Baldo et al. 2008). However, the common trend, especially for the energy sector, is that only GWP and a handful of other impact categories are regularly emphasized. Not considering the rest of the impact categories reveals the lack of sight of a holistic and systemic approach to identifying major pressure points. If we do not conscientiously measure the impact of the overarching planetary boundaries (Rockström et al. 2009), then we will fail to account for the complex interactions of the systems and implement interventions at the systemic level.

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Chapter 4
Chemical Fertilizers and Pesticides: Impacts on Soil Degradation, Groundwater, and Human Health in Bangladesh

Mohammad Enayet Hossain, Saif Shahrukh, and Shahid Akhtar Hossain

Abstract Agrochemicals in the form of fertilizers and pesticides were thought of as a boon for humankind. However, the advancement of science brought to the fore the fact that chemical fertilizers and pesticides cause considerable harm to soil and subsequently to groundwater. With the burden of feeding a burgeoning global population, modern agriculture is heavily dependent on the extensive use of agrochemicals. Given the fact that the human population will likely reach ~9.7 billion by 2050, the importance of agrochemicals is more than ever before. However, these agrochemicals are inherently persistent in nature and may degrade soil health and the utility of groundwater for various purposes. Soil microbial communities that sustain different nutrient cycles are affected to a great extent by the persistence of these recalcitrant agrochemicals. As humans are dependent on soil and water for their survival, they are also exposed to health hazards stemming from these agrochemicals. Contaminated groundwater, if consumed for a considerable period, may cause many human health problems, including hormone disruption, reproductive abnormalities, and cancer, etc. This chapter aims at reviewing various impacts of chemical fertilizers and pesticides on soil degradation, groundwater, and human health with some reference to Bangladesh perspective and suggesting ameliorative measures that would keep soil and associated ecosystems sustainable and lessen the health hazards for humans.

Keywords Agrochemicals · Modern agriculture · Soil health · Groundwater contamination · Human health · Sustainable agriculture and environment

4.1 Introduction

Modern agriculture is largely dependent upon the heavy input of agrochemicals in the form of fertilizers and pesticides. In the last century, sustainability in agricultural production has been possible by the effective management of pathogens and pests

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accompanied by the adequate application of nutrient elements in the form of chemical fertilizers. The industrial revolution followed by the green revolution proved to be a boon for the burgeoning world population because the episodes increased crop production per unit area. However, the revolutions caused a remarkable increase in the use of agrochemicals, i.e., fertilizers and pesticides. Currently, 1000 different pesticides are in use around the world (WHO 2018), and two-third of these pesticides are exclusively used for agricultural uses. Excessive use of fertilizers and pesticides has given rise to concerns related to soil biodiversity, ecological balance, environmental health, and more importantly human health. These concerns associated with agrochemicals have naturally drawn serious attention from the scientific community across the world.

The harmful impacts of pesticides on humans and the environment were first brought to attention by author Rachel Carson. In 1962, she authored a book named "Silent Spring," where she detailed the impacts of certain pesticides on the eggs of several birds. There was a paradigm shift when the industrial revolution occurred. Rapid industrialization and the quest for self-sufficiency in food have heightened the pressure on natural resources more than ever before. Soil is one of the precious resources which is regarded as a non-renewable resource. It is home to a myriad of microflora and microfauna. Microflora such as bacteria, fungi, protozoa, and algae regulate a number of critical and fundamental functions in soils that are vital for the agroecosystems. Nutrient cycling, decomposition of organic and inorganic matter and associated soil fertility, and improved availability of limited nutrients are regulated by this microflora all year round. Chemical fertilizers and pesticides have been reported to pose a range of undesirable effects on soil microfloral diversity. Soil biodiversity, especially soil microorganisms, is vital for the maintenance of soil health. Soil health refers to soil's capacity to sustain all the associated ecosystems. A healthy soil ensures a favorable condition for its microbes which in turn facilitates crop growth by maintaining soil fertility. Thus, global food security is dependent on the well-being of soil health and soil fertility. The other undesirable effects of agrochemicals originate from their contribution to the emission of greenhouse gases and from their role in causing resistance development among pests. The excessive use of agrochemicals is also responsible for acidification of soils, water pollution, and for causing loss of income because of their adverse effects on aquaculture. The presence of excess agrochemicals may render the drinking water treatment plant incur losses as water treatment will entail additional costs (Smith and Siciliano 2015). As contamination of soils and waters has been occurring unabatedly by the continual application of fertilizers and pesticides, the protection of public health has become a major challenge for humans (Belmans et al. 2018).

While it is difficult to recognize the chronic impacts on human health due to exposure to pesticides, many health-related problems are linked to pesticide exposure. Significant associations have been obtained between pesticide exposure and cancer (Krieger et al. 2010). Pesticides have also been implicated in neurological damage, reproductive and developmental health issues, and immune toxicity (Krieger et al. 2010). Some endocrine-disrupting pesticides have been identified as well (Mnif et al. 2011). In an estimate by the World Health Organization (WHO), every year

~3 million pesticide poisoning cases are reported globally. In developing countries, 220,000 people die every year due to pesticide poisoning (Upadhayay et al. 2020). Regulatory bodies around the world are taking measures by recognizing the deleterious effects of pesticides. Now, countries are either banning harmful pesticides or imposing increased restrictions on their use. The optimum and precise application of agrochemicals is likely to give better results in terms of increased food production and human health and environmental quality. As such, in the recent past, pesticides have become more tailor-made to be more species-specific with shorter half-lives because of some genuine efforts on the part of researchers and policymakers. The footprint of pesticides on the environment has decreased as a result. To ensure the sustainability of agriculture and the well-being of humans, it is imperative to evaluate the various impacts of persistent use of pesticides and fertilizers on soil degradation, groundwater, and human health. This book chapter is aimed at giving insights into what these agrochemicals are, their global use, the impacts they have on different niches of the environment, including humans, and how the negative effects of these agrochemicals can be minimized.

4.2 Types of Agrochemicals

4.2.1 Fertilizers

Fertilizers are substances that are employed to correct nutrient deficiencies and imbalances in crops. The Soil Science Society of America (SSSA) defined fertilizer as "any organic or inorganic material of natural or synthetic origin, other than liming materials that are added to soil to supply one or more plant nutrients essential to the growth of plants." Plants require sixteen (16) essential elements, out of which 15 are taken up from the soil. Fertilizers are added to soil to supply the major and sometimes the minor essential elements to plants for their healthy growth and functioning. Plants require primary nutrients such as nitrogen (N), phosphorus (P), and potassium (K) in greater amounts. Intensive agriculture in many countries led to a dire shortage of these essential elements in the soil. To maintain optimal growth and yield of crops, replenishment in the form of fertilizers is performed regularly. Synthetic or inorganic fertilizers are obtained from nonliving sources and consist of synthesized or processed chemicals. Unlike organic fertilizers, inorganic fertilizers are mostly readily dissolved in water and thereby readily available for plant uptake. When judiciously used, inorganic fertilizers meet the demand of the crops and are safe for the environment. Globally, N, P, and K are the predominant fertilizers that are used by farmers in their agricultural fields.

4.2.2 Pesticides

Pesticides have been in use since the beginning of human history. They are chemical substances that are used in agriculture, animal breeding, and public health. They are essentially employed to eradicate or control undesired organisms or "pests" (Colosio et al. 2017). They usually refer to chemicals such as fungicides, herbicides, insecticides, nematicides, and rodenticides. However, some other substances are also considered pesticides. For instance, plant growth regulators, defoliants, and fruit thinning agents are widely regarded as pesticides. The agents which are used for preventing premature fall of fruits are also considered pesticides. Desiccants such as diatomaceous earth and silica gel are physical pesticides. Pesticides are also added to crop after harvest to prevent crop loss during transport and storage. Pesticides are mostly synthetic chemicals of organic or inorganic origin. They can be classified based on a number of criteria such as target pests, chemical composition, half-life, etc. However, they are mainly classified based on their active molecule. It is considered to be most appropriate because it provides an outline of the efficacy, physical and chemical properties of pesticides. Based on the active molecule, the pesticides are categorized into organochlorines, organophosphates, carbamates, and pyrethroids pesticides. Ideally, a pesticide should possess the following characteristics: (a) it should only cause harm to target soil organisms, (b) it should have a low half-life in soil, (c) it should be cheap, and (d) it should be environmentally friendly and biologically degradable. Nevertheless, in effect, most pesticides exhibit acute and chronic toxicity to organisms and are able to cause harm to all other life forms in addition to the targeted pest (Zacharia 2011).

4.3 Global Use of Agrochemicals

The exponential growth of the global population has compelled farmers to produce more food, and the additional production was made possible by the application of agrochemicals. For instance, in China, grain production had increased significantly within a space of 62 years. From 1949 to 2011, per capita, grain production had increased from 209 to 424 kg/year. The increase in production was attributed to the application of a huge quantity of chemical fertilizers (Li et al. 2014; Scholz and Geissler 2018). To put things into perspective, chemical fertilizers are responsible for half the agricultural production of the world (Scholz and Geissler 2018). Table 4.1 represents the fertilizer consumption in Bangladesh, China, India, and the United States in the year 2002 and 2018.

In the present-day world, much of the global food production is attained by the use of three major nutrient elements (N, P, and K) in the form of fertilizers as can be seen by the statistics in Table 4.1. The consumption level of these nutrient elements has gradually increased, and the application is predicted to rise in future. By 2050, the use of N, P, and K is projected to increase by 172%, 175%, and 150%, respectively

Table 4.1 Nitrogen (N), phosphorus (P), and potassium (K) fertilizer consumption in Bangladesh, China, India, and the United States (in tons)

Country	Year 2002			Year 2018		
	N	P	K	N	P	K
Bangladesh	1,079,064	321,758	156,017	1,330,580	710,240	434,400
China	25,258,492	10,387,831	4,869,556	28,306,384	7,875,817	10,802,604
India	10,469,210	4,029,134	1,597,647	17,628,200	6,967,900	2,779,100
The United States	10,945,093	4,015,513	4,502,295	11,644,461	4,081,208	4,585,337

Source Data from http://www.fao.org/faostat/en/#data/RFN (accessed 08.05.21)

(Khan et al. 2018). This progressively higher fertilizer consumption has worsened the quality of soil and the nearby water resources. Nitrogenous fertilizers have been applied more compared to other fertilizers and are particularly responsible for water pollution (Khan et al. 2018).

Currently, Asia consumes the most pesticides in the world followed by Europe. Country-wise, China is the largest producer and consumer of pesticides in the world and is closely followed by the US (FAO 2021). India is also one of the largest consumers of pesticides in the world. In India, ~80,000 tons of pesticides are used annually in agriculture. The bulk of the pesticides is used in the production of cotton (45% of total pesticide use) and rice (23% of total pesticide use) (Arora et al. 2019). In Bangladesh, 15,144 tons of pesticides were consumed in 2018, whereas the consumption was 3170 tons in the year 2000 (FAO 2021). Thus, pesticide consumption has increased in Bangladesh by 5 times from 2000 to 2018.

4.4 Impacts of Chemical Fertilizers and Pesticides

Synthetic fertilizers and pesticides have been used in agriculture and the allied sectors for long. Consequently, they have caused considerable damage to the environment and humans. The excessive use of pesticides has elicited resistance in the pests against pesticides. As a result, it is becoming difficult to contain these pests with other means. When agrochemicals are applied onto crops, vegetables, and fruits, they may find their way into soils and through leaching to groundwater. Thus, agrochemicals end up in the drinking water of humans. For instance, when nitrogenous fertilizers are applied for crop growth, a significant fraction of the nitrogen is lost to surface and sub-surface water via different routes, e.g., runoff and leaching. On the other hand, pesticides, insecticides, and fungicides also undergo a number of transformations and losses and may enter the food chain. The pesticides may biomagnify along the food chain; that is pesticide levels become many times greater in organisms compared to the surrounding settings. A great many pesticides are capable of causing cancers in humans. Most of the fungicides (~90%) are potential carcinogens. Herbicides (~60%) and insecticides (~30%) are also able to cause cancers in humans (Baweja et al. 2020). The residues of these pesticides may also affect the central nervous system, respiratory and gastrointestinal systems.

4.4.1 Impacts on Soil

Soil is essentially the only medium for agriculture, which can feed the burgeoning world population. As the global population has been increasing exponentially over the last couple of decades, pressure on the soil has been mounting. Now, for humans, the maintenance of soil quality and fertility is of utmost importance. Overuse or misuse of chemical fertilizers and pesticides has been very common in different parts of the world. Long-term intensive application of chemical fertilizers and pesticides in soil may cause harm to the microbial community in the soil. The biochemical processes of nutrient cycling may also be compromised by the long-term application of pesticides. Some chemicals used in pesticides are persistent and may pose problems for centuries. Hence, the chemicals can badly affect soil conservation measures. Overall soil biodiversity is reduced by the long-term application of pesticides.

4.4.1.1 Soil Health and Properties

Soil health is key to sustaining the burgeoning world population. It is important to define soil health before discussing the impacts of agrochemicals on soil health. Soil health is synonymous with soil quality. A widely accepted definition of soil health is “the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health” (Doran et al. 1996; Van Bruggen and Semenov 2000). Healthy soils sustain a diverse community of soil microorganisms. These microorganisms play significant roles in controlling plant diseases, insects, and weed pests. They also form beneficial symbiotic associations with plant roots. The microorganisms also recycle essential plant nutrients by decomposition and mineralization processes. They also develop soil structure by producing gummy substances such as polysaccharides. A healthy soil structure ensures good soil water and nutrient holding capacities, thereby aiding in crop production. Thus, sustaining soil health is vital for sustaining agricultural production and maintaining soil biodiversity, including microbial biodiversity. Intensive agriculture in association with the continued use of synthetic fertilizers and pesticides at high doses has caused a great deal of deterioration in soil health.

Chemical fertilizers are meant for increased crop production. However, their overuse and increased application have created various soil health-related problems that in turn have posed problems for standing crops. The problems include soil hardening, soil acidification, and decreased fertility (Savci 2012; Lekeanju et al. 2016; Rahman and Zhang 2018). The reduction in soil pH may increase the availability of heavy metals in soils. To make the matters worse, some of these chemical fertilizers contain some heavy metals (Huang and Jin 2008). For instance, cadmium (Cd) may find its way to the soil through the application of phosphate fertilizers derived from phosphate rock (Roberts 2014). The fertilizers which contain high levels of sodium and potassium may increase soil pH and deteriorate soil structure (Savci 2012).Some nitrogenous fertilizers are able to form acids such as ammonium fertilizers. Long-term application of these fertilizers may lead to a decrease in soil pH, which, in turn, may affect the growth, yield, and quality of crops (Savci 2012; Rahman and Zhang 2018).

Soil organic matter (SOM) is a vital indicator of soil health. It has pronounced effects on a soil's physical, chemical, and biological properties. In previous studies, long-term fertilizer application was found to affect soil organic carbon (SOC) content, N content, and pH in soils. The availability of nutrients to microorganisms was found to be affected as well (Wu et al. 2005). If organic fertilizers are applied to soil for a reasonable number of seasons that helps in the accumulation of SOM because of the addition of increased litter and root biomass, which naturally improves soil health (Geisseler and Scow 2014).The application of inorganic N fertilizers, on the other hand, can exert complex interactive effects on carbon transformations in the soil. Despite having positive effects on crop yield, N fertilizers may negatively affect soil health due to their transformation products in soil. In a recent study in China, severe soil acidification was reported in a soil that had previously received a heavy application of synthetic N fertilizer (Guo et al. 2010). They also reported decreased crop production from their study. The decomposition and mineralization of soil organic matter were found to be affected by soil acidification. High nitrogen levels may hinder the growth of free-living fungi and N-fixing bacteria in soil (Velthof et al. 2011). Thus, high levels of N may negatively affect organic matter mineralization and nutrient cycling. In forest soils with natural vegetation, the removal of N and P is much smaller compared to agricultural soils. Thus, surplus application of reactive N and P in the form of fertilizers was found to affect the quality of forest soils (Velthof et al. 2011). Excessive P fertilizer application results in the build-up of soil P and the soil eventually becomes saturated vis-à-vis P. Hence, proper management of soil health is essential for the short-term and long-term productivity and profitability of a soil.

4.4.1.2 Soil Microflora

Soil microflora plays a vital role in nutrient cycles that are essential to life on the planet. Soil microflora helps to form and stabilize soil aggregates and thereby improves the soil's structure, porosity, aeration, and water infiltration (Srivastava et al. 2016). Soil microflora also helps in the bioremediation of anthropogenically contaminated soils and biocontrol of plant pathogens (Canet et al. 2001).

Pesticides pose a considerable threat to soil microflora and, as a result, interferes with soil health (Sattler et al. 2007). A great many investigations reported that the continued chemical fertilizers and pesticides disturbs the microbial communities in soil by affecting their structural and functional properties (Yang et al. 2000; Böhme et al. 2005). The beneficial soil microorganisms, that indicate the well-being of the soil, are negatively affected by the excessive use of inorganic fertilizers. As a result, the activity of various soil-based enzymes that catalyze a myriad of reactions goes down. Enzymes such as catalase, dehydrogenase, casein protease, urease, and arylsulphatase are particularly affected (Prashar and Shah 2016). Most of the pesticides are able to penetrate the cell walls of both target and non-target microorganisms present in the soil. After penetration, these pesticides interfere with their normal metabolism resulting in cell death. As mentioned previously, some fertilizers and pesticides are acid-forming. These acid-forming fertilizers and pesticides lower the pH of the soil. The reduced pH may pose a hostile environment for beneficial microorganisms. The sensitive microorganisms, which are an integral part of healthy soil, die immediately. Thus, when beneficial microorganisms die, the soils do not remain healthy any longer.

Soil microorganisms will respond differently to different pesticides. The factors such as the nature of pesticide and soil properties will govern how a microbial community will respond. A pesticide may modify the overall structural and functional diversity of a microbial population. If a specific pesticide is used for long that may lead to the predominance of only a limited number of functional microbial groups. As a result, certain biological processes will be affected (Lupwayi et al. 2009). At times, the microbial biomass may not exhibit significant pesticide effects. However, the overall functional structures of soil bacteria will be affected to a certain extent (Lupwayi et al. 2009). Moghaddam et al. (2011) worked with insecticide imidacloprid and observed a decline in total bacterial concentrations at high concentrations. They also reported a shift in the soil-dominating bacteria. Eisenhauer et al. (2009) investigated to see the impacts of different types of pesticides on some selected microbial parameters, including basal respiration and microorganism's specific respiration. The studied parameters were found to be affected by pesticides such as dimethoate, chlorpyrifos, and fosthiazate. However, the effects of pesticides were not found to be affected by either plant species or plant functional group richness. In a recent study, Rahman et al. (2020) studied the impact of long-term application of pesticides and chemical fertilizers on the anammox and denitrification bacteria present in rice field soils. The relative abundance of these bacteria was found to be much lower in rice field soils than in upland soils.

To sum up, chemical fertilizers unquestionably disrupt the structural and functional diversity of soil microbial communities. Since microbial populations play a substantial role in the soil ecosystems, shifts in their composition and structure significantly affect many soil functions and natural food webs. Since the microbial community is directly associated with soil quality and soil fertility, any changes in the microbial composition may jeopardize global food security. Therefore, it is evident that long-term use of chemical fertilizers and pesticides in excess amounts can have a wide range of deleterious effects on soil microflora. And, to mitigate the harmful effects of these agrochemicals, their excessive application must be reduced.

4.4.1.3 Soil Fertility

Soil fertility is defined as "the capacity of any soil to furnish nutrient elements in adequate amounts as required by plants for growth and development" (Lekeanju et al. 2016). Infertile soil is a major constraint that prevents high agricultural production. Lekeanju et al. (2016) reported that the naturally occurring nutrient elements in fertile soil decreased by the continuous use of chemical fertilizers. Soil fertility and crop growth and yield are dependent on the optimum and balanced supply of all the essential nutrient elements. Generally, when a particular nutrient element is used in excess that may lead to nutrient imbalance, which will eventually lead to soil degradation (Savci 2012). On the other hand, excessive application of alkaline fertilizers such as sodium nitrate may increase the pH of a soil, which will, in turn, reduce the fertility of the soil (Savci 2012). As soil microflora control the mineralization and decomposition of organic matter, they are crucial to maintaining nitrogen and phosphorus concentrations, the key elements in soil from the standpoint of plant nutrition. Therefore, a change in the microbial community structure of agricultural soil is likely to impact the overall soil fertility. As discussed above, pesticide application in most cases considerably affects the activities of microbes, which, in turn, affects the fertility of the soil. Yang et al. (2000) carried out a study and observed that soil contaminated with pesticide triazolone, and its intermediates had 58.5% less organic carbon, 54.8% less total N, and 55.0% less microbial biomass C compared to the soil without contamination. Thus, it is evident that pesticide application disrupts microbial population dynamics and thereby affects the nutrient balance and the availability of nutrient elements in the soil.

4.4.1.4 Crop Productivity

Chemical fertilizers and pesticides are indispensably used in conventional farming systems to sustain high-yield agriculture. Crops and leaves may be subjected to chemical burns due to the disproportionate use of fertilizers. The phenomenon may reduce crop productivity. Long-term application of chemical fertilizers may interfere with the synthesis of proteins in leaves, which may reduce the yield of crops. The nutritionally deficient food in turn may elicit pathological conditions in humans and animals (Talukdar et al. 2004). The herbicide glyphosate was reported to reduce seed quality. Exposure to clopyralid herbicide was found to decrease the yield of potato plants (Colquhoun et al. 2017).

The application of chemical fertilizers is most prevalent with vegetable crops compared to other classes of food crops. In a survey with the farmers in Buea, Cameroon, the consumption of vegetable crops dosed with chemical fertilizers was accounted for many health problems (Lekeanju et al. 2016). They listed a number of problems associated with the application of chemical fertilizers. Reduced taste, decreased shelf life, and loss of regenerative capacity of seeds were highlighted in the mentioned survey and some other surveys (Allen and Mangan 2015; Lekeanju et al. 2016). Some other studies demonstrated the fact that crops fertilized with synthetic fertilizers are less healthy compared to crops grown in organic farming (Isherwood 2000; Matt et al. 2011). Nitrogenous fertilizers can give off nitrites which were previously reported to cause a decline in the assimilation of protein, fat, and beta carotene. Nitrites were also found responsible for the decomposition of the B group of vitamins. Thus, nitrites issuing from applied synthetic fertilizers can detract the nutritional qualities of food crops (Matt et al. 2011). Short-cycle crops such as vegetables and maize, and root crops, e.g., carrots and tubers are susceptible to be contaminated by agrochemicals. However, the level of contamination will be governed by the type, the quantity, and the rate of application of fertilizers. When a high dose of fertilizer is broadcast on the surface that might affect the quality of root crops and tuber crops. The same applies to foliar application of chemical fertilizers. In the past, cases of food contamination from the consumption of vegetables were traced to the application of liquid fertilizer shortly before harvest (Lekeanju et al. 2016).

4.4.2 Impacts on Groundwater Resources

Water is indispensable for all ecosystems. Human life and health are entirely dependent on it. The water resource is threatened by a number of man-made problems, including contamination by uncontrolled urban and industrial wastes, contamination by injudicious application of chemical fertilizers and pesticides in agriculture, and overexploitation. Non-point sources of water contamination include both animal husbandry and agriculture (Khan et al. 2018). Pesticides move in soil and their movement is governed by their water solubility and applied quantity. Factors such as weather and climate also play a significant role in a pesticide's movement. Thus, the groundwater and surface water resources are always at risk of being contaminated with pesticides (Yadav et al. 2015). Fertilizer-laden water may percolate and contaminate the groundwater. For instance, excess nitrates from fertilizers may find its way to groundwater and thereby pollute it. When fertilizer-contaminated groundwater is consumed, it can pose many problems for humans and other animals (Khan et al. 2018). When fertilizers are applied, heavy metals are coapplied as contaminants. These contaminants may find their way to the nearby water bodies where they may adversely affect aquatic lives and render the water unfit for human consumption (Khan et al. 2018).

Belmans et al. (2018) studied water resources for contaminants and observed the presence of nitrates, phosphorous, and pesticides. Water resources are monitored for a number of parameters, such as nitrate, nitrite, phosphate, etc. Nitrate is mobile and the most prevalent form of dissolved nitrogen. As a result, a significant fraction of nitrate may be lost from the root zone via leaching and make its way to the nearby surface and groundwater. Nitrate is not very toxic in adult humans. In water, the maximum contaminant level for nitrate is 10 mg/L. However, nitrate can be very toxic for infants. Nitrate concentrations exceeding 50 mg/L in drinking water may lead to the "blue baby syndrome" (acquired methemoglobinemia in infants). When nitrates are converted into nitrites in the body by intestinal microflora, they can be very toxic (six to ten times more toxic than nitrates) for humans (Matt et al. 2011; Whittier 2011). One of the most detrimental effects of intensive application of fertilizers is related to its role in eutrophication. Phosphate is considered the main culprit along with nitrate for eutrophication. Eutrophication may affect the economy of a community that is dependent on aquatic resources (Hossain et al. 2018). Eutrophication triggers a series of events leading to a profusion of aquatic plants covering the surface of water bodies. Subsequently, the network of plants consumes dissolved oxygen which would otherwise be used up by fish and other aquatic animals. The plants also block sunlight from reaching the bottom-living species. As a result, the bottom-living species suffer from not having sufficient sunlight for their physiological and metabolic activities. Finally, undesirable species (e.g., algae) flourish in the water bodies smothering the aquatic life permanently. When algal bloom expires, the decomposition process sets in creating a bad odor. As a result, water bodies lose recreational values and esthetic values. There is a dearth of studies on the occurrence of pesticides residues in the surface and groundwater in Bangladesh. Very few studies were attempted to investigate the presence and concentrations of pesticide residues. The findings of those studies are given in Table 4.2.

4.4.3 Impacts on Human Health

The ubiquity of chemical fertilizers and pesticides has been a concern for humans. The presence of pesticides in fresh vegetables and fishes has drawn the attention of scientific community in developing countries like Bangladesh. Hossain et al. (2015b) carried out a study to detect the residual presence of organophosphorus pesticides such as acephate, chlorpyrifos, ethion, fenitrothion, parathion, and malathion in tomato, eggplant, and okra collected from a local market in Dhaka. Alarmingly, the pesticides were detected in 10 samples out of 15 samples tested in the investigation. In a subsequent study, Hasan et al. (2017) confirmed the residual presence of dimethoate and quinalphos in country bean sampled from different markets of Dhaka district in Bangladesh. In some separate studies in Bangladesh, researchers obtained the presence of pesticide residues in bean, cabbage, cauliflower, eggplant, and other vegetables (Habib et al. 2021; Islam et al. 2019; Nahar et al. 2020; Nisha et al. 2021). The presence of organochlorine pesticides in fishes was confirmed in a number of studies conducted by the researchers in Bangladesh (Bhuiyan et al. 2008, 2009; Hasan et al. 2014). In a recent study in Bangladesh, Rahman et al. (2021) analyzed vegetables, cultured fish, and fish feeds in order to observe the presence of residual pesticides. They reported that ~89% of vegetable samples contained high level of organophosphate pesticides. In their findings, they attributed the presence of pesticides in cultured fishes to fish feeds. Fruits (e.g., mango and guava) were also found to be contaminated with organophosphate and pyrethroids (Prodhan et al. 2021).

Table 4.2 Occurrence and level of pesticide concentrations in surface and groundwater sample of Bangladesh

Sampling location	Water type	Detected pesticides	Concentration (µg/L)	References
BIT, Khulna	Surface water	DDT	0.0195	Rahman and Alam (1997)
		DDE	0	
		Endrin	0	
		Heptachlor	0.0002	
Kittonkhola, Barisal	Surface water	DDT	0.035	Rahman and Alam (1997)
		DDE	0	
		Endrin	0	
		Heptachlor	0.0002	
Anowara, Chittagong	Surface water	DDT	0	Rahman and Alam (1997)
		DDE	0	
		Endrin	0.075	
		Heptachlor	0	
Amin Bazar, Dhaka	Surface water	DDT	0	Rahman and Alam (1997)
		DDE	0.01	
		Endrin	0.014	
		Heptachlor	0.00023	
Bamandanga Beel	Surface water	p,p′-DDE	0	Rahman and Alam (1997)
		Dieldrin	0.00064	
		p,p′-DDT	0.0015	
Hand TubeWell (Nayerhat, Dhaka)	Groundwater	p,p′-DDE	0	Rahman and Alam (1997)
		Dieldrin	Traces	
		p,p′-DDT	Traces	
Niger bell (Comilla)	Surface water	p,p′-DDE	0.0001	Rahman and Alam (1997)
		Dieldrin	0	
		p,p′-DDT	6×10^{-6}	
Begumgonj, Sylhet	Surface water	p,p′-DDE	0.00046	Rahman and Alam (1997)
		Dieldrin	0	
		p,p′-DDT	0.019	
Samples collected from different regions of Bangladesh	Surface water	p,p′-DDE	0.013–0.060	Matin et al. (1998)
		p,p′-DDD	0.014–0.038	
		p,p′-DDT	0.015–0.068	
		Heptachlor	0.150–1.020	
Samples collected from different regions of Bangladesh	Groundwater	p,p′-DDE	0.010–0.084	Matin et al. (1998)
		p,p′-DDD	0.014–0.365	
		p,p′-DDT	0.027–1.204	

(continued)

Table 4.2 (continued)

Sampling location	Water type	Detected pesticides	Concentration (µg/L)	References
		Heptachlor	0.025–0.789	
Samples collected from 48 different locations in Bangladesh	Surface water	Aldrin	ND	Islam et al. (2007)
		Dieldrin	ND	
		Endrin	ND	
		p,p′-DDT	ND-0.5401	
		Heptachlor	ND-1.479	
		Lindane	ND-1.826	
Buriganga river	Surface water	Chlorpyrifos	484.00	Khatun et al. (2008)
		Diazinon	19.00	
Pond water samples collected from different regions of Bangladesh	Surface water	Aldrin	ND	Bagchi et al. (2009)
		Dieldrin	ND	
		Endrin	ND	
		DDT	ND-0.316	
		DDD	ND-0.052	
		DDE	ND-0.014	
		Lindane	ND	
		Heptachlor	ND-0.048	
		Carbaryl	ND-0.609	
		Carbofuran	ND-1.760	
Water sample from paddy field and Kaliganga River, Manikganj	Surface water	Cypermethrin	BDL-0.51	Bhattacharjee et al. (2012)
		Chlorpyrifos	BDL-0.34	
		Diazinon	BDL-0.027	
Samples from paddy and vegetable field collected from Savar and Dhamrai, Dhaka	Surface water	Malathion	ND-105.2	Chowdhury et al. (2012a)
		Diazinon	ND-0.9	
		Carbaryl	ND-18.1	
		Carbofuran	ND-198.7	
Samples collected from the paddy fields, Rangpur	Surface water	Chlorpyrifos	ND-1.189	Chowdhury et al. (2012b)
		Carbofuran	ND-3.395	
		Carbaryl	ND-0.163	
Pond water collected from Nabinagar, Brahmanbaria	Surface water	Malathion	ND-46.3	Uddin et al. (2012)
		Carbofuran	ND-62.9	
		Cypermethrin	ND-90	
Samples collected from pond water in Meherpur	Surface water	Diazinon	32.8–79	Uddin et al. (2013)
		Chlorpyrifos	ND-14.3	
		Carbofuran	ND-38.7	

(continued)

Table 4.2 (continued)

Sampling location	Water type	Detected pesticides	Concentration (µg/L)	References
		Carbaryl	ND	
Water samples from the lakes, Rangpur	Surface water	Chlorpyrifos	0.544–0.895	Chowdhury et al. (2012b)
		Carbofuran	0.949–1.671	
		Carbaryl	ND-0.195	
Samples collected from different spots in Bangladesh	Surface water	Aldrin	ND	Chowdhury et al. (2013)
		Dieldrin	ND	
		DDE	ND-4.06	
		DDD	ND	
		DDT	ND-8.29	
		Endrin	ND	
		Lindane	ND	
		Heptachlor	ND-5.24	
Water samples collected from Jessore	Surface water	Quinaphos	ND-0.241	Fatema et al. (2013)
Samples collected from the paddy fields, Gazipur	Surface water	Fenitrothion	ND-1470	Shammi et al. (2014)
		Diazinon	ND-1260	
		Chlorpyrifos	ND-23500	
		Carbaryl	ND-1800	
Water samples collected from near the vegetable fields of Savar	Surface water	DDT	BDL	Hossain et al. (2015a)
		Chlorpyrifos	BDL-9.31	
		Diazinon	BDL-7.86	
		Ethion	BDL	
		Fenthion	BDL-56.3	
		Fenitrothion	BDL-33.41	
		Malathion	BDL-59.9	
		Parathion	BDL-6.23	
		Carbaryls	BDL-6.3	
		Carbofuran	BDL-43.2	
		Cypermethrin	BDL-80.5	
		Methoxychlor	BDL	
Samples collected at different spots from Dhamrai, Dhaka	Both surface and groundwater	Malathion	ND-922.8	Hasanuzzaman et al. (2017)
		Diazinon	ND-31.5	
Samples collected from water bodies of north-west Bangladesh	Surface water	Acephate	ND-3.4	Sumon et al. (2018)
		Chlorpyrifos	ND-9.1	

(continued)

Table 4.2 (continued)

Sampling location	Water type	Detected pesticides	Concentration (μg/L)	References
		Diazinon	ND-9.0	
		Dimethoate	ND-3.0	
		Ethion	ND-2.3	
		Fenitrothion	ND-4.9	
		Fenthion	ND-2.9	
		Malathion	ND-3.2	
		Methyl-parathion	ND-3.0	
		Quinalphos	ND-7.1	

ND Not detected; *BDL* Below detection limit

The problem with these pesticides lies in their persistence. They stay in the soil for a longer duration. Due to their persistent nature and long half-lives, these agrochemicals can stay in human bodies, and depending on the exposure level they can exhibit various health effects like skin diseases, delayed development, and cancers. In a study in Bangladesh, researchers found the presence of metabolites such as 3,5,6-trichloro-2-pyridinol (TCPY) and nitrophenol in the urines of pregnant women in rural Bangladesh (Jaacks et al. 2019). This is alarming because gestational exposure to pesticides may affect the prenatal development. In previous investigations, pesticides present in environmental systems were found to be linked to both acute and chronic effects on humans. The most alarming is the fact that pesticide use enhances the likelihood of cancer risks. Cancer risk may come through different mechanisms such as genotoxicity, epigenetic changes, immunotoxicity, etc. Parrón et al. (2014) carried out a case study to assess prevalence rate and cancer risks. Higher prevalence rates and higher cancer risks were seen in those districts where pesticide use was higher. The opposite phenomenon was observed in districts with lower pesticide use. Other researchers reported kidney diseases, male and female infertility, hormonal disorders, and neuron disorders in humans. Children having been exposed to chronic pesticide residues poisoning were found to exhibit behavioral disorders (Agnihotri 1999). Exposure to pesticides was found to cause neurological problems such as compromised motor coordination, weakened motor conduction velocity, and deficient verbal memory (Misra et al. 1988; London et al. 2012; Starks et al. 2012). Drinking well water contaminated with pesticides in rural areas has been implicated in Parkinson's disease. The effects of pesticides on humans can be classified into mild or moderate and severe. Mild or moderate problems associated with pesticide poisoning include headache, dizziness, gastric problems, unclear vision, and neurological problems, etc. The patient may be paralyzed, lose sight, or even die when the effects of pesticides are severe (Abhilash and Singh 2009; Yadav et al. 2015).

There has been evidence that infants that were exposed to organophosphate pesticides during their antenatal and postpartum periods may exhibit neurodevelopment disorders at all stages (Sapbamrer and Hongsibsong 2019). The effects of pesticides were more prominent in boys compared to girls (González-Alzaga et al. 2015). In developing countries, the bulk of the pesticides is consumed in crop farming where pesticides are applied to smother the undesirable plants and to prevent the proliferation of pests. Pesticides are also employed in checking vector-borne diseases such as dengue and malaria. Gilden et al. (2010) have also found their use in household equipment and food packaging materials. Pesticides are intended to kill the target organisms, and as a result, pesticide exposure can be extremely hazardous for unintended organisms. Studies around the world demonstrated the impacts of pesticides on the health of farmers exposed to pesticides (Azmi et al. 2006; Recena et al. 2006; Tijani 2006; MacFarlane et al. 2008; Oluwole and Cheke 2009; Lu and Cosca 2011; Embrandiri et al. 2012; Ghimire 2014).

4.5 Alternatives to Chemical Fertilizers and Pesticides

In recent years, chemical fertilizers and pesticides have been a cause for serious concern. The concepts of sustainable agricultural development have been brought to the fore by scientists by debate and deliberations. Sustainable agriculture is believed to provide food security to the global human population. Sustainable agriculture is being thought of as a panacea to issues related to ecology, economy, society, and philosophy. Consequently, sustainable agriculture development is vital for the holistic development of any nation. Sustainable agriculture includes organic farming, biofertilizers, and biocontrol agents. Nowadays, different methods of sustainable agriculture are gaining popularity among scientists, farmers, and the general public worldwide. A revolution is brewing in the field of agriculture; this revolution took shape when scientists brought to the fore the harmful and unintended effects of the Green Revolution. In the recent past, people realized that their existence is dependent on the well-being of their environment and the associated biodiversity. As a result, the regulatory bodies in the different countries in the world have put public health, loss of biodiversity, and environmental pollution on the priority list. People are now ready to pay extra money for organic food which is deemed safe for humans. The concept of sustainable agriculture has triggered creative and innovative thinking in the agricultural world. In the following subsections, light is shed on the alternatives to chemical fertilizers and pesticides.

4.5.1 Organic Farming: A Sustainable Alternative

Organic farming is environment friendly, and it does not pose any problems to the components of the ecosystems. It is one of the tools of sustainable agriculture, which safeguards food safety for humans. Organic farming is a special form of cultivation technique where nature is kept at its optimum. Despite representing only 1% of the world's agricultural area, organic farming is gaining popularity and a booming sector in world agriculture. In the developed countries, more and more people are consuming some amount of organic food today. Organic farming is believed to be a holistic approach that promotes soil health which in turn fosters biodiversity of soil microorganisms and other flora and fauna that are an integral part of biogeochemical cycles. Organic fertilizers support crops by directly providing them with nutrients and indirectly by stimulating microbial actions. Biocontrol agents or biopesticides are an integral part of organic farming. They are not harmful like chemical pesticides and thus are considered eco-friendly alternatives to chemical or synthetic pesticides. The biocontrol agents encompass bacteria, fungi, yeasts, and biochemicals derived from plants, animals, and microorganisms. They are also obtained from certain minerals. For instance, canola oil has pesticide properties and is considered a biocontrol agent. *Fusarium graminearum* is effectively controlled by the combined application of bacteria (*Bacillus subtilis* and *Lysobacter enzymogenes*), yeasts (genera *Rhodotorula*, *Sporobolomyces*, and *Cryptococcus*), and filamentous fungi (*Trichoderma*) (Kant et al. 2017). The biocontrol agents also include procedures involving the incorporation of DNA into crops that give protection against a particular pest. Biocontrol agents confer a number of benefits (Moazami 2019). They are target-specific. As a result, they do not pose hazards to humans, animals, and the environment. They protect biodiversity and help restore natural ecosystems. Biocontrol agents offer a safe environment for people who are otherwise exposed to chemical pesticides. In organic farming, biocontrol agents are adopted along with green manure, compost (e.g., vermicompost), biofertilizers, and crop rotations. Biocontrol agents are inexpensive, natural, and inherently nonpolluting. Thus, organic farming safeguards water quality and aids in pest and disease control. The application of organic manures reduces the bioavailability of heavy metals and persistent pesticides in soils. Organic matter in organic manures tends to form complexes with heavy metals and thus reduce their bioavailability.

4.5.1.1 Biofertilizers

Biofertilizers are natural fertilizers that are composed of live biomass or dormant cells of effective microbial strains (Ginni et al. 2020). Biofertilizers are cultures of special bacteria and fungi that are different from conventional synthetic and organic fertilizers. Biofertilizers are not able to provide any nutrients directly to crops. Some widely used biofertilizers include nitrogen-fixing soil bacteria (*Azotobacter*, *Rhizobium*), nitrogen-fixing cyanobacteria (*Anabaena*), phosphate-solubilizing bacteria (*Pseudomonas* sp.), and arbuscular mycorrhiza (AM) fungi (Umesha et al. 2018). Biofertilizers have an edge over chemical fertilizers because the installation cost is exceptionally low for biofertilizers production. They are applied to soil, seeds, or plant surface. When they are activated, they can aid in enhancing the availability of nutrients to crop plants. Thus, in future, biofertilizers could be a significant tool in global agricultural ecosystems. A myriad of microorganisms performs in solubilizing and recycling nutrients in an agricultural ecosystem. However, the population of these microorganisms in soil is often sparse. Therefore, the required microorganisms are purposefully supplemented in the form of biofertilizers. Biofertilizers are usually sourced from microbes, algae, fungi, and agro-waste. Of late, seaweeds are garnering attention for their potential use as biofertilizers. Seaweeds are a source of nutrient elements, plant growth hormones, antioxidants, and bioactive molecules (Akila and Jeyadoss 2010; Ramarajan et al. 2013; Ismail and El-Shafay 2015; Pacholczak et al. 2016). Seaweed extracts were reported to restore plant growth under high salinity stress (Nabti et al. 2010; Pacholczak et al. 2016). The rhizosphere of plants is home to a myriad of microorganisms and the zone verily acts as a hotspot for soil bacteria and other organisms (Vessey 2003). In the rhizosphere, one gram of root contains ~10^{11} microbial cells (Bhowmik and Das 2018).The bacteria that grown in, on, and around plant tissues enhance plant growth by a number of mechanisms. These bacteria are collectively known as PGPR (plant growth-promoting rhizobacteria). These PGPR have also been identified as a substitute for chemical fertilizers. PGPR may be an important tool for enhancing soil fertility and crop production in sustainable agriculture (Wu et al. 2005).

4.5.1.2 Blue-Green Algae (Cyanobacteria)

Blue-green algae are emerging microorganisms for sustainable agriculture. They are Gram-negative prokaryotes that obtain energy through photosynthesis. They can act as natural biofertilizers by performing a special role in maintaining soil fertility and agricultural productivity (Song et al. 2005). They can increase the porosity of soil and enhance the water holding capacity of soil by dint of their jelly structure (Roger and Reynaud 1982). They secrete phytohormones (e.g., auxin, gibberellins, etc.), vitamins, and amino acids (Roger and Reynaud 1982; Rodríguez et al. 2006). They can increase the availability of phosphorus by releasing organic acids (Wilson 2006). Some of the cyanobacteria can fix atmospheric nitrogen. Nitrogenase enzymes present in the heterocysts (nitrogen-fixing cells or factories) enable those special groups of cyanobacteria to fix atmospheric nitrogen. Cyanobacteria are special because they are capable of surviving on a bare minimum of light, carbon dioxide (CO_2), and water. As a result, they naturally occur in agroecosystems such as paddy fields and Antarctica, and also in Arctic poles (Singh et al. 2016). The symbiosis between *Anabaena azollae* and the leaves of the aquatic fern Azolla is found in the rice fields. In the recent past, they have received great attention because of their high nitrogen-fixing capacity. In rice fields, they can fix over 1 kg N/ha/d which is sufficient for rice crops. The *Anabaena-Azollae* symbiosis is able to secrete growth hormones, vitamins, and sugars; these substances may be utilized by other microorganisms. Thus, the symbiosis promotes biodiversity and the colonization of microorganisms.

4.5.1.3 Seaweeds

Seaweeds are large plants residing in the sea. They include various marine algae such as rockweeds, kelps, sea lettuce, and dulses. They are a rich source of various macro- and micro-nutrients and are very promising for sustainable agriculture. They have been used in agriculture from time immemorial. However, their importance in agriculture has increased in the wake of the recent attention in organic farming (Nabti et al. 2017). They are receiving importance particularly for the high abundance of different growth-promoting substances. Brown algae members are the most common among the seaweeds that are used as biofertilizers. Some of the examples are *Ascophyllum nodosum*, *Dictyopteris australis*, *Durvillea potatorum*, *Ecklonia maxima*, *Fucus* sp., *Laminaria* sp., *Macrocystis pyrifera*, *Sargassum* sp., and *Turbinaria.* These seaweeds are used in agriculture for stimulation of seed germination, root and shoot elongation, and frost and saline resistance. Because of these utilities, seaweed biofertilizers are often considered a superior alternative to chemical fertilizers (Nabti et al. 2017).

4.5.1.4 Mycorrhizal Fungi

Mycorrhizae could be a very good weapon in sustainable agriculture because of its ubiquity and its interactions with most plants (Berruti et al. 2016). They are a symbiotic association between fungi and the roots of plants. Both plants and fungi get benefitted from the association. They exchange food between themselves. More specifically, the host plant is provided with water nutrients and protection from pathogens, whereas the fungi are reciprocated with photosynthetic products (Berruti et al. 2016). Fungi or more specifically arbuscular mycorrhizal fungi (AMF) helps plants to flourish under stressful conditions. The fungi accomplish this by carrying out a series of communication events with the host plant (Birhane et al. 2012). Host plants were reported to exhibit better resistance against stresses such as salinity, drought, temperature, diseases, and metals (Ahanger et al. 2014; Abdel-Salam et al. 2018). AMF is ubiquitous and they can develop associations with ~90% of plant species, including bryophytes, pteridophytes, gymnosperms, and angiosperms (Ahanger et al. 2014; Delaux et al. 2015). AMF develops vesicles, arbuscules, and hyphae in the roots of the host plant and because of the hyphal network, and AMF can considerably enhance roots access to a larger volume of soil (Bowles et al. 2016). As a result, plants can access the immobile nutrient elements (e.g., phosphorus) in the soil. AMF was found to enhance the uptake of zinc and copper, thereby increasing the yield (Sadhana 2014). AMF also helps plants indirectly by improving soil structure and aggregation (Sadhana 2014).

4.5.1.5 Composting

Besides agrochemicals, solid waste is a major problem facing mankind. A huge amount of solid waste is being generated which is posing many problems to ecosystems. Management of crop residues, which is a solid waste, is also a challenge for humans in addition and municipal and industrial wastes. Crop residues are materials left on cultivated land that has been generated as part of any agricultural activities. The direct application of crop residues in a crop field may pose problems associated with nutrient management. Therefore, instead of leaving crop residues over, they can be composted into products that will improve soil health and provide plants with nutrient elements. Composting technology is a cost-effective and environment-friendly alternative. When composted materials are applied to soil, they can enhance soil health and soil fertility which will, in turn, increase agricultural productivity. Compost helps to improve soil biodiversity by creating a conducive environment for organisms. Composting involves a series of steps where crop residues are decomposed biologically. For a proper composting process, several factors are controlled optimally. For example, C:N ratio is a vital factor that is optimally kept at 30:1 for an ideal composting process. Moisture content is another important factor that needs to be maintained at ~60% throughout the composting process. The addition of inoculum accelerates the composting process to a great extent. Composting can be performed in many ways. The composting processes can be classified based on the organisms involved such as vermicomposting, microbial composting, and fungal composting. The composting process can be categorized based on the process such as aerobic and anaerobic composting. They can also be categorized based on the spaces used such as onsite composting, offsite composting, vessel composting, tank composting, etc. Vermicomposting is a process by which organic waste is degraded and detoxified by the joint action of earthworms and microorganisms (Domínguez et al. 2010). The conversion product is utilized for agronomic purposes. Vermicomposting is an eco-friendly and cost-effective method and an efficient option to handle solid waste produced in urban settings. It is extremely useful for organic farming which is substantiated by its effect on plant growth. In a recent study on the vermicompost effect on plant growth, vermicompost was found to increase the average commercial yield by 26% (Blouin et al. 2019).

4.5.2 Integrated Pest Management

The use of pesticide invariably develops resistance in pests and cause them to reappear with more vigor. Pesticides may also poison food items and the different niches of the environment. People who deal with pesticides without any protective gear might also be exposed to them. As a result, pesticides may pose health hazards to people directly and indirectly (Yadav et al. 2015). If pesticides could be used judiciously and sustainably following the principles of integrated pest management (IPM), the contamination level could be reduced. IPM is considered an effective and environmentally sensitive approach to eliminate harmful pests without affecting human health and the environment. IPM approaches focus on the use of biopesticides and biofertilizers (Yadav et al. 2015). The IPM strategy makes use of the physical, biological, cultural, and chemical methods to manage pests without compromising the quality of the crop and the integrity of the environment. As such, IPM is aimed at minimizing dependence on synthetic pesticides, switching over to alternatives of low risk, and checking pest menace via better crop management. IPM was recognized as one of the prerequisites for achieving sustainable agriculture in Agenda 21 of the United Nations Conference on Environment and Development at Rio de Janeiro (Weiss 1992).

4.5.3 Biocontrol Agents for Reducing Pesticide Consumption

Biocontrol agents are environmentally benign, and they involve an approach that relies on natural enemies to control the populations of harmful organisms. It can be defined as "the use of natural or modified organisms, genes, or gene products to reduce the effects of undesirable organisms (pests) and to favor desirable organisms such as crops, trees, animals, and beneficial insects and microorganisms" (Cook 1987). This broad definition encompasses all the strategies that are employed to biologically control pests of all types. The approaches use biochemical substances, microorganisms, and substances secreted by genetically modified plants. In genetically modified plants, genetic materials are added into plants which enable plants to secrete pesticidal substances. If these biopesticides are used in combination, they completely obviate the need for synthetic pesticides. Biological control agents are highly target-specific, kill the targeted pests slowly, persist in the environment through secondary cycling. As a result, biological control agents are needed to be applied less frequently. The corollary of this phenomenon is biological control agents being more environmentally friendly and being less hazardous for humans and livestock (Doelle et al. 2009). Biocontrol agents can control pathogens or pests in many ways: they can kill or suppress pathogens and pests by parasitizing them, they can vie for space or nutrients with the pests, they can secrete toxins to kill, and they can trigger a physiological or biochemical change in the host plant rendering it tolerant to pests and pathogen attack. Biological control agents include a variety of organisms and substances. Predators are employed to control populations of pests. Both vertebrates and invertebrates predators are deployed. Included among vertebrates are amphibians and fishes, reptilians, birds, rodents, and mammals. Invertebrates commonly used are spiders and insect herbivores, mites, flies, ants, beetles, dragonflies, and water bugs. Parasitoids, which are parasites that attack other parasites, are deployed to prey on insects. Pathogens, including fungi, bacteria, viruses and virus-like particles, protozoa, nematodes, and earthworms, are also used for killing and controlling pests. Pheromones and botanicals such as plant products/extracts such as nicotine, azadirachtin, sesamin, and sesamolin, etc., are employed to kill and control pests (Kwenti 2017). There are three broad approaches for controlling pests: conservation, classical biological control, and augmentation (Gurr and Wratten 2012). The conservation process refers to practices that foster a conducive environment for natural enemies. Classical biological control involves the introduction of a useful natural enemy into the setting of the target pest, and permanently establishing them so that they can control pests without any human intervention or with minimal involvement. In Tamil Nadu, India, the papaya mealy bug (*Paracoccus marginatus*) was biologically controlled by the introduction of *Acerophagus papaya* (Mani et al. 2012). Augmentation of natural enemies is carried out by environmental manipulation and their periodic releases in the setting (Hoy 2008). The populations of natural enemies are released in enough quantity so that they can keep in check the pest population in a particular area. *Trichoderma* spp., for example, has been used effectively as a biological control agent of plant pathogens and as a plant growth enhancer.

4.5.4 Other Approaches

A number of approaches have been discussed so far. Some other approaches are also effective. One such approach is intercropping. In this method or practice, two or more crops are cultivated in the same space at the same time. Intercropping presents a number of advantages such as better yield, improved soil fertility with the use of legumes, increased soil conservation due to better plant coverage, lessened pest incidence, and suppression of weeds. The requirements of fertilizers and pesticides will be reduced and consequently, the loading of harmful chemicals will diminish in the environment (Baweja et al. 2020). Wheat and maize, for instance, are widely used for intercropping (Baweja et al. 2020).

4.5.5 Green Chemistry

When agrochemicals are manufactured, waste is generated; some of the wastes are more toxic and some less toxic. In the recent past, scientists are emphasizing using green chemistry for manufacturing these agrochemicals. Green chemistry involves changing the protocols of preparation methods and production processes that will minimize or eliminate the use and generation of hazardous chemicals. The advocates of green chemistry outlined some principles which should be followed to move forward with the challenges of agrochemicals (Omran and Negm 2020): (1) It is highly desirable to prevent waste from being generated or disposed of, (2) Preparation methods should be such that most reactors are incorporated into the final product, (3) The manufacturing methods should be selected so that the least toxic substances are being used for reaction, (4) The chemical substances should have the highest efficacy and lowest toxicity, (5) Those reactions should be preferred which do not use solvents or use solvents with the least toxicity, (6) Energy-saving manufacturing should be preferred, (7) Non-renewable materials should be avoided, if possible, (8) Products must be designed so that they do not stay in the environment after their intended functions and biodegrade into benign materials.

4.6 Conclusions

The demand for chemical fertilizers and pesticides is likely to rise as the world population is likely to increase and feeding the extra population will become a global challenge. The people in the underdeveloped countries will be hardest hit if the crop production does not increase significantly. According to a report by FAO, the world population is growing at a breakneck rate of 160 persons per minute, and 70% more food needs to be produced for an additional 2.3 billion people by 2050. To achieve that goal, one basic approach will be the introduction of new and improved crop varieties and the use of various agrochemicals which, in turn, augment nutrient availability to crops as well as protect the crops from existing and emerging pests. Modern agriculture, as a result, has become capital-, chemical-, and technology-intensive. The excessive use of agrochemicals and technology in modern agriculture has resulted in serious environmental degradation in many parts of the world.

It is difficult to determine exactly the impacts of chemical fertilizers and pesticides on the environment and the risks associated with the consumption of agrochemicals-contaminated foods by humans. However, it has been seen from previous studies that the long-term application of pesticides can severely affect soil quality, soil fertility, and consequently, crop productivity by interfering with the biochemical equilibrium in soil. Injudicious long-term application of synthetic fertilizers and pesticides has also led to extensive soil pollution that has adversely affected the soil biodiversity. The soil microbiota has been exposed to an elevated concentration of toxic and persistent chemical fertilizers and pesticides that is undesirably modifying their structural and functional diversity. The fertilizers and pesticides are also affecting agricultural soils by degrading their vital properties such as nutrient contents, predominant soil species, activities of soil enzymes, and many more. Groundwater is also being contaminated by these agrochemicals and as a result, becoming unfit for drinking and other domestic uses. Exposure to pesticides can give rise to both acute and chronic health effects (e.g., neurotoxicity) in humans. The health effects associated with pesticide use are not limited to only a few categories of these pesticide classes. Therefore, further studies should be conducted to determine the toxicity of all the pesticides and efforts should be made to control or eliminate the exposure of humans to these pesticides, wherever possible. Through rigorous research, the contaminations need to be distinguished whether they are specifically tied to chemical fertilizer sortied to pesticides. Organic amendments and biocontrol agents should be prioritized in preserving the overall soil quality and fertility, and for robust sustainable agriculture. As organic amendments are cost-effective as well as environment-friendly options compared to chemical substances, we must move forward with the continued application of organic amendments. More studies are required to better understand the impact of specific agricultural practices, such as organic amendments, crop rotations, tillage, and pesticide use, on soil regenerative capacity. The findings will aid farmers to identify opportunities for improving their production systems.

4.7 Recommendations

Pesticide pollution and the occupational health issues of farmers are major concerns not only in Bangladesh, but also in other developing countries. Adequate measures must be taken to protect human life and the environment from the adverse effects of pesticides. Although the government's long-term goal should be to adopt a more sustainable pest control technique, Bangladesh requires a concerted and targeted response to address the current pesticide usage surge. Considering the Bangladesh's current socio-economic and environmental condition, the government and other concerned regulatory bodies should implement a holistic, systematic, and effective risk management approach to periodically check pesticide residues in fish and vegetable samples in order to avoid, control, and reduce pollution and limit health hazards. As precision and accuracy in pesticide quantification, as well as enhanced safety profiles, are critical for reducing potential negative effects on human health and the environment, respective ministries in charge of the monitoring program must work in tandem with academic institutions to conduct research to that end. It is imperative that major policy thrusts be initiated for introducing stringent pesticide regulation and for their successful implementation to protect the indigent farmers who are solely dependent on their agricultural livelihoods. Sensitizing farmers on the implications of pesticide use is absolutely vital. Because the majority of farmers are illiterate or semi-literate, with no reading skills, pictograms highlighting the environmental dangers of pesticides and human health safety should be devised. To avoid abuse of pesticides, farmers should be informed about the recommended amounts during application. In the final analysis, the foundation of efficient pesticide governance lies in a country's ability to manage pesticides efficiently. Pesticide governance systems must strive toward capacity building in a coherent and assertive manner that connects national policies, laws, and institutions within a conducive environment that allows for their implementation. Recommendations could include not only aligning laws and regulations with international agreements and standards, but also improving the implementation and enforcement of current rules and regulations, as well as registration, and quality control.

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Part III
Treatment or Remediation Technologies

Chapter 5
Environmental Impacts and Necessity of Removal of Emerging Contaminants to Facilitate Safe Reuse of Treated Municipal Wastewaters

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Abstract Contaminants of emerging concern or more precisely, emerging contaminants (ECs) are set of bio-refractory compounds that originate in the water cycle from the technosphere. A more direct pathway is via reuse of treated wastewater that might have residual concentration of ECs that are not easily degraded in the current wastewater treatment practices. In this context, it is pragmatic to firstly understand the pathways of EC release, as well as the physiochemical interactions and transformation of theses ECs in the environment. This understanding of potential impacts can be translated into discharge guidelines for target ECs. This is important, as often variation in discharge standards can dictate the type and degree of treatment required. To understand this stated fact more clearly, this chapter discusses the necessity to undertake removal of the ECs in light of spread and extent of environmental contamination caused by ECs. The advanced oxidation processes that are capable of removal of these pollutants are also being discussed. Thus, attempt has been made to summarize appearance of ECs in aquatic environment, their ecological impacts, and removal methods to produce reusable quality treated water safe for reuse.

Keywords Advanced oxidation processes · Bio-refractory compounds · Emerging contaminants · Environmental contamination · Treated wastewater

5.1 Introduction

Emerging contaminants (ECs) are chemical compounds that as on date have limited or no published health standards and are characterized or recognized by verifiable threats to the environment or human health. Over the past few decades, varieties

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of ECs, mainly of anthropogenic origin were identified and have captured a lot of attention of scientific community due to their harmful impacts on both environment as well as on human health (Lei et al. 2015). These ECs are relatively newly detected pollutants, and hence, a huge gap exists between the knowledge and their fate, effect, behaviors, and identification as well as treatment or removal technology (Gogoi et al. 2018).

Due to the rapid development of industry, transportation, agriculture, and urbanization, release of these chemicals as hazardous wastes that is harmful to the environment is increasing (Rosenfeld and Feng 2011). The ECs may be of vivid origins, such as industrial, agricultural, municipal (domestic), laboratory, hospital wastewater, man-made nanomaterial, and gasoline additives (Fig. 5.1), which are generated from the products, services, and lifestyle prevalent in the modern society (Kroon et al. 2020; Matamoros et al. 2020; McKenzie et al. 2020). To a major extent, the contaminants of emerging concern in question are categorized in four broad groups, namely pesticides and herbicides, pharmaceutical and personal care products (PPCPs), dyes, and industrial chemicals. The presence of the ECs in the environment is alarming owing to the eco-toxicity posed by these chemicals. The route through which these ECs find their way in the environment is majorly via liquid discharges from industry, domestic, and agricultural sources.

The current technologies adopted for wastewater treatment cannot remove ECs; hence, cannot prevent the release of ECs into water bodies. Although, a lot of work has been done on nutrient removal and other categories of contaminant removal, the data availability on ECs, technologies best suitable for their removal, and harmful impacts of these chemical compounds on aquatic life and human health are not concisely documented (da Silva Vilar et al. 2021). At present, highly advanced wastewater treatment technologies are available and are being used for removal of some of the ECs; however, the standardization of design for ECs removal is yet to be achieved.

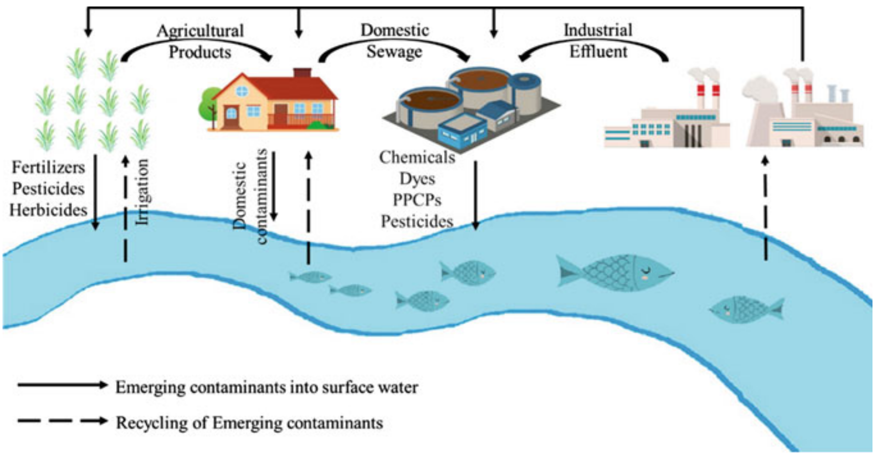

Fig. 5.1 Sources of emerging contaminants

This is majorly due to the diverse physiochemical nature of these ECs that do not allow designing "one-fits-all" approach. Additionally, due to lack of published health standards that may provide the guidelines for acceptable safe concentrations of ECs in treated water and hence deciding the level of removal required, there is no true comparison of the different technologies and the respective efficiencies exhibited by these technologies demonstrated in the past investigations. Such inconsistency in performance results in uncontrolled or inadequately controlled discharge of the ECs into the environment (da Silva Vilar et al. 2021).

Physicochemical wastewater treatment methods that are in currently used, such as screening, sedimentation, flocculation, and coagulation, although have low energy and even in majority cases low-cost footprint, however, these are unable or only partially able to remove PPCPs, pesticides and herbicides, dye, and other ECs. Treatment options commonly considered to remove ECs from drinking water and wastewaters include advanced oxidation processes (AOPs), reverse osmosis (RO), nano-filtration (NF), and adsorption. However, there are limitations associated with these methods in the form of high investment and maintenance costs as well as generation of toxic sludge (Grassi et al. 2012). Among all these treatment processes, AOPs are considered as comparatively more effective and robust for the removal of ECs (Grassi et al. 2012). There are two strategies of AOPs for removal of ECs, such as physical technique and chemical technique. Physical technique is mainly categorized as ultraviolet (UV) radiation and ultrasound treatment; while, chemical species-based AOPs include ozonation, hydrogen peroxide, and generation of other reactive oxygen species (Fast et al. 2017). The chapter highlights the important ECs, their effects, and occurrence in wastewater and environment in the first part. The later part of the chapter discusses the different AOP-based strategies using single or hybrid techniques as reported by earlier investigations.

5.2 Types of Emerging Contaminants of Persistence

The main sources of ECs are pharmaceuticals industries, fertilizer industries, pesticides, herbicides, laboratory chemicals, personal care products, surfactants, artificial sweeteners, cleaning solvents, sun protection cosmetics, etc. As discussed earlier, these ECs are categorized into four types, such as pesticides and herbicides, PPCPs, dyes, and industrial chemicals (as shown in Table 5.1).

5.2.1 Pesticides and Herbicides

Pesticides and herbicides are considered as potentially toxic products used for agriculture, horticulture, aquaculture, and household purposes to control the infections and adverse effect of pests, grass, weeds, fungus, insects, and rodent (Md Meftaul et al. 2020). Use of pesticides and herbicides are very common in agricultural sector

Table 5.1 Classification and sources of ECs

Types of ECs		Sub-types of ECs	Representative ECs	Major sources[a]
PPCPs	Pharmaceuticals	Antibiotics	Penicillin, sulfonamides, tetracyclines	Pharmaceutical industrial effluent, domestic wastewater, hospital effluent, aquaculture effluent, and livestock farms effluent
		Lipid regulators	Ezetimibe, colesevelam, torcetrapib, avasimibe, implitapide, niacin	
		Antidepressant	Citalopram, escitalopram, fluoxetine, fluvoxamine, paroxetine	
		Nonsteroidal anti-inflammatory drugs (NSAID)	Ibuprofen, naproxen, diclofenac, celecoxib, mefenamic acid	
		Anticonvulsants	Acetazolamide, carbamazepine	
		Beta-blockers	Metoprolol succinate, metoprolol tartrate	
		Hormones	Anastrozole, premarin	
	Personal care products	Fragrances (musk compounds)	Tonalide, galaxolide, musk xylene, musk ketone	Domestic wastewater effluent, personal care products industrial effluent, cleaning effluent from all sector
		Sunscreens	Benzophenone-4 (BP-4), 2-phenylbenzimidazole-5-sulphonic acid (PBSA)	
		Beauty products	Lotions, deodorants	
		Cleaning products	Detergents, soap, phenyl	
Pesticides		Fungicide	Calcium polysulfide, carbamate fungicides, carbanilate fungicides	Agricultural runoff, aquaculture effluent, domestic effluent, livestock farms effluent
		Insecticides	Aldrin, chlordane, chlordecone, DDT	
		Molluscicides	Metal salts, metaldehyde, methiocarb	
Dyes		Natural	Jack fruits, turmeric, onion, hina	Textile industrial effluent, domestic effluent, laboratory effluent
		Synthetic	Fast green, picric acid, orange G, oil red O, eosin Y	
Industrial chemicals		Flame retarder	Mineral wool, gypsum boards, asbestos cement	Industrial effluent, domestic wastewater, laboratory effluent
		Plasticizer	Di-ethylhexyl phthalate (DEHP), di-isononyl phthalate (DINP)	

[a]Gita et al. (2017), Mahmood et al. (2016), Rout et al. (2021)

and contain varieties of ingredients having specific chemical and physical properties that inhibits the spread of bacteria, fungi, and other organisms that damages the crop (Rathi et al. 2021). Owing to the toxic biocidal nature of these compounds, these compounds usually affect the pests by blocking its vital metabolic process.

The pesticides and herbicides have its beneficial effects as high agricultural yield and quality as well as reduction in harvest loss. Worldwide, every year almost 3 million metric tons of pesticides are used, which have high toxicological effect on the natural systems (Sharma et al. 2020). Pesticides are source of one of the toxic chemicals to human's health and their consumption for agricultural and other purposes need to be closely monitored. Indoor residential spraying of pesticide, such as di-chloro diphenyl trichloroethane (DDT), is used to avoid spread of vector-born disease like dengue and malaria (Sharma et al. 2020), though in majority countries, it is forbidden. It has been reported that only 0.1% of pesticides that are used reach the target, and remaining portion is washed off and responsible for environmental contamination (Pimentel 1995). The environmental contamination by pesticides mainly happens through its leaching into waterbodies, groundwater, vaporization into air, and plant uptake (Sharma et al. 2020). As these pesticides are applied for various purposes, such as gardening, horticulture, and tree plantations, hence the residual quantities result in various acute and chronic health issues for many people, wildlife, animals, and fish when these contaminants enter the food chain (Campos et al. 2016). Therefore, its effect and target species and environment are the topic of international relevance.

On the basis of origin, pesticides and herbicides are broadly categorized as natural, synthetic, and target organisms. Natural pesticides are the chemicals that are isolated from natural sources like plants or microorganisms and they do not have any toxic effect on mammals as well as they are biodegradable in nature. The most commonly used natural pesticides and herbicides are neem, rotenone, nicotine, and pyrethrum. The pesticides which are synthesized by the modification of chemical compounds are known as synthetic pesticides. Synthetic pesticides are one of the most extensively used pesticides in the world. On the basis of chemical nature, synthetic pesticides are categorized as inorganic and organic synthetic pesticides, the latter being the most stable pesticide in nature (Jayaraj et al. 2016). The target organism pesticides are another type of pesticides, which is effective to only certain kinds of pests (2, 2D effective to broadleaf weeds, it is not harmful to most turf-grasses).

5.2.2 Pharmaceutical and Personal Care Products

The PPCPs are mixture of specific synthetic chemicals, such as antibiotics, painkillers, hormonal drugs, vaccines, nonsteroidal anti-inflammatory drugs, disinfectants, cotton pads, fragrances, shampoo, soap, facial tissue, eye liner, lotion, toothpaste ingredients, facial treatments, and shaving cream, which have been extensively used to improve the standard of living as well as human health (Yang et al. 2017). The biotechnological revolution in the production of PPCPs has led to the major improvement in health sector. However, these products have received attention as unique group of ECs due to their detrimental effect on the environment as well as the human health even at very low concentration (Ebele et al. 2017). The consumption of PPCPs products has increased significantly, many PPCPs are sold without any medical prescription resulting in its presence in various compartments of environment owing to the uncontrolled usage (Rodriguez-Narvaez et al. 2017). The presence of these products in groundwater has become a global concern, as it poses direct impact on human health and aquatic ecosystem (Muir et al. 2017). Although, these products are detected at very low concentration in freshwater, however, many of them are biologically active even at such low concentrations that can impact the non-targeted aquatic organisms, such as fish (Liu et al. 2020).

The physicochemical properties of many PPCPs present in drinking water suggest that they cannot be easily removed by the conventional water treatment method; and therefore poses a potential hazard to environment, specially to human health, and aquatic ecosystem (Snyder 2008). Extensive study of PPCPs removal from water advocate the persistency of these products (Bu et al. 2013). The widespread pattern of the common PPCPs found globally, along with the launch of new drugs in the market, plays a key role in the environmental persistence of these chemicals and the activation of their metabolites in the aquatic environment. However, all PPCPs are not persistent, due to their continual usage and subsequent release into environment makes them persistence, these PPCPs can be considered as “pseudo-persistent.” Pseudo-persistent PPCPs can also show apparent environmental persistency owing to their continuous release in the environment even when past contamination is being acted upon by different degradation processes, such as biodegradation and photodegradation. Therefore, PPCPs that may degrade in environment exhibit apparently persistence because of their continuous release into the waterbodies (Houtman et al. 2004).

The main concern regarding the toxic effect of PPCPs is that these compounds are specifically designed to impact certain targeted cell-signaling, enzymatic or metabolic mechanisms at very low quantity. The PPCPs enter the aquatic environment through wastewater treatment plants, agricultural runoff, and domestic effluent. The toxic effects of PPCPs on aquatic environment and biota are of substantial concern (Kim et al. 2009). Though, these products are designed to function in a targeted mode of action, however, unintentionally these show toxic activity to non-target organisms, such as fish, daphnia, and alga (Fabbri and Franzellitti 2016). Synthetic estrogens commonly used in oral contraceptives, such as endocrine inhibitors PPCP, can affect reproduction system of aquatic organisms even at very low concentrations. Several studies have indicated that exposure of synthetic estrogen to fish has reproductive effects, such as changes in sperm density, gonadal size, decreased egg viability, and male sex changes.

5.2.3 *Dyes*

A natural or synthetic substance used to color or change the color of something is known as dye. Synthetic dyes can be considered as ECs and are potentially toxic when found in aquatic environments. There are no rules and regulations available to state the maximum allowed concentration of dyes in effluent to be discharged in water bodies that ensure the protection of aquatic organisms and humans. Textile effluent discharge has led to the presence of carcinogens in environment that affect the living being. Textile dyes belong to the category of ECs, as it has not been included in environmental quality monitoring and regulatory programs (Torres et al. 2019). These ECs are characterized as water soluble synthetic organic compounds that absorb visible light. The chemical composition of dyes is very complex having compounds or elements of various molecular weights and aromatic structure. Dyes have a wide range of applications, such as in pharmaceutical, food, leather, cosmetics, textile, pulp and paper, wood, paint, and petroleum products (Hernández et al. 2019).

Discharge of dye laden textile effluent of relevant industry without treatment results in huge damage to ecosystem, like depletion of dissolve oxygen that enormously impair the aquatic organisms (Mondal et al. 2017). Additionally, dyes are one of the most photo-chemically stable products and possess carcinogenic, recalcitrant and mutagenic properties and generates acute toxic effect on human health (Tang et al. 2018). Currently, uses of synthetic dyes are increasing tremendously, which has posed research challenges in area of industrial effluent treatment (Sharma and Kaur 2018). Therefore, this research problem requires much more attention for the effective, economic, and specific treatment technology. According to the literature, greater than 10,000 different pigments and dyes are used in industries and around 7×10^5 tons of synthetic dyes are produced around the globe throughout the year (Chaudhary and Violet 2020). However, study suggests that 15% of dyes are lost during production and packaging and 20% of lost dyes comes in the industrial effluent discharge (Kanawade and Gaikwad 2011).

There are number of ways to classify dyes, such as chemical properties, source, application, nuclear structure, color index, nature of chromophore, and interaction with the coloring material and solubility. These can also be classified on the basis of partial charge present on it (cationic, anionic, and non-ionic) in soluble form (Sardar et al. 2021). However, the broad classification of dyes is based on their application, source of dye, i.e., natural or synthetic and their chemical structure as shown in the Fig. 5.2.

5.2.4 *Industrial Chemicals*

The present global ongoing industrial practices are generating enormous amount of ECs having toxic effects on receiving environment, which are being discharged intentionally or unintentionally into the water bodies as well as in atmosphere. Thousands

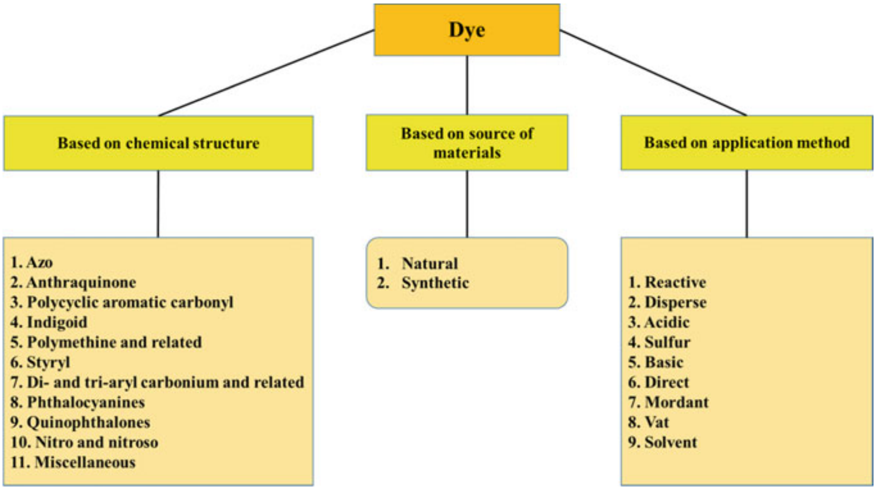

Fig. 5.2 Classification of dyes (Chaudhary and Violet 2020; Sardar et al. 2021)

of compounds are used as intermediate product in the chemical industry, antioxidant, food additives, and surfactants. These compounds also contribute a huge addition in the quanta of ECs that are consequently released into environment as industrial effluents and also through domestic wastewater when these compounds are used. Industrial chemicals such as volatile organic compounds (VOCs) are among the hazardous ECs in groundwater. These VOCs are generally introduced into the environment through different industrial practices. The VOCs that generally found in groundwater includes aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, xylenes, as well as chlorinated solvents like tetrachloroethylene (PCE), trichloroethylene (TCE), and vinyl chloride (VC). These VOCs are considered as potential mutagenic, neurotoxic, genotoxic, and carcinogenic substances. Therefore presence of any or multitude of these in groundwater is matter of concern (Li et al. 2021). Other organic contaminants originating from industrial operations that are found in groundwater are polycyclic aromatic hydrocarbons (PAHs), e.g., naphthalene, chrysene and benzo(a)pyrene. Naphthalene, chrysene, and benzo(a)pyrene found in groundwater are identified as carcinogenic chemicals to human (Abdel-Shafy and Mansour 2016).

The main effect associated with industrial ECs is endocrine disruptor, which alters the function of endocrine system. Some of these are identified to be responsible for serious problem to aquatic life as well as atmosphere. Currently, hundreds of industrial chemicals exhibit estrogenic activity (Harris et al. 1997). These chemicals show high persistency in the environment and in biosphere. The most general industrial chemicals that result in endocrine disruption are polychlorinated alkanes, flame retardants, plasticizers, perfluoroalkylated compounds, antioxidants, and chlorinated solvents (Cranor 2017).

5.3 Occurrence of ECs in Wastewater and Environment

5.3.1 Occurrence of ECs in Effluent Treatment Plant

Occurrence of EC in effluent treatment plant has been detected as early as 1970s, and with the advent of more sophisticated analytical techniques, more and more ECs have been identified and listed. The list includes hormones, pharmaceuticals and personal care products, biocidal compounds, pharmaceutically active compounds, antibiotic resistant genes, etc., which qualify as ECs. The United States Environmental Protection Agency (USEPA) defines the ECs as compounds of synthetic or natural origin that are considerably new and are harmful toward environment as well as different organisms (Rout et al. 2021). Hence, the scope and definition of ECs are an ever-morphing domain, which requires a multidisciplinary vigilant and continual scanning. The primal source of EC contamination in the environment is the liquid and the solid discharges from the sewage/effluent treatment plants (STP/ETPs) (Kasonga et al. 2021). This, however, does not include the non-point discharge from the surface runoff directly to inland water bodies and percolation in the groundwater table. As the STP/ETPs play a functional role in the accumulation, partial removal and discharge of the ECs to the environment, hence discussion on the present status of the EC occurrence in the liquid as well as the biosolids discharge of the STP/ETPs is per se important.

5.3.1.1 Occurrence of EC in Wastewater Treatment Plant Effluent

The occurrence of EC in the wastewater treatment plant ranges between ng/L and μg/L concentration. As mentioned earlier, the ECs cover a vast range of natural as well as synthetic compounds that are not biodegradable. For example, an investigation carried out in the Kavoor wastewater treatment plant located in the Mangalore city in the state of Karnataka in India indicated presence of nonsteroidal anti-inflammatory drugs in high concentrations (Thalla and Vannarath 2020). Five drugs, namely diclofenac, naproxen, ibuprofen, ketoprofen, and acetylsalicylic acid were reported to be present in the highest concentration of 721.4, 2132.5, 2109.9, 2747.3, and 2213.4 μg/L, respectively, in the effluent of Kavoor treatment plant having a capacity of 43.5 million liters per day (Thalla and Vannarath 2020). In a more extensive investigation carried out in China, grab samples from two domestic wastewater treatment plants exhibited presence of more than 45 synthetic compounds (Huang et al. 2020). Notably, presence of ketamine, a controlled drug in different Asian and European countries, was detected at high concentrations (930 ng/L) along with other pharmaceutical compounds such as ibuprofen (900 ng/L) (Huang et al. 2020). In addition, toxic and/or carcinogenic compounds, such as bisphenol-A (5000 ng/L), TMDD (2,4,7,9-tetramethyl-5-decyne-4,7-diol, no.4; 1200 ng/L), caffeine (20,000 ng/L) and chlorinated compounds such as climbazole (1100 ng/L), were also detected. It is interesting to note that the occurrence of the reported contaminants in the influent and post biological treatment was comparable. This demonstrated that the biological processes are incapable of oxidizing/metabolizing such recalcitrant compounds. In comparison, concentrations of certain compounds were attenuated post UV treatment. The effect of such tertiary advanced oxidation process is discussed in detail in Sect. 5.4.1.

In European context, contaminants such as caffeine (26.11 μg/L), theobromine (39.28 μg/L), theophylline (49.05 μg/L), and amoxicillin (3.14 μg/L) were detected in the effluent of a Spanish wastewater treatment plant (Egea-Corbacho et al. 2019). The investigation further established successful removal of the aforementioned compounds by nanofiltration. In a different investigation that involved modeling the fate of ECs in a wastewater lagoon system treating 400 million liters daily, six ECs, namely 2,4-dichlorophenoxyacetic acid, caffeine, carbamazepine, diuron, simazine, and sulfamethoxazole, were identified. Investigations focusing on removal of EC from wastewater often report in tracing the fate of the ECs in sludge as collateral research finding. While understanding the fate of the ECs in the liquid discharge of the ETP, it is imperative to understand the contribution of sludge adsorption of the ECs as in such case the scenario may not be considered as a removal via degradation and rather a phase transition owing to the physiochemical property of the pollutant in question. In general, factors such as molecular weight of the compound, acid solubility (pK_a), and the octanol–water partition coefficient (K_{ow}) play a role in deciding this fate. While the pK_a decides the surface charge of the compound, the K_{ow} defines the ratio of the solute that can be present in two immiscible solvents (in this case octanol and water). In other words, K_{ow} is a measure of the lipophilicity of the compound. As a thumb rule, compounds with higher K_{ow} are more prone to be adsorbed in sediment and biosolid phase in natural water bodies and wastewater treatment plant sludge, respectively.

For example, the concentration of ibuprofen was found to be 14.6–31.3 μg/L in wastewater stream and in the range of 741 ng/g of dried sludge from samples collected from a wastewater treatment facility treating 42 million liters per day (Radjenović et al. 2009). Similar trend of higher accumulative tendency in sludge was noticed for ofloxacin, which was measured in the range of 0.89–31.7 μg/L in wastewater and 380.7 ng/g in dried sludge. However, several other ECs were detected in the wastewater stream in addition to ibuprofen and ofloxacin that were undetected in sludge. For example, lipid regulators gemfibrozil (2.0–5.9 μg/L) and bezafibrate (1.9–29.8 μg/L), β-blocker atenolol (0.84–2.8 μg/L), hypoglycemic agent glibenclamide (0.12–15.9 μg/L), and a diuretic hydrochlorothiazide (2.3–4.8 μg/L) were detected in wastewater stream. The removal of the detected ECs from the liquid stream was hypothesized to be occurring via sorption process while a minor removal was via oxidative metabolic pathways in the aforementioned case study. The above discussion indicates that the occurrence of different ECs in sludge has to be detailed in order to attain a holistic picture.

5.3.1.2 Occurrence of EC in Treatment Plant Sludge

As mentioned earlier, the adsorption and occurrence of different ECs in the sludge are governed by the K_{ow} coefficient for the same. The K_{ow} is not only a physiochemical parameter that differs for compounds of different chemical groups, but may also vary for the compounds that belong to homologous groups. A prominent example would be the difference between bisphenol-A (BPA) and its analogs that are presently being manufactured and utilized as a substitute product of BPA. It has been observed that BPA has higher occurrence in the wastewater sludge as compared to bisphenol-S or bisphenol-F (Hu et al. 2019).

A common group of xenobiotic compounds that are recurringly reported to be present in sludge worldwide are antibiotic and anti-inflammatory drugs or their derivatives. The concentration of antibiotics like ciprofloxacin and azithromycin was estimated to be in the range of 500–600 ng/g of sludge (Benedetti et al. 2020) in a particular investigation carried out in Italy. The presence of antibiotics not only reduces the value of the sludge for reuse but also induces modifications in the microbiota present in the sludge, thereby affecting further bioprocessing of the sludge. In an investigation, it was reported that the bacterial community structure changed in presence of the antibiotic sulfamethoxazole (Kang et al. 2018). In addition to altercations in the bacterial community structure, the exposure to antibiotics for prolonged period aids the formation of antibiotic resistant genes (ARG) among the exposed bacterial species. Interestingly, these ARGs can be further transmitted to other bacteriological species via horizontal gene transfer, which is reported to further increase the immunity of different bacterial species toward prevalently used antibiotics (Kim et al. 2014).

In addition to antibiotics, organotin compounds that are widely used as biocidal compounds were also found to be present in sewage sludge in the concentration of 18 mg/kg of sewage sludge. It was further reported that the target organotin compound tributyltin underwent minimal degradation during anaerobic digestion of the sludge as a post processing step in sludge management (Voulvoulis and Lester 2006). Similar to organotin, triclosan and triclocarban were also examples of biocidal agents that were found in high concentration in the sludge. Concentrations of triclosan and triclocarban were reported to be 0.61 and 0.08 mg/kg of sludge (Healy et al. 2017). The investigation further reported wash-off of the adsorbed biocides in surface runoff when the sludge was applied as a biosolid in the agricultural fields. However, as the concentration of both biocides were low in the agricultural runoff, hence the re-entry path of these compounds in the water cycle was not confided clearly.

It can be observed that several contaminants of emerging concern were found to be present in sewage sludge with majority cases leading to contamination of the environment that comes in contact with the sludge. Another issue of concern toward the presence of ECs in the sludge is the induced changes in genetic structure of the bacteriological species present in the sludge, which is anticipated to enhance the resistance of these bacterial species toward these biocidal and antibacterial agents. Partitioning of the compounds into sludge from the liquid phase is hence an apparent benefit and any further disposal/usage of such contaminated sludge would require extensive investigation to determine the concentration and fate of the adsorbed ECs in sludge. The concentration of different contaminants presents in sludge not only depends on the physiochemical properties of the compound, namely hydrophobicity, molecular weight, pK_a, water solubility, and resistance to biodegradation, but are also largely dependent on the sludge characteristics, such as pH, organic matter, and cations concentration. Hence, for future agricultural applications of sludge as biosolids, it would require detailed investigation on case specific basis to understand the ecological viability.

5.3.2 Occurrence of ECs in Environment

The occurrence, fate, and transmission of ECs in the environment depend on several factors, such as physicochemical profile of the compounds, their sources, climate condition, available sewage or water treatment method, and characteristics of water. India is 2nd most populated country in the world, and studies on ECs in aquatic environment in India suggests that out of the total ECs occurrence that are found in the water bodies the break-up are 57% pesticides, 17% pharmaceuticals, 15% surfactant, 7% personal care product, and 5% phthalates (Gani and Kazmi 2017). Several case studies advocate the present of ECs in water bodies, such as pesticides, PPCPs, endocrine-disrupting chemicals (EDC), and artificial sweeteners (ASW).

5.3.2.1 Occurrence of EC in River Sediment and Transformation

In river systems or during wastewater treatment processes, the partition of ECs mainly occurs between aqueous phase and sludge and sediments. The degree to which this partition of ECs occur depends on the physicochemical properties of individual compounds, environmental factor, and composition of sludge and sediments. Some ECs show long persistency by transforming into new ECs. The main source of ECs in river sediments is of municipal, agricultural, and industrial origin. The municipal wastewater is treated in domestic wastewater treatment plant (WWTPs), however, these WWTPs are primarily designed to remove organic matter, suspended and flocculated particles, nutrients, and to some extent pathogens. The WWTPs are not capable of removing micro-contaminants that are the source of major ECs. Although, wide variety of advanced treatment options are available to remove these macro-contaminants, most of the municipal WWTPs typically use secondary biological processes, such as activated sludge processes, which are capable of removing only a fraction of the emerging contaminants. Therefore, WWTPs effluent is considered as major source of ECs to river sediments.

The occurrence study of ECs was conducted, where 16 target compounds including PPCPs and hormones have been detected in Yamuna River in India from the samples collected from 13 locations spanning 575 km along the main river as well as from the meeting point of Hindon river and Hindon canal. The mean concentration of target compounds was in the range of 25.5–2187.5 ng/L. The highest concentration was found to be for trimethoprim (8807.6 ng/L) during summer, followed by caffeine (6489.9 ng/L) and gemfibrozil (2991 ng/L) in post-monsoon. The estrone (10.7 ng/L) exhibited lowest concentration for the summer period. In summer, the river bed dries up, which causes the adsorption of chemical compound on the river sediments (Biswas and Vellanki 2021). In another study of river Riva that flow across Udaipur city of India, the concentration of ECs mainly pharmaceuticals, such as carbamazepine, antibiotics and nonsteroidal anti-inflammatory drugs, was found to be similar to high income countries as high as 1900 ng/L. The concentration of steroid estrogens, steroid androgens, benzotriazoles, DEET, BPA, and caffeine was detected up to 124 ng/L, 1560 ng/L, 11 μg/L, 390 ng/L, 300 ng/L, and 37.5 μg/L, respectively, which were similar to previously reported chemical concentration in wastewater of high income area (Williams et al. 2019).

The occurrence of the ECs in river sediment is a function of amount of EC received in the system, the degree to which biotransformation occurs, and other physiochemical factors, such as sorption/desorption from media, and also chemical transformation due to redox reactions. Transformation of contaminants in river sediments mainly takes place due to different biotic and abiotic process like hydrolysis, photolysis, oxidation, and microbial metabolism. The transformed contaminants those are biologically active and resistant to biodegradation are considered as ECs (Picó and Barceló 2015). Transformation of ECs by the process of biodegradation that takes place in the river sediments depends on the environmental factors, such as pH, temperature, nutrient availability, salinity, and river flow (Wilkinson et al. 2017).

The photochemical transformation of organic contaminants in river environment takes place by direct solar radiation as well as indirectly via reaction with photosensitized species. In both the mechanisms, solar energy is used directly or indirectly to breakdown strong covalent bond of complex contaminants into simpler compounds (Richard and Canonica 2005). In direct photochemical transformation, the reaction mechanism involves non-reversible bond cleavage or rearrangement of organic molecule by exposure of energy from sunlight in the water environment. The indirect photochemical transformation pathway is mediated by the chromophoric components present in aquatic environment, which are capable of being photo-stimulated by solar radiation. The excited energy generated by this photo-stimulation is then passed on to organic compounds breaking chemical bonds to degrade the molecule (Richard and Canonica 2005).

The rate photochemical degradation of ECs such as PPCPs in water sediments is the combined effect of both direct and indirect photo transformation. Direct degradation via absorption of solar radiation as well as simultaneous indirect oxidation by H_2O_2 was identified as the major pathway for phenol degradation into methanoic acid and oxalic acid in water (Wu et al. 2001). Some PPCPs may degrade by only one photo degradation pathway, photo degradation of cimetidine takes place by indirect photo degradation pathways by reacting with singlet oxygen species (Latch et al. 2003). Since degradation mechanism differs for different compound or contaminants, hence, to advocate the process of degradation case-by-case investigation is essential to be conducted.

5.3.2.2 Occurrence of EC in Aquatic Life and Bio-assimilation

Aquatic life is the largest ecosystem that is the habitat of different flora and fauna including fish, aquatic wildlife, amphibians, plants, and other biota. ECs in aquatic life pose a potential threat to the aquatic organisms inhabiting there. Each day varieties of ECs are being identified and the most common ECs are micro-plastics, trace metals, different pesticides and herbicides, nanomaterials, and PPCPs. The main source of these ECs in aquatic life is land-based including runoff from agricultural source, surface runoff, and WWTP discharge. Long-term presence of these ECs in aquatic environment may result in more toxic form by the transformation upon liability to diverse climatic condition, such as pH, temperature, sunlight, and salinity. The transformed ECs get accumulated in the food chain and affect the entire ecosystem (Srikanth 2019). Although the pharmaceuticals are designed for specific metabolic function to target human and animal, its entrance in aquatic environment starts unexpected effect to non-target organisms.

Bio-assimilation is considered as hazardous phenomena, which has a long-term effect sometimes recognized in a later phase of life. The bio-assimilation also has multigenerational effects, and as the bio-assimilated concentrations are higher for each trophic level in the food chain, hence the adverse effects can be more hazardous in higher members of the food chain (van der Oost et al. 2003). The thumb rule for the ability to bio-assimilation of any substances proposed that substances having octanol–water partition coefficient (log K_{ow}) values higher than or equal to 3 show bio-assimilation in biological tissue (Huerta et al. 2012).

In a recent study of bioaccumulation 16 emerging chemicals in tissue of *H. Tubulosa* in a marine echinoderm was investigated, the investigation suggested that most of the ECs sediment–water distribution coefficients (log K_d) were in the range 0.78–2.95. In the same study, bioaccumulation factor (BAF) was calculated, and for most of the compounds, the Log BAF > 1 was obtained (Martín et al. 2020). Bioaccumulation behavior of halogenated flame retardant (HFRs), synthetic musks (SMs), organochlorine pesticides (OCPs), and polychlorinated biphenyls (PCBs) in plankton, fish, and invertebrates was investigated in an urban catchment of Singapore. The K_{ow} values were obtained in the range of 10^3–10^{11} (Wang and Kelly 2018). In another investigation, bioaccumulation of organophosphorus plastic additives (OPPAs) was investigated in wildlife fish (7 consumable fish species) of the Pearl River system, China. In the same investigation, Tris(2-chloropropyl) phosphate was identified as major compound with the median concentration of 18.8 ng/g lipid weight. The log BAF values for most of the OPPAs were identified in the range of 1.2–3.3 in this investigation (Peng et al. 2021).

5.3.2.3 Occurrence of EC in Fresh and Marine Water

Groundwater is the major source of fresh water and a large population of world uses groundwater for drinking purpose. However, in past decades, ECs were identified in groundwater as well, particularly the developing countries are most affected

(Mekonen et al. 2016). Generally, the concentration of PPCPs in groundwater is expected to be lower than any other sources of surface water. However, many studies suggest that groundwater is not safe to drink anymore if ECs are present. In a groundwater analysis for ECs in Chandigarh of India, 54 samples were taken to analyze suitability for potability. The limit detection of endosulphane and hexachlorohexane was identified 1.0×10^{-3} and 2.4×10^{-3} mg/L, respectively, (Vashisht et al. 2020). In some investigations, concentration of ECs, such as pesticides and pharmaceuticals, in groundwater was found to be similar to that of surface water (Olaitan et al. 2017; Vashisht et al. 2020). Maximum concentration of ECs of pharmaceutical origin was found to be 18 µg/L (paracetamol) and 4 µg/L (ibuprofen) in groundwater and treated water of Nigeria (Olaitan et al. 2017). Again in Kenya, relatively high concentration of nevirapine (1.6 µg/L) was reported in groundwater (K'oreje et al. 2016).

Similar to groundwater and other surface water bodies, marine water is also reported to be contaminated by ECs of different origin. In an investigation of 58 ECs were found in the surface water of the Western Mediterranean Sea, in which 70 samples were taken from 10 different sampling sites. In this investigation, 11 types of PPCPs, 3 types of pesticides, and 2 types of artificial sweeteners were detected. Among all these ECs, pharmaceuticals, caffeine, carbamazepine, naproxen, paracetamol, antibiotic sulfamethoxazole, antibacterial triclocarban, artificial sweeteners acesulfame, and saccharin as well as the herbicide terbuthylazine were identified in all the analyzed samples. In the same work, the highest concentration of saccharin (up to 5.23 ng/L) was detected (Brumovský et al. 2017).

5.4 Advanced Oxidation Strategies for Removal of ECs

5.4.1 Application of Physical Techniques

5.4.1.1 Ultraviolet Radiation

Ultraviolet advanced oxidation process (UV-AOP) is a versatile advanced processing technique used for simultaneous neutralization, photolysis, and oxidation of target chemicals in water and wastewater treatment systems. Use of UV ray's irradiation as AOP is a time-tested method that has been documented in scientific research and has been applied to several field-scale applications (Darby et al. 1993; Kang et al. 2004; Lindenauer 1994). The UV ray is the form of electromagnetic energy having wavelength in the range of 200–400 nm. Depending on wavelength, UV can be categorized as UVA, UVB, and UVC whose wavelength ranges are 320–400 nm, 280–320 nm, and 200–280 nm, respectively. The UVC is absorbed by the dissolved organic matter present in wastewater, which causes DNA damage, thus resulting in deactivation of bacterial cells (Amin et al. 2010; Gray 2014). The UVB is also capable of DNA damage of any bacterial cells with relatively milder extant than UVC radiation (Kim et al. 2013). The xenobiotic compound degradation takes place either by ROS activation, when photocatalyst releases electron from valance band absorbing UVA radiation or by simply lysis due to UVC radiation.

5.4.1.2 Ultrasound

Among the physical techniques, ultrasound (US) is used for remediation of wastewater contaminated with ECs either by coupling with other AOPs or as a standalone unit. The mechanisms of US can be understood by their vibrational function, where US enables the formation and collapse of micro-bubbles created by the compression and rarefaction of ultrasonic wave (Camargo-Perea et al. 2020). Due to the continuous collapse of micro-bubble, formation of high heat of several thousand kelvin as well as high pressure of almost 1000 atmospheric pressure occur (Mahamuni and Adewuyi 2010). However, implementation of this process as AOP is costly and to overcome this cost bottleneck, hybrid systems that involve coupling of US with other available techniques are used (Adewuyi 2005a, b). For example, the cost of removal of trichloroethane (TCE) from 3785 L of wastewater was estimated as 25$ with a hybrid US-UV system and as 91$ when single US-based AOP was implemented (Mahamuni and Adewuyi 2010).

5.4.2 Application of Chemicals Techniques

5.4.2.1 Ozonation

Ozone is highly reactive unstable gas composed of 3 oxygen atoms and is used as disinfectant as it has ability to lyse the bacterial cells. It also has oxidizing tendency to oxidize organic compounds present in the water. The oxidative mechanism using O_3 follows direct and indirect oxidation of target compounds present in the water. In direct oxidation, the target compound (R) is directly oxidized by O_3 molecule (Eq. 5.1), whereas in indirect oxidation pathways, the target compound is oxidized by secondary reactive oxygen species such as $HO_2^{\cdot}$ (Eq. 5.2) and $^{\cdot}OH$ (Eq. 5.3) (Rice 1996). The end and intermediate product formed in these direct and indirect mechanisms are different (Rice 1996).

$$R + O_3 \rightarrow R_{\text{oxidised}} \tag{5.1}$$

$$O_3 \rightarrow HO_2^{\cdot} + R \rightarrow R_{\text{oxidised}} \tag{5.2}$$

$$O_3 \rightarrow {}^{\cdot}OH + R \rightarrow R_{\text{oxidised}} \tag{5.3}$$

For better efficiency of ozonation as AOP method, there are various design parameters that should be taken into consideration. Some important parameters out of them are hydraulic retention time, quantity of ozone dose transferred, and composition of wastewater (Xu et al. 2002). Other factors associated with this method is that O_3 cannot be stored, therefore on-site production is required that makes it a costly method. The on-site production of O_3 can be done either using an ozone generator that is fed by an oxygen source or an oxygen concentrator (Rekhate and Srivastava 2020). In a past investigation, a novel approach was adopted by the generation of ozone at high pressure and voltage via electrolysis of water (Tanner et al. 2004).

Ozone is potentially hazardous compound, because it is a compressed gas, strong oxidizing agent and can produce carcinogenic by-products. Concentration of O_3 more than 23% is highly explosive. Ozonation can remove almost 90% of ECs in wastewater, therefore this method is considered as one of the best methods for ECs removal. However, hybrid method in conjugation of ozonation is more favored because hybrid method is comparatively more effective and sustainable.

5.4.2.2 Hydrogen Peroxide

Hydrogen peroxide is considered as a safe, abundant, and easy to implement chemical reagent, widely used as oxidative agent as well as disinfectant. The application of H_2O_2 as AOP relies on its ability to produce ROS from its dissociation into either two hydroxyl radicals (Eq. 5.4) or one hydroperoxyl radical ($HO_2^{\cdot}$) and one proton (Eq. 5.5). These ROS have ability to oxidize dissolve organic matter as well as disinfect the water. However, the self-dissociation of H_2O_2 is very slow and has to be accelerated to enhance the ROS yield. To increase the ROS yield or H_2O_2 dissociation catalyst Fe is introduced that catalyze the H_2O_2 dissociation (Wang et al. 2017; Xu et al. 2020). In presence of Fe^{+2}, the H_2O_2 is dissociated into two OH radicals, by oxidizing Fe^{+2} to Fe^{+3} (Eq. 5.6). The ferric ions thus generated are further reduced to Fe^{+2} while dissociating the H_2O_2 to $HO_2^{\cdot}$ and H^+ (Eq. 5.7). This is known as Fenton's reaction and the Fe along with H_2O_2 is popularly known as the Fenton's reagent (Fenton 1894).

$$H_2O_2 \rightarrow 2^{\cdot}OH \tag{5.4}$$

$$H_2O_2 \rightarrow HO_2^{\cdot} + H^+ \tag{5.5}$$

$$H_2O_2 + Fe^{+2} \rightarrow {}^{\cdot}OH + OH^- + Fe^{+3} \tag{5.6}$$

$$H_2O_2 + Fe^{+3} \rightarrow Fe^{+2} + {}^{\cdot}OOH + H^+ \tag{5.7}$$

The Fenton's-based process is considered as a promising approach, however, formation of $Fe(OH)_3$ sludge in the treatment process limits its application. To overcome this limitation, electro-Fenton could be implemented (Petrucci et al. 2016).

5.5 Hybrid Systems for Augmentation of Performance

The above discussion indicates that the individual success of AOPs, such as UV, H_2O_2, O_3, or US may be limited, however, its efficiency in terms of energy usage and operating expenditure can be improved if these are merged into a single stage AOP (Lado Ribeiro et al. 2019). These processes that rely on two or more stage AOPs hydraulically connected or integration of two or more AOPs into a single chamber are known as hybrid AOPs. This hybrid AOPs can be advantageous in some instances, such as it can increase the treatment efficiency as well as it can be operated at a lower cost than individual unit to achieve similar efficiency. In a study, it has been observed that using a US/O_3/UV hybrid system, the cost of removing phenol from 3785 L of wastewater was \$ 89, while the cost was \$ 15,536 for the same removal efficiency with US as the sole AOP (Mahamuni and Adewuyi 2010).

5.5.1 O_3-UV Advanced Oxidation Systems

The O_3-UV is a viable hybrid approach that has been studied in many investigations as a disinfectant technique (Shi et al. 2021) as well as for oxidation of organic compounds (Malik et al. 2020). In an investigation, it was observed that using ozone as a single unit required a ozone dose concentration of 5 mg/L and a contact time of 10 min for a 5.3-log inactivation of microorganisms, however, in the same study using O_3-UV integrated system, an ozone dose concentration of 3 mg/L and a UV dose of 20 mJ/cm^2 resulted in a 6-log scale inactivation (Shi et al. 2021).

In O_3-UV hybrid system, the organic matter oxidized by O_3 reduces the turbidity of the effluent that has equivalent UV transmittance at lower dose. In O_3-UV, the UV radiation dissociate dissolved O_3 to form hydroxyl radicals that have higher oxidation potential (2.8 eV). The O_3 absorbs radiation of wavelength 254 nm as it has a high molar extinction coefficient 3300/mol.cm. In the presence of UV radiation, O_3 attains excited state, and in the presence of H_2O, this excited O_3 is capable of producing H_2O_2 that further dissociates into $^{\cdot}OH$ (Eqs. 5.8 and 5.9), which has higher oxidation potential (Peyton and Glaze 1988). It is to be noted that the theoretical yield of $^{\cdot}OH$ is higher for UV radiation assisted photolysis of O_3 (67%) as compared to peroxone-based theoretical yield (equimolar mixture of H_2O_2 and O_3, yield-50%).

$$O_3 + H_2O \xrightarrow{hv} H_2O_2 + O_2 \tag{5.8}$$

$$H_2O_2 \xrightarrow{hv} 2^{\cdot}OH \tag{5.9}$$

5.5.2 O_3-H_2O_2 Advanced Oxidation Systems

The combination of O_3-H_2O_2 hybrid process is also known as "peroxone." Presence of $^{\cdot}OH$ in peroxone plays the main role for the oxidative treatment of ECs as well as disinfection of wastewater. In this system, chemical reaction between HO_2^- and O_3 produces HO_5^- (Eq. 5.10), again HO_5^- dissociate to form $HO_2^{\cdot}$ and $O_3^{\cdot-}$ (Eq. 5.11), further $HO_2^{\cdot}$ dissociates into H^+ and $O_2^{\cdot-}$ (Eq. 5.12), this $O_2^{\cdot-}$ reacts with O_3 to produce O_2 and $O_3^{\cdot-}$ (Eq. 5.13). Then, the $O_3^{\cdot-}$ produced in (Eq. 5.11) and (Eq. 5.13) dissociate into O_2 and $O^{\cdot-}$ (Eq. 5.14). Further, this $O^{\cdot-}$ reacts with H^+ to form $^{\cdot}OH$ (Eq. 5.15). Thus, entire chemical reaction can be summarized as the dissociation of HO_5^- is the primary step to generates $HO_2^{\cdot}$ and $O_3^{\cdot-}$, these both intermediate species end up as $^{\cdot}OH$ radical. The associated empirical equations are given in Eq. 5.10 through Eq. 5.15. In accordance with the IUPAC convention, the equations are represented in the direction of reduction.

$$HO_2^- + O_3 \rightleftharpoons HO_5^- \quad (5.10)$$

$$HO_5^- \rightleftharpoons HO_2^{\cdot} + O_3^{\cdot-} \quad (5.11)$$

$$HO_2^{\cdot} \rightleftharpoons H^+ + O_2^{\cdot-} \quad (5.12)$$

$$O_2^{\cdot-} + O_3 \rightleftharpoons O_2 + O_3^{\cdot-} \quad (5.13)$$

$$O_3^{\cdot-} \rightleftharpoons O_2 + O^{\cdot-} \quad (5.14)$$

$$O^{\cdot-} + H^+ \rightleftharpoons {}^{\cdot}OH \quad (5.15)$$

Theoretically, two moles of $^{\cdot}OH$ should be recoverable from two moles of O_3 and one mole of H_2O_2, however, the typical yield of $^{\cdot}OH$ is half that of the theoretical yield as predicted by the stoichiometric equations (Eqs. 5.10–5.15). This loss can be understood by the fact that another parallel dissociation reaction of HO_5^- occurs that dissociates into $^3O_2$ (triplet state of oxygen, the most common and stable allotropic state of oxygen) and OH^- scavenges ½ of the total HO_5^- available (Eq. 5.16).

$$HO_5^- \rightleftharpoons 2\,{}^3O_2 + OH^- \quad (5.16)$$

Though, the application of peroxone for wastewater treatment is highly affected by this parallel chemical reaction (Eq. 5.16), however, the cost of peroxone process is lower than O_3-UV systems and the yield of $^{\cdot}OH$ is only 50% as compared to O_3-UV process that can generate 67% of the theoretical yield, making this hybrid system superior. Additionally, peroxone process has been identified in many investigations as effective for removal of different xenobiotic compounds. In an investigation evaluating performance of peroxone versus ozonation, it was observed that the peroxone process could reduce the ozone dose requirement by 36% as compared to single ozonation unit for the effective reduction of ozone-resistant micropollutants, namely acetamiprid, atrazine, and ibuprofen from wastewater. Same investigation also suggests that due to reduced ozone requirement, even after considering the energy equivalent for the H_2O_2 production, a reduction of 21% in energy requirement could be achieved in case of peroxone process as compared to ozonation (Cruz-Alcalde et al. 2020).

5.5.3 UV and Cl_2 Integrated Advanced Oxidation Systems

The hybrid system UV-Cl_2 is identified as relatively more efficient as compared to UV system because in this hybrid system, reactive chlorine species (RCS) also generates in addition to ROS. The UVA radiation cause the photolysis of Cl_2 that resulted as RCS species generation along with ROS and therefore enhance the degradation of otherwise refractory micropollutants in the wastewater. The chemical reaction mechanisms in this hybrid system can be understood by the chemical Eq. 5.17 through Eq. 5.22.

$$HOCl/OCl^- \xrightarrow{hv} {}^{\cdot}OH/O^{\cdot -} + Cl^{\cdot} \tag{5.17}$$

$$Cl^{\cdot} + Cl^- \rightleftharpoons Cl_2^{\cdot -} \tag{5.18}$$

$${}^{\cdot}OH + HOCl \rightarrow ClO^{\cdot} + H_2O \tag{5.19}$$

$${}^{\cdot}OH + OCl^- \rightarrow ClO^{\cdot} + OH^- \tag{5.20}$$

$$Cl^{\cdot} + HOCl \rightarrow ClO^{\cdot} + H^+ + Cl^- \tag{5.21}$$

$$Cl^{\cdot} + OCl^- \rightarrow ClO^{\cdot} + Cl^- \tag{5.22}$$

The liberation of ROS and RCS in the chemical reactions of this system occurs in two reactive stages. In the 1st reactive stage, photolysis of Cl_2 generates ${}^{\cdot}OH$ and $Cl^{\cdot}$ as primary ROS and RCS, respectively (Eq. 5.17), however, in 2nd reactive stage, $Cl_2^{\cdot -}$ and $ClO^{\cdot}$ are liberated as secondary RCS (Eqs. 5.18–5.22).

The Cl_2-UV sequential system can be considered as advantageous due to the formation of RCS with high redox potential as well as it has been identified as increased genotoxicity of the effluent. It has also been observed that toxic by-products are formed on degradation of hydrochlorothiazide. Few of these by-products are reported even more toxic than the hydrochlorothiazide (Mansor and Tay 2020). However, these toxic by-products were formed during chlorination as well as during Cl_2-UV oxidation of hydrochlorothiazide. Moreover, the oxidation efficacy of the Cl_2-UV process was higher than the single chlorination. The limitation associated with single chlorination system is the formation of chloramines and further derivatives of chloramines. This limitation can be reduced using UV-Cl_2 sequential system that inhibits the bacterial activity by UV irradiation, thus enabling to a more ready reaction between Cl and the bacterial cell (Zhang et al. 2015). Therefore, Cl_2-UV can be considered as more advance process for wastewater treatment than UV or chlorination.

5.6 General Discussion

The presence of ECs in natural environment and the wastewater treatment plants indicates that the effective management and removal of ECs from the wastewater streams are essential, which is the main point source of EC discharge. The presence of ECs is not only alarming for the human health but it is also detrimental toward the ecological balance as the ECs cause drastic changes in the structure of the bacteriological community of the contaminated medium. Moreover, biocidal and antibacterial agents are aiding in development of antibiotic resistant genes in the microbes, which is also alarming from clinical health point of view. In addition, the physiological changes in the different aquatic species are leading to the deformation and destruction of the biodiversity as several species are demonstrating teratogenic and mutagenic effects on exposure to heightened concentration of ECs.

In recent past, the European Commission had emphasized on replacement of different industrial and synthetic products with different biogenic products under the sustainable development goals set under the 7th framework program (FP-7). The FP-7 program clearly talks about the development of different organic-based products for the replacement of such industrial and synthetic products. One of the advantages of such product development would be attainment of easy mineralization of the residual concentrations of the target products using bioremediation itself. Furthermore, prior to discharge of treated effluents, removal of ARGs is also pre-requisite as the discharge of such ARGs into natural water system would facilitate mass scale gene transfer and modification of the wild strains found in river sediments and river water.

The application of AOPs for the removal of ECs is a robust and effective technique that should only be adopted when the operation is aided by vigilant monitoring of the fate of these compounds. Two stage AOP combinations, preferably chemical dosing followed by a physical perturbative technique, such as UV or ultrasound would render the added advantage of higher removal of ECs owing to enhance ROS generation due to the downstream physical AOP. The removal of EC is presently a major concern from both liquid as well as solid phase.

5.7 Recommendation

Presence of ECs in environment, especially in waterbodies, is challenge for present and future generation. The ECs can be divided in three group such as the compounds recently introduced into the environment; compounds that are present in the environment for which there is not much information available; and the compounds that are well known and their adverse effects on ecosystem as well as on human health are well known. There are several ways to minimize the release of ECs in environment. The most effective way is the preventive measure of limiting use of synthetic products that can result as ECs in environment. To enforce this preventive measure effectively, alternative nature-based products should be explored and encouraged to be used as substitute for synthetic compounds. Presently, under the H2020, goal bio-based solutions are the popular research topics ventured by several research labs. For example, natural pesticide can be used as an alternative to synthetic pesticides. Although, not every synthetic product can be replaced, however, the reduction of its usage can also reduce the environmental burden. Therefore, the most effective ways to minimize the ECs in environment are proper use of resources (Colombo et al. 2019; Mengal et al. 2018).

Apart from source monitoring and regulation, the identification of ECs is also important to aid the regulatory authorities in framing guidelines. In addition, more focus should be towards long-term investigation to understand the effects of different ECs on the ecosystem and different trophic levels. For tracking the fate and transport of different ECs, more sophisticated analytical techniques are required. This requires continual development of the existing technique and invention of newer techniques for faster and reliable detection (Badea et al. 2020; Martín-Pozo et al. 2019).

There are several technologies available to remove ECs or to degrade into less toxic by-products, such as adsorption, AOPs, membrane separation, and bioremediation. Among them, AOPs are considered as most effective wastewater treatment technology to remove ECs. It is used in different stages of treatment process from initial stage of pre-treatment of raw wastewater to final stage as water treatment station for human use. Hybrid AOPs are also coming up as most effective method for removal of ECs. However, many disadvantages are also associated with AOPs. It has been observed that when UV light-based AOPs are used for treatment process, organic compounds are transformed into degradation product that could be more toxic than initial ECs. In addition, the installation and operating costs of AOPs are also very high making it expensive option.

For effective and economical treatment of wastewater to remove ECs, the integration of technologies might be a good approach. These AOPs are capable of improving the biodegradability of wastewater. As AOPs are costly and demands high energy, AOPs can be associated with other treatment method to improve the efficiency as well as economic viability of process. AOPs can completely mineralize ECs or can convert it into simpler molecule, these simpler molecules may be easily assimilated by the robust planktonic species, such as the microalgae. Therefore, AOPs as initial stage of pre-treatment followed by microalgae-based wastewater treatment for the removal of ECs might be a better approach. Incorporating the microalgae-based treatment in a wastewater process can be a sustainable approach as in addition to the wastewater remediation microalgae biomass can be harvested to be used as a feedstock for biofuel production (Almomani et al. 2019; He et al. 2020).

5.8 Conclusion

The chapter emphasizes on the alarming presence of ECs in natural and built environment and discusses briefly the fate of the same in nature. The evaluation of the wastewater treatment plants both in terms of point source of discharge of ECs and also as techniques to remove ECs was covered to render an idea about the present status of the research on EC's fate and removal. The application of several AOPs for the removal of the ECs from wastewater indicates high efficacy of such processes; however, often at the cost of toxic oxidation by-product formation. A further discussion on present status indicates that application of AOPs, close monitoring of the discharge from the wastewater treatment plants, and replacing different synthetic compound-based ECs with organic equivalents can lead toward a mitigated and safer future.

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Chapter 6
Emerging Biotechnological Processes in Controlling Nitrogen Pollution to Minimize Eutrophication of Surface Waters in Asia

Sabumon Pothanamkandathil Chacko

Abstract Nitrogen pollution from domestic, industrial, and agricultural sources leads to eutrophication and other adverse effects in aquatic systems. Therefore, nitrogen removal from wastewaters before disposal into water bodies is necessary. Many countries have enforced stringent discharge standards as less as10 mg/L as N to control nitrogen pollution. This book chapter reviews the emerging biotechnological processes in controlling nitrogen pollution cost-effectively and helps in meeting stringent discharge standards in contrast to the conventional nitrification–denitrification process. The emphasis of review is on process description and influencing parameters, merits/demerits of each process, and the reactor types employed using the literature reported in the last two decades. Finally, a comprehensive evaluation is done on the process performance for selecting the appropriate process for controlling nitrogen pollution from wastewaters, and recommendations are included.

Keywords Nitrogen pollution · Wastewater · Eutrophication · Anammox · Feammox · Denitrification

6.1 Introduction

Water is one of the dynamic natural resources, and it is critical for sustaining all forms of life, food production, and overall economic development. Lakes and rivers are important surface water resources required for supplying quality water to meet the demands of various users from domestic, industrial, and agricultural sectors. Because of increased activities in past decades from these sectors and as a result of the continuous disposal of untreated or partially treated wastewater to the lakes and rivers, the water quality has deteriorated to a great extent in many parts of Asia. Nitrogen pollution in surface waters consists of organic nitrogen, NH_4^+-N, NO_2^--N, and NO_3^--N. Among these, NH_4^+-N has long been acknowledged as an

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important pollutant in water. The presence of NH_4^+-N in the municipal wastewater and in the effluent from industrial operations and agricultural fields is as harmful as it is widespread (Reddy and Char 2006). Ammonia contributes to excessive algal growth leading to death and decay resulting dissolved oxygen depletion in water and ultimately causing eutrophic conditions in lakes and rivers. Ammonia concentration as small as 0.3–0.4 mg/L is toxic to certain species of algae and fishes, while 2.5 mg/L is the recommended maximum concentration of ammonia. Also, ammonia and metabolic by-products of algae growth will increase the chlorine demand in disinfection units in the water treatment plants further affecting the economy of the treatment processes. In late 1990s, many countries have prescribed less than 10 mg/L as stringent nitrogen discharge standard to reduce nitrogen pollution in water bodies.

A variety of biological and physicochemical processes are used for ammonia removal. Physicochemical methods like air stripping, breakpoint chlorination, ion exchange, and membrane process and its combinations can be employed to meet the discharge standards. However, these processes are very costly (Hussain et al. 2007) and require stringent process control and maintenance. On the other hand, biological nitrogen removal processes, for instance, nitrification followed by denitrification or its process modifications are employed as a relatively cost-effective treatment for removal of ammonia from wastewaters. However, existing nitrification and denitrification process for control of NH_4-N from wastewater is neither an economical nor a stable process. For example, the energy consumption during supplying oxygen for nitrification process alone accounts for 60% of the whole wastewater treatment (Lefebvre et al. 2012). To succeed these demerits and to meet the strict nitrogen discharge standards, extensive studies have been carried out to develop new biotechnological processes (Khim and Annachhatre 2004). The processes such as partial nitritation–denitrification, anaerobic ammonia oxidation named as anammox, single high-rate ammonia removal over nitrite named as SHARON, combined SHARON–anammox, complete autotrophic nitrogen removal over nitrite named as CANON, NOx, oxygen-limited autotrophic nitrification–denitrification named as OLAND, deammonification named as DEMON, denitrifying ammonium oxidation named as DEAMOX, simultaneous partial nitrification, Anammox and denitrification named as SNAD, bio-augmentation batch enhanced named as BABE, FeO_x/MnO_x-mediated nitrification and denitrification, and Feammox/Mnammox have been developed for nitrogen removal from wastewaters (Khim and Annachhatre 2004; Ahn 2006; Kalyuzhnyi et al. 2006; Anjali and Sabumon 2015; Swathi et al. 2017, and Desireddy et al. 2018; Chen et al. 2020). This chapter describes briefly these new biotechnological processes with influencing parameters, merits/demerits of each process, and the reactor types employed and evaluate the process performance of a few selected processes for potential applications. Finally, recommendations are provided to choose appropriate process suitable for nitrogen control.

6.2 Emerging Biotechnological Processes in Controlling Nitrogen Pollution

6.2.1 Partial Nitritation–Denitrification

Conventional nitrification–denitrification is a multi-step process requiring huge amounts of aeration and external supply of organic carbon and makes the process very expensive. To overcome these problems, a shortcut biological nitrogen removal process called as partial nitritation–denitrification was developed. In this process, the nitrification is short circuited so that once NH_4^+ is oxidized to NO_2^-, it further prevents the oxidization to NO_3^-. Partial nitritation–denitrification is beneficial as it can save 25% oxygen demands in the first step of nitrification and a reduction in supplies of organic matter (40%) in the second step of denitrification, and additionally a reduction in the excess sludge produced in the process (Ruiz et al. 2003, 2006; Jianlong and Ning 2004).

The chemical reactions involved in partial nitritation–denitrification are given in Equations. (6.1) to (6.3).

$$NH_4^+ + 1.05\,O_2 \rightarrow NO_2^- + H_2O + 2H^+ \tag{6.1}$$

$$NO_2^- + 2.4\,g\,COD + H^+ \rightarrow 0.5\,N_2 + 0.9\,g\,biomass \tag{6.2}$$

$$NH_4^+ + 1.05\,O_2 + 2.4\,g\,COD \rightarrow 0.5\,N_2 + H_2O + H^+ + 0.9\,g\,biomass \tag{6.3}$$

Effective partial nitritation–denitrification requires two pre-requisites such as (i) nitrification must be inhibited beforehand oxidation of NO_2^- to nitrate and (ii) denitrifying sludge must be acclimatized to NO_2^-, which is capable of toxic even at low concentrations of NO_2^- (Chung and Bae 2002; Ruiz et al. 2006). In classical nitrification, NH_4^+ oxidation and NO_2^- oxidation are mediated by distinct group of microbes such as Nitrosomonas and Nitrobactors. Partial nitritation–denitrification takes advantage of this fact and achieves the required conditions by providing conducive environment for ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA) to thrive but not for the survival of nitrite-oxidizing bacteria (NOB). Such conditions enable only NH_4^+ oxidation toward NO_2^- (Bernet et al. 2005; Paredes et al. 2007) and not NO_2^- to nitrate.

6.2.1.1 Process Control

At low pH, NOB grows faster than AOB. So, a higher pH of around 7.5–8.5 is maintained to wash out NOB (Hellinga et al. 1998). Optimum temperature reported for the process was around 30–40 °C (Jetten et al. 1997). At temperatures above 25 °C, growth rate of AOB can out-compete NOB (Schmidt et al. 2003; Xue et al. 2009). At those temperatures, free ammonia ($NH_3{}^0$) can be formed which is more inhibitory to NOB. It is been reported that 1 to 5 mg/L of $NH_3{}^0$can inhibit oxidation of $NO_2{}^-$ but not oxidation of $NH_4{}^+$ to accumulate $NO_2{}^-$. At a pH of 8.5 and temperature of 20 °C, the optimal $NH_3{}^0$ concentration was 5mg/L for maximum nitritation and minimum nitratation (Yoo et al. 1999; Paredes et al. 2007). Another selection pressure is at high operating temperatures, if the retention time of the sludge matches the growth rate of AOB, the NOB will be selectively washed out (Fdz-Polanco et al. 1994).

AOBs are more robust toward low DO than NOBs. Therefore, accumulation of $NO_2{}^-$ can be accomplished by regulating the DO at low concentration. This is possible by the variation in oxygen saturation coefficients according to the Monod kinetics. Oxygen saturation coefficients for nitritation and nitratation are reported as 0.3 and 1.1 mg/L, respectively (Hanaki et al. 1990; Tokutomi 2004). It is also been observed that when the low DO is less than 1 mg/L, AOBs growth rate is 2.56 times quicker than NOBs (Tokutomi 2004; Peng and Zhu 2006; Aslan et al. 2009). Therefore, operating the process at pH (7.5–8.5), temperature (30–40 °C), and low DO (<1 mg/L) can be considered as a good strategy to promote nitritation–denitrification process.

6.2.2 ANAMMOX

ANAMMOX is the abbreviation for anaerobic ammonia oxidation. The feasibility of anammox was first discovered by Broda (1977) in theory while comparing the Gibbs free energies of the ammonia oxidations in anoxic (−357 kJ/mol) and the aerobic (−118 kJ/mol) conditions. First, experimental confirmation of anammox by bacterial metabolism was reported (Mulder et al. 1995) in the Netherlands. This is based on the observation that an unaccounted nitrogen loss from a laboratory-scale denitrifying anaerobic pilot plant employed in treating effluent from a methanogenic reactor. This novel cost-effective process for elimination of ammonia (anammox) from high strength wastewaters has attained the status of matured technology, and more than 110 full-scale installations are in place (Tomaszewski et al. 2017). The anammox bacteria have unique metabolic ability to perform anoxic oxidation of $NH_4{}^+$ using $NO_2{}^-$ as the preferred electron acceptor while producing gaseous N_2 and small amounts of $NO_3{}^-$ as per Equation (6.4) (Strous et al. 1998). The attractive feature of this new process is that it does not require any organic carbon (Kuenen 2008) unlike in conventional denitrification where generally methanol to be added externally. Anammox is a highly exergonic process interconnected to the energy metabolism of the specific microbes and is mediated by a group of Planctomycetes bacteria. Ahn (2006) reported two fresh water species *Candidatus Kuenenia stuttgartiensis* and *Candidatus Brocadia anammoxidans* and three marine species, *Candidatus Scalindua sorokinii*, *Candidatus Scalindua wagneri* and *Candidatus Scalindua brodae*, and a mixotrophic anammox bacterium *Candidatus anammox globuspropionicus belong to* Planctomycetes bacteria. The rate of anammox by planctomycetes is much higher (25 times) than that of anaerobic ammonia removal by *Nitrosomonas* strains (Jetten et al. 1999).

$$\begin{aligned} NH_4^+ + 1.31\,NO_2^- + 0.066\,HCO_3^- \\ + 0.13\,H^+ \rightarrow 1.02\,N_2 + 0.26\,NO_3^- \\ + 0.066\,CH_2O_{0.5}N_{0.15} + 2.03\,H_2O \end{aligned} \quad (6.4)$$

The requirement of long start-up time is identified as the major problem in the practical application of anammox process because of extremely slow growth rate of anammox bacteria. It is also reported that organic matter (OM) present in wastewaters unfavorably disturbs anammox performance (Schalk et al. 1998; Wang and Kang 2005), and co-existence of denitrifiers and anammox species could slow down anaerobic ammonia removal during start-up (Ahn 2006).

6.2.2.1 Process Control

The optimum pH for the activity and growth of anammox bacteria was reported to be between 6.7 and 8.3 (Strous et al. 1999). However, anammox growth is detected in a wide range of pH varied between 6.5 and 9.3 (Egli et al. 2001; Tang et al. 2010; Jin et al. 2012). The rate of NO_2^- transformation to hydroxylamine is significantly slower at very low pH. On the other hand, NH_4^+ is excessively converted to NO_2^--N when pH is too high. That means, too low or too high pH decreases the rate of anammox reaction (Schalk et al. 1998). Also, the fluctuations in pH change the equilibrium of ammonium and NH_3^0, leading to free ammonia toxicity.

In any biological process, temperature can affect cell growth and metabolic activity. The optimum temperature for anammox process is 40 °C and capable of anammox operation at a temperature range of 20–40 °C. But, the most recent studies on the anammox species *C. Brocadia sinica* and *C. Kuenenia stuttgartiens are* proved that the occurrence of anammox is possible at low temperatures (10–15 °C) on long-term adaptation (Tomaszewski et al. 2017).

Dissolved oxygen (DO) is identified as one of the critical parameter in the operation of anammox process (Jung et al. 2007). Anammox gets inhibited temporarily at a low DO level (of <2% air saturation) (Strous et al. 1997), while an irreversible inhibition was reported at higher oxygen concentrations greater than 18% of air saturation (Egli et al. 2001). Hence, strict control of DO is required to avoid inhibition of anammox process. Inorganic carbon can stimulate the growth of anammox bacteria (Kimura et al. 2011), while the presence of non-toxic OM affects the anammox process (Van de Graaf et al. 1996). Generally, majority of the waste waters contain both COD and ammonia. Chamchoi et al. (2008) reported that an OM concentration over 300 mg COD/L and COD/N ratio of 2 can inhibit anammox communities when both anammox and denitrification are involved. This limitation of anammox bacteria to perform in higher COD/N ratios limits its application in main stream wastewater treatment and in many industrial effluent treatments.

NH_4^+ and NO_2^- are the two basic substrates of anammox bacteria. But, these can be inhibitors under high concentrations. Studies revealed that free ammonia (NH_3^0) and free nitrous acid (HNO_2) rather than ionic NH_4^+ and NO_2^- were the actual inhibitors (Chen et al. 2008). Free ammonia (FA) and free nitrous acid (FNA) can diffuse through the cell membrane more easily than NH_4^+ and NO_2^-, and then, inside the cell, they change the intracellular pH and neutralizes the transmembrane potential which leads to death of cells (Martinelle et al. 1996). FA concentration rises at high pH and falls at low pH, whereas the concentration of FNA falls at high pH and rises at low pH (Carvajal-Arroyo et al. 2013). Various studies reported that FA concentrations of 20–187 mg/L caused inhibitory effects on the anammox bacteria (Jin et al. 2012). The reported threshold concentrations of NO_2^- were between 5 and 280 mg N/L under diverse experimental circumstances and operating methods (Jin et al. 2012). Ferna´ndez et al. (2012) observed an irreversible decrease in the activity of anammox and nitrogen removal efficiency at FNA concentrations >1.5 μg/L and a reversible inhibition at FNA concentrations <0.5 μg/L.

From the above descriptions of process control, it is clear that anammox process works as per Equation (6.4) when all the conducive environments prevail and suitable for removing higher concentrations of ammonia from wastewaters/effluents free from toxic substances.

6.2.3 SHARON

SHARON is a process employed for the removal of nitrogenous compounds from wastewaters contaminated with ammonium concentrations greater than 0.5 g N/L (Jetten et al. 1997; Van Dongen et al. 2001). SHARON involves partial nitrification of NH_4^+ to NO_2^- without any biomass retention and is operated in a simple continuous stirred tank reactor (CSTR) with intermittent aeration. NO_3^- formation by NOB is prevented by operating the process at high temperature (35 °C) and pH (>7) (Hellinga et al. 1998). This process takes the advantage of the dissimilarity of maximum growth rate of AOB and NOB at higher temperatures. Here, aerobic and anoxic phases are carried out alternately to enable nitritation and denitrification. During nitrification phase, a high DO concentration of 3 mg/L is required. Nitrification is an acidifying process, which is then followed by denitrification to balance the pH as denitrification produces alkalinity. The main parameter that distinguishes SHARON from other biological wastewater treatment processes is the absence of sludge retention in the SHARON reactor. This is achieved by microbial growth and washout of sludge from the reactor always in equilibrium. The stoichiometries of the SHARON reactions are represented by Equations. (6.5) to (6.7) (Ahn 2006).

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H_2O + 4H^+ \tag{6.5}$$

$$2NO_2^- + 4.8\,gCOD + 2H^+ \rightarrow N_2 + 1.8\,g\,sludge \tag{6.6}$$

$$2NH_4^+ + 3O_2 + 4.8\,gCOD \rightarrow N_2 + 2H^+ + 1.8\,g\,sludge \quad (6.7)$$

SHARON is the first successful process in which partial nitritation–denitrification has been accomplished satisfactorily (Van Dongen et al. 2001). Stable partial nitritation is obtained by controlling significant operating variables like temperature, pH, hydraulic retention time (HRT), substrate concentration, and DO (Hellinga et al. 1998); provided enough alkalinity is present in wastewater.

6.2.3.1 Process Control

At higher temperatures (30–40 °C), AOB showed a significant higher specific growth rate of 1/d compared to NOB growth rate of 0.5/d (Hunik et al. 1993). Also, AOB requires minimum solids retention time (SRT) at temperatures >20 °C. Thus, by operating at desired high temperatures and adjusting the aerobic retention time to 1 day without sludge retention, NOB is washed out of the reactor, and the oxidation reaction stops at NO_2^- (Hellinga et al. 1998). NOB shows a lower affinity for DO compared to AOB. So, a low DO concentration is restrictive for the growth of NOB.

NH_4^+ oxidation is recognized as an acidifying process and thus decreases the bulk pH. So, pH control is very important for avoiding inhibition of the process (Van Dongen et al. 2001). At pH values less than 6.5, the concentration of FA drops which leads to insufficient growth of AOB. On the other hand, at pH values higher than 8, too much of NH_3^0 is produced which is toxic to AOB and NOB (Abeling and Seyfried 1992). Hence, an optimum pH of 6.5–7.5 can be used to achieve the desired NH_4^+/NO_2^- ratio in the effluent from SHARON reactor, when combined SHARON–ANAMMOX is employed.

A suitable HRT to be maintained to enable NOBs is washed out, while AOBs could stay in the reactor. The conversion efficiency in SHARON process is also determined by the influent NH_4^+ concentration. For a given load, considerable NH_4^+ removal efficiencies can be obtained by increasing the HRT. The ammonium loading rate is determined by the concentration of influent NH_4^+. Therefore, the cost of the process depends on the concentration of influent NH_4^+, and operational costs increase when NH_4^+ –N concentration decreases (Schmidt et al. 2003). The optimum influent substrate concentration for significant removal was reported to be 0.5–1.5 g NH_4^+–N/L (Hellinga et al. 1998; Van Dongen et al. 2001). Therefore, SHARON can work well in high influent ammonia concentrations with optimal pH (6.5–7.5) and temperature (30–40 °C) with appropriate control of HRT.

6.2.4 SHARON–ANAMMOX

This process combines two novel independent technologies, anammox and SHARON. For the anammox process to function properly, a constant NO_2^- supply is required. For this, the NH_4^+ in the influent must be partly pre-oxidized to NO_2^- but not to NO_3^- before being fed to the anammox reactor. The main goal behind the combined SHARON–anammox process is to attain the required stoichiometry (molar NH_4^+/NO_2^- ratio of 1:1.32) as per Equation (6.4) by incorporating a partial nitrification step in a SHARON reactor preceding anammox. The process could run in two reactors in series. The overall reaction of combined SHARON–anammox process is given in Equation (6.8) (Shalini and Joseph 2012).

$$2.3\,NH_4^+ + 2.95\,O_2 + 1.2CO_2 \rightarrow 1.2CH_{1.8}O_{0.2} + N_2 + 0.3NO_3^- \quad (6.8)$$

The attractive feature of this process is that it does not require any external addition of organic carbon (measured as COD), and the process can be performed either using two separate vessels or in a single vessel. For the full-scale application, the partial nitritation process can be performed in a CSTR or a sequencing batch reactor (SBR), as it is easier to manipulate SRT. Whereas, a biofilm or granular-based bioreactor is preferred for anammox process which is capable of retaining a high biomass concentration in the reactor (Van Hulle et al. 2010). The process control conditions as mentioned in the previous sections of anammox and SHARON have to be maintained to obtain a stable performance.

6.2.5 CANON

CANON denotes completely autotrophic nitrogen removal over nitrite. This process is also a blend of partial nitritation and anammox. But, unlike SHARON–anammox process, CANON is performed in a single aerated reactor (Sliekers et al. 2002). In this process, two groups of autotrophic bacteria (aerobic *Nitrosomonas* like bacteria and anaerobic *Planctomycetes* like bacteria) cooperate and accomplish simultaneously two sequential reactions in low DO concentrations (Third et al. 2001). These autotrophic bacteria are capable of converting NH_4^+ directly to N_2 gas with NO_2^- as an intermediate. Initially, the aerobic nitrifiers oxidize NH_4^+ to NO_2^- as per Equation (6.9). This reaction consumes oxygen and creates anoxic conditions required for the anammox process. Afterward, anaerobic ammonium oxidizers transform remaining NH_4^+ along with the formed NO_2^- to N_2, and trace quantities of NO_3^- are produced as per Equation (6.10) (Khim and Annachhatre 2004). Here, NO_2^- helps as an electron donor for the realization of biomass from CO_2, and the generation of NO_3^- in the reaction is stoichiometrically coupled to growth. The overall stoichiometry of CANON process is given in Equation (6.11) (Khim and Annachhatre 2004).

$$NH_4^+ + 1.05O_2 \rightarrow NO_2^- + H_2O + 2H^+ \quad (6.9)$$

$$NH_4^+ + 1.3NO_2^- \rightarrow 1.02N_2 + 0.26NO_3^- + 2H_2O \quad (6.10)$$

$$NH_4^+ + 0.85O_2 \rightarrow 0.435N_2 + 0.13NO_3^- + 1.3H_2O + 1.4H^+ \quad (6.11)$$

6.2.5.1 Process Control

The oxygen-limited conditions below 0.5% air saturation or DO <0.4 mg/L (Hao et al. 2002) deliver a satisfactory environment for a stable collaboration between *Nitrosomonas* like aerobic microorganisms and *Planctomycetes* like anaerobic bacteria (Ahn 2006). The lower limit of ammonium loading rate for stable and effective nitrogen removal to inert N_2 was 100 mg/L/d, while the higher limit was about 300 mg/L/d. At these loading rates, activity of heterotrophic denitrifiers and aerobic NOB will not be effective (Sliekers et al. 2002).

Most CANON systems achieved the maximum nitrogen removal rate when operate data temperatures of about 30–35 °C (Sliekers et al. 2002). This is because AOBs grow faster than NOBs, and besides, growth of anammox bacteria is increased in its optimal temperature. In biofilm reactors, a very thin biofilm thickness of <0.2 mm might not support CANON process as an anaerobic layer is difficult to form under aerobic conditions. The optimum biofilm thickness was reported to be around 0.2–0.7 mm. But, when the ammonium loading rate is high, a thicker biofilm is required to achieve maximum efficiency in nitrogen removal (Hao et al. 2002). Therefore, CANON process can be operated successfully on a DO and temperature-controlled reactor for treating wastewater with moderate concentrations of ammonia free from organic matter.

6.2.6 *NO_x*

Ammonia oxidation by *Nitrosomonas* like aerobic AOB was reported to happen in both oxygen-independent and oxygen-dependent pathways in the presence of NO_x (Arp and Stein 2003). The presence of NO_x stimulates the denitrification activity of *Nitrosomonas* (Schmidt et al. 2003). These microbes can simultaneously nitrify and denitrify in the presence of NO_x even under complete oxic conditions and generates inert N_2 gas as the main product. The nitrification, denitrification, and the overall reactions are shown in Equations (6.12) to (6.14) where in [H] denotes the reducing equivalents, for example, an external C-source (Schmidt et al. 2003).

$$3NH_4^+ + 3O_2 \rightarrow N_2 + 4H_2O + NO_2^- + 4H^+ \quad (6.12)$$

$$NO_2^- + H^+ + 3[H] \rightarrow 0.5N_2 + 2H_2O \quad (6.13)$$

$$NH_4^+ + 3O_2 + 3[H] \rightarrow 1.5N_2 + 3H^+ + 6H_2O \quad (6.14)$$

NO_x (NO/NO_2) in little amounts with ratio of NH_4^+/NO_2 varied from 1000/1 to 5000/1 can induce denitrification activity of AOB (Schmidt et al. 2001). In the nitrification step, about 40% of the NH_4^+ is converted to NO_2^-. As a consequence, 50% of the reducing equivalents [H] is reassigned to NO_2^- as terminal electron acceptor (Eq. 6.12) as a substitute of oxygen. The subsequent denitrification step consumes less COD (Eq. 6.13). This process can be effortlessly incorporated into existing wastewater treatment plants with minimal costs.

Figure 6.1 shows the conceptual process diagrams of all processes explained above. Table 6.1 gives the merits and demerits and reactor types of emerging biotechnological process in controlling nitrogen pollution. To keep the chapter in short, further description of the emerging processes which are modification of the above described processes is kept as brief.

6.2.7 OLAND

Kuai and Verstraete (1998) reported first time a process called as oxygen-limited autotrophic nitrification–denitrification (OLAND) from Ghent University (Belgium). The major difference between CANON and OLAND process is that CANON incorporates the anammox process, whereas OLAND utilizes the denitrification activity of conventional aerobic nitrifiers dominated by ammonium oxidizers (Jetten et al. 2001). *Nitrosomonas eutropha is* the main species involved in the OLAND process as it has a unique ability to thrive heterotrophically (Pynaert et al. 2004) unlike anammox species. The process is by means of the co-existence of aerobic AOB and anaerobic AOB in anoxic conditions and in the absence of organic electron donors (Pynaert et al. 2003). This process can be applied for a variety of wastewaters like reject wastewater from anaerobic digestor, land fill leachate, specific industrial wastewaters, blackwater digestate, and digested manure (Vlaeminck et al. 2012).

6.2.8 DEMON

Deammonification (DEMON) process was first reported in Hanover University (Germany) where 90% of inorganic nitrogen losses was observed in the nitrification step while treating ammonium rich landfill leachate using a rotating biological contractor (Hippen et al. 1997).

The main principle of DEMON is similar to that of CANON and combines two processes, including partial nitrification (50%) and anammox (50%) under oxygen-limited conditions to occur in a single reactor system. Morales et al. (2015) reported a single-stage system, where aerobic AOB and anoxic AOB are cultivated concurrently under low DO conditions to preserve a suitable dynamic balance between them and to overpower the growth of NOB and heterotrophic bacteria (Magri et al. 2013). In the single-stage systems, a conventional SBR operation is adopted to demonstrate

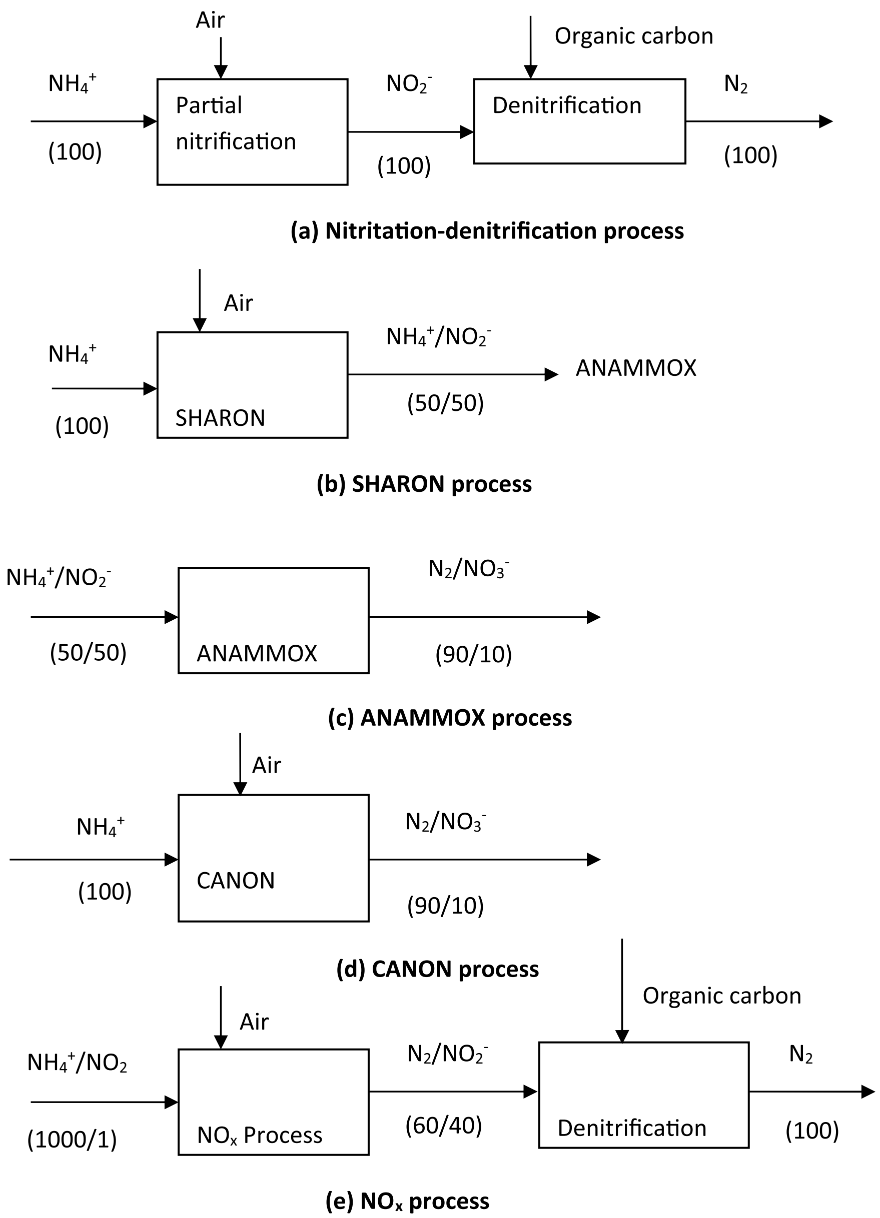

Fig. 6.1 Conceptual process diagrams of selected emerging nitrogen removal processes. (S*ource* Sabumon 2008)

Table 6.1 Merits and demerits and reactor types of emerging biotechnological process in controlling nitrogen pollution

Sl. No	Process	Merits	Demerits	Reactor types
1	Partial nitritation–denitrification (PND)	25% less of oxygen demand 40% less of COD demand 20% less in CO_2 emission Less sludge production	Needs pH and temperature control Needs strict DO control Process inhibition at low nitrite concentrations	Suspended growth type reactor—CSTR or a sequencing batch reactor
2	Anammox	60% less of oxygen demand No need of organic matter (100% saving in COD demand) 90% reduction in greenhouse gases (CO_2 and N_2O) High ammonia removal rate Suitable for high ammonia bearing wastewater 60% reduction in operational costs 90% reduction in excess sludge production Less foot print required	Long start-up time Not easy to get the seed biomass Very sensitive to high concentrations of DO and organic compounds Sensitive to pH and temperature fluctuations Process could get easily inhibited by heavy metals, FA, FNA, OM, salts, phosphate, and sulfide	Both suspended and attached growth types reactors capable of high biomass retention—SBR, fixed bed, fluidized bed, airlift, upflow anaerobic sludge blanket reactor (UASB)
3	SHARON	Similar to PND	Similar to PND	Similar to PND
4	SHARON–anammox	Cost-effective 100% less in CO_2emission	Needs pH and temperature control Needs strict DO control Long start-up time Nitrate accumulation	Both suspended and attached growth types reactors capable of high biomass retention—SBR, fixed bed, fluidized bed, airlift, up flow anaerobic sludge blanket reactor (UASB)
5	CANON	No need of organic matter (100% saving in COD demand) Cost-effective Less foot print required 60% less of oxygen demand	Difficult to control the process for consistent performance Not suitable for high nitrogen loading rates	SBR, sequencing batch biofilm reactor, airlift reactor

(continued)

Table 6.1 (continued)

Sl. No	Process	Merits	Demerits	Reactor types
6	NOx	50% less of aeration 80% less of COD demand	Needs strict process control	Suspended growth type reactor—CSTR or a sequencing batch reactor
7	OLAND	Can treat various types of wastewaters	Low nitrogen loading rate	
8	DEMON	Same as CANON, useful for high ammonia concentrations	Not suitable for sewage treatment because of long start-up and recovery after process upsets	SBR, sequencing batch biofilm reactor, rotating biological contactor
9	DEAMOX	Relatively easy to control the process, enhances the granulation of biomass, less greenhouse gas emission	Suitable for sulfate/sulfidebearing effluents, process inhibition due to sulfides	Suspended growth type reactor—CSTR or a sequencing batch reactor
10	SNAD	Less oxygen, organic carbon and less foot print requirement	Not suitable when COD/NH_4^+ ratio > 1	SBR, fixed bed reactor
11	BABE	Can easily incorporated to existing wastewater treatment plants	Difficult to control the process in high organic loadings	CSTR
12	FeO_x/MnO_x-mediated nitrification and denitrification	No need of aeration, no alkali required to support pH fluctuation, 70% saving in organic carbon, less sludge production, FeO_x/MnO_x can undergo multiple Red-Ox cycles to sustain the process performance, easy to operate	Not suitable at higher organic loading rates	SBR, upflow packed bed reactor filled with granulated nanoscale oxides of Fe/Mn
13	Feammox/Mnammox	No need of aeration	Oxides of iron and manganese to be added and excess concentration may inhibit the process	SBR and any suitable continuous reactor

DEMON. The SBR is exposed to intermittent aeration by using alternating non-aerated and aerated periods, and the process is controlled by adjusting time, pH, and DO. In the reaction phase, both PN and ANAMMOX occur.

The first full-scale DEMON plant was demonstrated satisfactorily at Strass wastewater treatment plant in 2004 (Wett 2007). The DEMON process can be employed as side-stream treatment for supernatant from anaerobic sludge digester and as mainstream treatment for wastewater having low ammonia concentrations (Feng et al. 2017). However, the process has certain limitations such as requirement of long start-up duration and recovery after failures periodically in operation, which limit its extensive application in municipal wastewater treatment (Feng et al. 2017).

6.2.9 DEAMOX

Denitrifying ammonium oxidation (DEAMOX) is based on the combination of the anammox reaction in autotrophic denitrifying conditions using sulfide as an electron donor. This process does not need a separate production of NO_2^- using AOBs, and NO_2^- is produced from NO_3^- using sulfide. DEAMOX is primarily used for the treatment of Baker's yeast effluent which is an example of a high-strength nitrogenous and sulfate-bearing wastewater (Kalyuzhnyi and Gladchenko 2009). This process functions in a blend of a three numbers of reactor system such as anaerobic reactor, nitrifying reactor, followed a DEAMOX reactor (Bagchi et al. 2012) and thus increases the operational complexity.

The pre-treatment step of strong nitrogenous and sulfate-bearing wastewater in anaerobic reactor produces the effluent rich in NH_4^+ and sulfide as per Equation (6.15). This effluent is then partly fed to the nitrifying reactor, where NO_3^- is produced as the major product and sometimes NO_2^- in minor concentrations as per Equation (6.16). The remaining effluent from anaerobic reactor and effluent from nitrifying reactor are fed to the DEAMOX reactor, where the denitrification of NO_3^- and NH_4^+ oxidation occurs simultaneously. In the DEAMOX reactor, NO_3^- gets reduced to NO_2^- in the presence of sulfide mediated by autotrophic denitrifying bacteria as per Equation (6.17), and the NH_4^+ is oxidized to N_2 using NO_2^- as an electron acceptor mediated by anammox bacteria as per Equation (6.18). Kalyuzhnyi et al. (2006) reported that more than 90% removal efficiency is possible at a maximum loading rate of 1 kg N/m^3/d.

$$\mathrm{N-organics} + SO_4^{2-} \rightarrow NH_4^+ + HCO_3^- + CH_4 + HS^- \tag{6.15}$$

$$NH_4^+ + O_2 \rightarrow NO_3^- + NO_2^- \tag{6.16}$$

$$4NO_3^- + HS^- \rightarrow 4NO_2^- + SO_4^{2-} \tag{6.17}$$

$$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O \tag{6.18}$$

6.2.10 SNAD

SNAD stands for simultaneous partial nitrification, anammox, and denitrification. This process can be employed for simultaneous removal of organic carbon and ammonia effectively from wastewaters containing low organic carbon to nitrogen ratio (Chen et al. 2009). SNAD process integrates partial nitrification, anammox, and denitrification to occur simultaneously in oxygen-limited conditions in a single reactor. In the SNAD process, initially, AOB converts NH_4^+ partially to NO_2^-, which creates anoxic conditions by consuming oxygen. Subsequently, anammox bacteria convert NH_4^+ and NO_2^- into N_2 gas and NO_3^- as per Equation (6.4). Finally, denitrifiers reduce NO_3^- produced by anammox bacteria to N_2 using organic carbon as reducing agent (Anjali and Sabumon 2015).

SNAD process is effective when COD/NH_4^+ ratio ≤ 1 and when the ratio exceeds anammox process get inhibited, and the process is not effective. SNAD has been successfully employed for simultaneous removal of organic carbon (COD) and ammonia from different wastewaters like synthetic wastewater, landfill leachate, swine digester liquor, optoelectronic industrial wastewater, and fertilizer industry effluent (Anjali and Sabumon 2015). Wang et al. (2010) reported the first full-scale application of SNAD process in a landfill-leachate treatment plant at Taiwan.

6.2.11 BABE

Bio-augmentation batch-enhanced (BABE) process was developed and patented by DHV in collaboration with the Technical University in Delft (Zilverentant 2003). The process aims to treat nitrogen-rich sidestream and to bio-augment nitrification in the mainstream-activated sludge process in a conventional wastewater treatment plant that operated at sub-optimal SRT (Salem et al. 2003). In the design of BABE process, a nitrification reactor is added in the return sludge line. Effluent from the sludge treatment plant which is rich in ammonia is fed to the nitrification reactor. Then, from this reactor, the nitrifiers grown would reach the activated sludge reactor. This helps in augmenting the nitrification capacity of the activated sludge process. The full-scale application of BABE technology has been demonstrated in The Netherlands at the wastewater treatment plant at Garmerwolde in Groningen (Bagchi et al. 2012).

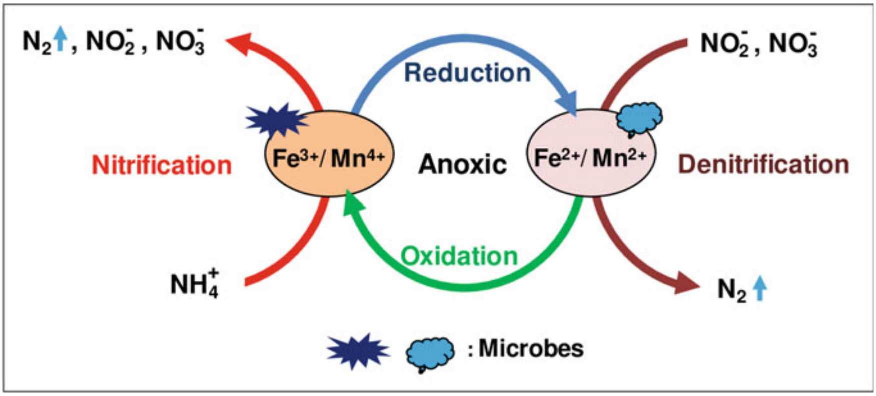

Fig. 6.2 Schematic of FeO_x/MnO_x-mediated nitrification and denitrification. (*Source* Desireddy 2021)

6.2.12 FeOx/MnOx-Mediated Nitrification and Denitrification

A patented process (Sabumon et al. 2021) is developed in author's research laboratory where ammonia reacts with oxides of Fe/Mn to give nitrite, nitrate, or directly nitrogen gas. Here, the oxygen required for nitrification was supplied by oxides of Fe/Mn. During this process, the oxides of Fe^{3+}/Mn^{4+} (oxidized form) undergo reduction and gets converted to Fe^{2+}/Mn^{2+}. These Fe^{2+}/Mn^{2+} can in turn take the oxygen from nitrite or nitrate released during the previous step to give N_2 gas. At the same time, these reduced species gets oxidized to give back Fe^{3+}/Mn^{4+}, and this cycle continues. This entire process is mediated by various species of microbes under anoxic environments. In order to increase the efficiency and efficacy of the process, granulated nano-oxides or oxyhydroxides of Fe/Mn were used (Swathi et al. 2017; Desireddy et al. 2018), and the schematic of the process developed is shown in Figure 6.2. This process has been studied in SBR and in up flow-fixed bed reactor (Swathi et al. 2020) and appears to be promising for effective and economic removal of NH_4-N from wastewater where high organic matter is not present.

6.2.13 Feammox/Mnammox

In the feammox process, autotrophic denitrification is enabled by anammox consortia using Fe^0 /Fe^{2+}. Fe^0 can activate abiotic reduction of nitrate by linking surface catalysis. Li et al. (2018) showed that $NO_3{}^-$ is ultimately reduced to $NH_4{}^+$ in an abiotic environment using Fe^0 as per Equation (6.19). Also, Fe can be oxidized to Fe^{3+} by suitable iron oxidizing microbes, and in the process, $NO_3{}^-$ gets reduced to $NO_2{}^-$. Both $NO_2{}^-$ and $NH_4{}^+$ are important substrates required for anammox bacteria as per Equation (6.4). Therefore, Fe^0/Fe^{2+}-mediated reduction of nitrate coupling with anammox can treat wastewater containing nitrate. In future, more economical nitrogen removal technology is expected using iron as a valuable transition metal for nitrogen removal.

$$NO_3^- + 10H^+ + 4Fe \rightarrow NH_4^+ + 3H_2O + 4Fe_2^+ \quad (6.19)$$

Anaerobic ammonium oxidation mediated by MnO_2 (Mnammox) is a newly discovered microbial nitrogen removal pathway. In the process, simultaneous NH_4^+ oxidation and MnO_2 reduction occurred during the reaction and the production of NO_2^-, NO_3^-, N_2, and Mn^{2+} as detected (Chen et al. 2020). Though the processes described in Sections. 2.12 and 2.13 are identical, the preferred terminology to use Feammox/Mnammox is when anammox species are involved in anoxic ammonia oxidation.

Table 6.2 provides essential information for evaluation on the process performance of selected biotechnological processes treating low COD/N ratio wastewaters. The processes are suitable, once the major portion of biodegradable organic matter present in the wastewater is removed either by conventional aerobic or anaerobic process.

6.3 Recommendations

Based on the review it is recommended that:

(i) Partial nitrification in a CSTR followed by anammox process in an upflow packed bed reactor could be the best option for treating wastewater containing high concentration of NH_4–N ($\geq$500 mg/L) with less COD ($\leq$100 mg/L).

(ii) SNAD process in a down-flow packed bed reactor with high hydraulic conductivity can be used for treating wastewater having COD/NH_4-N ratio less than $\leq$1, and NH_4-N concentration varies between 200 mg/L and 500 mg/L. The same process in an SBR is suitable for NH_4-N concentration varies between 50 mg/L and 200 mg/L.

(iii) Pilot scale studies are required using patented granulated FeO_x/MnO_x-mediated nitrification and denitrification process for treating wastewater containing concentration of NH_4-N $\leq$ 50 mg/L with less COD ($\leq$100 mg/L) before full-scale application.

6.4 Conclusion

Most of the emerging biotechnological processes in controlling nitrogen pollution available in the literature in the last two decades are reviewed with the aim to enable the selection of right process for controlling nitrogen pollution from wastewaters. Nitritation–anammox/SHARON–anammox process is more suitable in cases where

Table 6.2 Comprehensive evaluation on the process performance of selected biotechnological processes treating low COD/N ratio wastewaters

Sl. No	Process	Operational parameters	Influent	Performance
	(Reactor type)	(a) Volume (L) (b) HRT (h) (c) DO (mg/L) (d) Temperature (°C) (e) Start-up time (d)	(a) COD (mg/L) (b) NH_4^+–N(mg/L) (c) COD/Nratio	(%) Removal of (a) COD (b) NH_4^+–N (c) TN
1	Nitritation-anammox (Upflow micro-aerobic reactor)	(a) 4.9 (b) 8 (c) 1–3 (d) 35±1 (e) 102	(a) 308±35 (b) 292±13 (c) 0.84	(a) 77.9±3.2 (b) 86.2±2.5 (c) 87.2±2.5
2	SHARON–anammox (CSTR-SBR)	(a) 10 (b) 1 (c) – (d) – (e) 110	(a) – (b) 1180 (c) –	(a) – (b) 53 (c) 46
3	Membrane bioreactor–CANON system	(a) 5.5 (b) 1.9 (c) 0.1–0.2 (d) 25 (e) 78	(a) 300 (b) 88±3.5 (c) 3.4	(a) 60 (b) – (c) 70
4	OLAND (Rotating biological contactor)	(a) 2.5 (b) 1.85 (c) 3–4 (d) 29 (e) –	(a) 110 (b) 23–46 (c) 2	(a) – (b) – (c) 42±5
5	DEAMOX (Upflow continuous reactor with immobilized anammox)	(a) 6 (b) 4 (c) – (d) 30 (e) 94	(a) 80±44.7 (b) 30 (c) 3.66	(a) 88.5 (b) 71 (c) 84
6	SNAD (SBR)	(a) 5 (b) 60 (c) <0.5 (d) 15–30 (e) 100	(a) 387±145 (b) 292.1±13 (c) 0.75	(a) 76 (b) 96 (c) 80
7	SNAD (Downflow reactor packed with plastic media)	(a) 2.4 (b) 3 (c) 0.2–0.3 (d) 28–30 (e) 9	(a) 675 ± 48 (b) 675 ± 26 (c) 1	(a) 94 (b) 51 (c) 47

(continued)

Table 6.2 (continued)

Sl. No	Process	Operational parameters	Influent	Performance
8	FeO_x/MnO_x-mediated nitrification and denitrification (Upflow packed bed reactor)	(a) 3.56 (b) 12 (c) – (d) 30±2 (e) 59	(a) 90±8 (b) 40±1.1 (c) 2.25	(a) 66.4±14 (b) 93.2±2.3 (c) 86.4±6

Source Desireddy (2021)

high concentration of NH_4-N is present at very-low COD/N ratio bearing wastewaters. However, there shall be enough adapted anammox culture available to start-up the process quickly; otherwise, the process development will takes long time. SNAD process can be very well used for cost-effective wastewaters treatment when COD/NH_4-N ratio is less than ≤ 1. Granulated FeO_x/MnO_x-mediated nitrification and denitrification process also demonstrated as an effective anoxic process for the simultaneous removal of COD and NH_4-N up to COD/NH_4-N ratio ≤ 2.2. This process does not require addition of oxygen, organic carbon, and alkalinity and can easily performed in a single reactor.

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Chapter 7
Hybrid Anaerobic Baffled Reactor and Upflow Anaerobic Filter for Domestic Wastewater Purification

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Abstract Anaerobic baffled reactor (ABR) is an expanded septic tank consisting of a series of upflow anaerobic sludge blanket (UASB) processes without granulation for its treatment. The vertical baffled series in ABR stimulates the wastewater to flow through several compartments as it passes from inlet to outlet. Despite the ABR recognition for low operating and maintenance cost and high removal of organic matter and solids, the existing ABR reportedly has more deficient nutrient and pathogen removal performance. This study investigated the reduction of the pathogen from domestic wastewater through the hybrid system of the ABR and upflow anaerobic filter (UAF). Experiments were conducted at the ABR site in Islamic Boarding School in Malang, and untreated sewage was taken from the inlet. The untreated wastewater is fed into lab-scale ABR with a 145 cm × 45 cm × 50 cm dimension with several natural filter media. The rate of the wastewater was 220 ml/min with a detention time of 24 h. The wastewater which flew through ABR was then re-treated using UAF to eliminate the pathogen from wastewater. The hybrid system proved the efficiency of removing 88, 78, 90, 70, 34, and 75% for BOD, COD, TSS, NH_3, PO_4, and total coliform. Therefore, this hybrid treatment can be considered a low-cost treatment to produce an alternative to clean water resources.

Keywords Anaerobic baffled reactor · Hybrid system · Upflow anaerobic filter · Wastewater

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7.1 Introduction

Water is an essential requirement for supporting human life and is driving a vital function in economic growth (Hutton and Chase 2017). However, freshwater availability is currently decreasing due to population, urbanization, and economic development. Moreover, anthropogenic activities can lead to environmental degradation, and miserable water management causes the decrease of freshwater quality (Mohan et al. 2021; Widiyanti and Dittmann 2014). Projection of water storage per capita in Indonesia until 2019 is about 12.56 billion m^3 with the capacity storage of approximately 52.55 m^3 per capita. However, this number is less than the other Asian countries (ADB 2016), and reveals that the Indonesian water resources system is prone and sensitive to environmental degradation and climate change issues (ADB 2016). Moreover, approximately, 9.5% of Indonesian people do not have enough access to sanitation facilities in 2016 (Kerstens et al. 2016; UNICEF 2021). These conditions lead to explore water recovery from the others sources such as wastewater as a clean water alternative.

Indonesia is home to 270.20 million people in 2020, with a density of 141 people per km^2 (BPS 2020a, b), and this number generating a significant volume of wastewater daily. Water demand is ascending about twice due to the increase of the global population, and therefore, recycling the wastewater is becoming an alternative to providing clean water demand. Although Indonesia is categorized as one of the rich countries in water resources, the country has faced water shortages due to deterioration in clean water sources availability per capita. This condition is triggered by poor wastewater treatment and management and inefficient freshwater consumption. Sustainable wastewater treatment is one solution to alleviate water scarcity and secure national water security (Liao et al. 2021). The wastewater can be reused as freshwater substitution, such as firefighting, agricultural uses, lawn watering, flushing toilets, and gardening (Akpan et al. 2020). Wastewater recycling for irrigation has been used for centuries because it can reduce freshwater and fertilizer use. However, the impacts of wastewater reuse should be considered for human health safety (Leonel and Tonetti 2021).

There are two main functions in treating wastewater. Firstly, wastewater treatment is applied for sanitation purposes services in an urban and suburban areas. Also, to fulfill the consequent requirement for treated wastewater discharge into the environment. The second purpose is to indicate the reuse of treated wastewater may available for freshwater substitution, which is expected to increase in the next future (Salgot and Folch 2018).

A wide range of wastewater treatments has been used for treating wastewater worldwide. This range of wastewater was applied for natural, conventional, and advanced treatment.

7.2 Anaerobic Baffled Reactor

A high anaerobic bioreactor technology development rate becomes an essential parameter in implementing anaerobic technology in wastewater treatment (Barber and Stuckey 1999). High-rate anaerobic bioreactor is classified into three groups of mechanical processes to achieve biomass detention: biofilm suspended growth and hybrid treatment (Barber and Stuckey 1999; Metcalf and Eddy 2004). Globally, an anaerobic bioreactor system is implemented as UASB for 67% (Lettinga 1980), CSTR for 12% and anaerobic filter for 7% (Young and McCarty 1969), and others for 14%. Around the same time as Lettinga, Mc Carty developed RBC, a suspended growth system, and when they removed the disk from the RBC, they developed ABR (McCarty 1981).

The ABR design typically consists of hanging and standing baffles in several compartments. These baffles will consent to the wastewater to move upflow and downflow from one compartment to another (Foxon et al. 2004). Several studies have investigated the potentiality of the ABR application in many countries in treating various types of wastewater. Researchers have proven that the ABR has widely been operated for treating a low concentration of domestic wastewater pollutant (Krishna et al. 2008; Nasr et al. 2009a; Jamshidi 2014), wheat flour starch production (Movahedyan et al. 2007), traditional pharmaceutical industrial wastewater (Liu et al. 2009), and wastewater of the soybean processing (Zhu et al. 2008). Although the ABR technology has revealed the significant advantages of treating many types of wastewaters, deficiencies in eliminating pollution have been observed from previous studies. Typically, treated wastewater of the ABR still consist of high concentration in nitrogen and phosphorus and remaining pathogen (Nasr et al. 2009a; Jamshidi 2014; Pillay et al. 2008; Yu et al. 2014). As a result, these parameters will surely cause deterioration of the surface water quality.

Regarding the type of the ABR construction, the previous research builts the ABR in a rectangular shape, and the water flows down over the reactor (Fig. 7.1).

Figure 7.1a is a more common recognized ABR for wastewater treatment (Barber and Stuckey 1999; Bachmann et al. 1982). In comparison, Figure 7.1c was the original design developed by Fannin et al. (1981), which aimed to enhance reactor performance to maintain a high rate of a methanogen process using a vertical baffled to treat high solids slurry. Based on that research, several reactor modifications (Fig. 7.1b, h–j) were developed, which were the main driving force in designing the reactor detail to enhance the solids retention capacity (Barber and Stuckey 1999). Numerous ABR types with different designs on the baffled water flow pattern have been developed and implemented for wastewater treatment for many years. For instance, Zwain et al. (2014) introduced such design on the inclining baffled to enhance the suspended growth in ABR; some baffled modifications were improved by Jamadi and Alighardashi in 2017 to investigate the hydrodynamics characteristic (Jamadi and Alighardashi 2017), and the solids particle sedimentation improvement and methane gas production were also added by using an individual separation of the four-compartments ABR (Hahn et al. 2015).

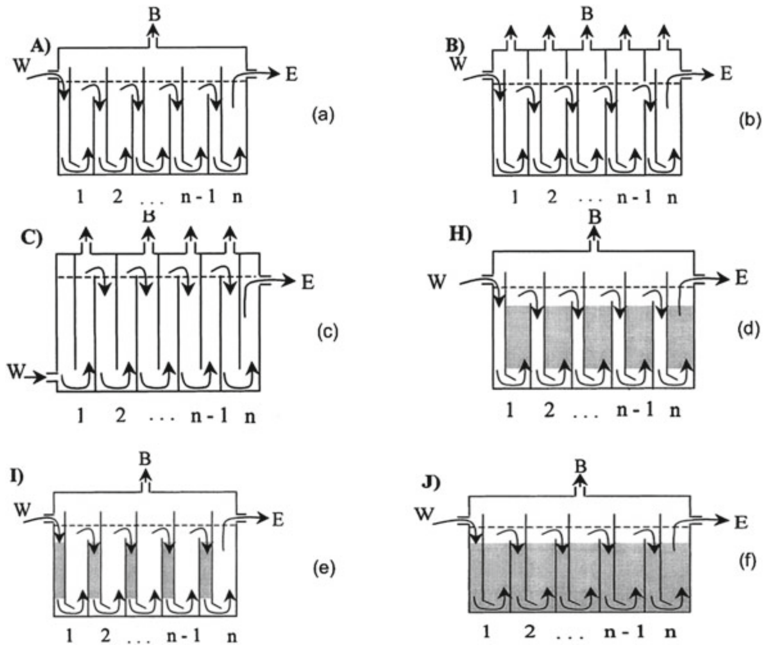


Fig. 7.1 Variation of baffled reactor. (**a**, **b**) single gas headspace, (**c**) vertical, (**h**) up-comers, (**i**) down-comers, (**j**) whole reactor, W = wastewater, B = biogas, E = effluent

Furthermore, the potential of a novel structure of the ABR extension was also tested to treat the corn ethanol wastewater in thin stillage through anaerobic treatment enhancement. This hybrid system reduced the biomass washout, increased the solids retention time, and improved solids phase separation. However, this treatment produced effluent with a higher concentration of pollutants than the discharge requirement in Indonesia (Sayedin et al. 2018). Moreover, a scum remover innovation has been applied as a lab-scale experiment in Japan. This innovation was used to treat lipid-rich wastewater and solids in wastewater. The technology eliminates COD concentration in the wastewater up to 90%, in which 70% of the COD has converted into biogas (Takuya et al. 2018).

However, in actual implementation, the rule of thumb of the upflow velocity ABR should not be higher than 2 m/h (Sasse 1998), and this number is designed as the limit upstream. A pilot scale has been implemented in the US to treat 1 m^3 of municipal wastewater (Hahn and Figueroa 2015); if the retention time was 12 h and an assumption of 0.5 m height, the reactor area required is 2 m^2 of reactor area. Moreover, the treatment of wastewater produced by 100 houses will need 400 m^2 of land area to build the rectangular ABR. ABR system has been implemented in Indonesia mainly for decentralized wastewater treatment. For instance, in Malang city (Indonesia), the ABR served about 3% of the total population and showed that the ABR could reduce BOD, TSS, NH4, and TP at 74, 66, 43, and 21%, respectively (Yulistyorini 2019a).

Nevertheless, in certain circumstances, this ABR type is challenging to implement in densely populated areas due to land area availability limitations. In addition to the ABR design, the knowledge contribution on the compact ABR achievable to construct in a densely populated place is poorly studied. The deficiency of ABR in nutrient and pathogen reduction forms is considered a crucial issue to be handled. Therefore, an innovation of the current ABR development is significantly essential to investigate the potential implementation of the compact modified ABR in the community, particularly in a densely populated area.

7.3 Anaerobic Filter for Wastewater Treatment

An anaerobic filter (AF) is an attached biofilm system where the water can be flow-through biofilm attached to the support media. Through that process, non-settleable material and dissolved solids will be removed (Morel and Diener 2006; Wang and Serventi 2019). The AF treatment process is based on the hybrid process of physical and biological treatment. The water in AF flows through the filter, and it can be operated by single-fed and multi-fed as the water passes upflow, downflow, or horizontal direction in the filter media (Rajagopal et al. 2009). It will contact the biomass on the filter media and be exposed to the anaerobic degradation process (Morel and Diener 2006). A configuration of the typical anaerobic filter is presented in the following picture.

AF is categorized as low-cost wastewater treatment technology and used as a post-treatment option for further effluent treatment (e.g., septic tank) due to its technical and economic considerations: low operation and maintenance costs, modesty in operation, and less sludge production (Oliveira Cruz et al. 2019).The application of the AF in hot-climate countries is favorable because high temperatures triggered anaerobic microorganism growth. Although this low-cost technology has several advantages on the treatment performance, it shows less significance in reducing nutrients (N and P). Therefore, further tertiary treatment is still needed to fulfill the discharge regulation (Oliveira Cruz et al. 2019). This technology can remove suspended solids and BOD typically as 50–80%, but nitrogen removal is limited to 15% (Tilley et al. 2014). The AF can be applied for household wastewater treatment or a decentralized system in a more extensive catchment area. The following table has listed the advantages and disadvantages of the AF application (Table 7.1).

AF has been widely adopted for treating numerous types of wastewaters, and it can be implemented for high and low strength wastewater. Yet, organic loading rate (OLR) is becoming a limiting variable when the AF is fed by high-strength wastewater (Rajagopal et al. 2009). It has been implemented in rural Brazil to reduce wastewater treatment effluent treatment using a septic tank. Then, the effluent of the AF was further treated in a sand filter. It was reported that the quality of the treated wastewater by AF was met European legislation standards (Oliveira Cruz et al. 2019). Treatment of high-strength dairy wastewater was also proved by using AF, and it was observed at short HRT and high OLR (Prazeres et al. 2012). As

Table 7.1 Advantages and disadvantages of anaerobic filter

Advantages	Disadvantages
No electrical is acquired	Demanding of the detail design construction
Low operating costs	Less pathogens and nutrients reduction
Durable service	Tertiary treatment is required
Efficient on the organic matter and solids removal	Clogging issues
Low sludge production	Cleaning of the clogged filter is needed
Less area requirement	

Source (Tilley et al. 2014)

used for the pretreatment of cheese whey, the upflow anaerobic filter (UAF) can be removed COD for more than 90% (Prazeres et al. 2012; Gannoun et al. 2008). UAF was also revealed as a promising method for treating cold meat industry wastewater because it can be efficiently removed COD and BOD for 81–87%, respectively, for over 15 days. This work was possible to startup the UAF treatment in a short period (León-Becerril et al. 2016). Bouted and his co-worker conducted improvement of AF treatment system. The addition of insulation into the AF was used to treat office building wastewater. They added the electric heater to stimulate the waste heat input from the air conditioner into an insulated anaerobic filter (Bouted and Ratanatamskul 2018). This method promoted a high reduction of SS, COD, TKN, and TP at 68, 61, 51, and 21%, respectively, for heat application of 4.7 Wh.

In Indonesia, AF is widely used for decentralized wastewater treatment in which most of them are hybrid systems with ABR (Yulistyorini 2019a). This hybrid system was also implemented in Malang city mainly for domestic wastewater treatment in the small residential area.

7.4 Experimental Study of the Hybrid System (ABR and AF)

7.4.1 Lab-Scale Hybrid System

A lab-scale experiment was conducted to investigate the efficiency of the hybrid ABR-AF in treating wastewater of the Islamic boarding school in Malang, Indonesia. An ABR system uses in treating collected wastewater from the boarding school, and raw sewage was taken from the inlet. The wastewater was pumped into a 250-L container equipped with a mixer blade to keep the wastewater homogenous before being fed into the hybrid system. A peristaltic pump was inserted to maintain a specific flow rate of wastewater that fed into the hybrid ABR-AF system (Fig. 7.3).

The hybrid reactor is made from acrylic that consists of four baffled compartments and six AF. The AF was filled with palm fiber, gravel, and volcanic sand. The first compartment was used for sedimentation to reduce the solid particle concentration before flew into the next chamber. The dimension of the hybrid system was 143.75-cm length × 43.75-cm width × 50-cm height.

The hybrid system was operated in intermittent flow rate using a peristaltic pump. The total flowrate was 220 ml/min for a detention time of 24 h.

7.4.2 Sampling and Parameter Analysis

The continuous wastewater sample was collected from three different sampling ports in the reactor as inlet (1), compartment before anaerobic filter (4), and outlet (11). The continuous samples were collected in 2 months, and they were taken every 2 days. In addition, several domestic wastewater parameters of BOD, COD, TSS, NH_3, PO_4, and total coliform were analyzed to investigate the hybrid system's efficiency in organic pollutant reduction.

7.5 Results and Discussion

7.5.1 Wastewater Characteristic

The wastewater characteristic results at different sampling ports of the hybrid system (Table 7.2) show the domestic wastewater parameters at separate treatment compartments. It shows the concentration in all parameters declined in ABR and UAF compartments at 24 h HRT. The BOD and TC concentration after UAF meets

Table 7.2 Wastewater characteristic at different sampling ports

Parameters	Units	Influent	Before UAF, compartment 4	Effluent
BOD	mg/l	218 ± 33	86 ± 20	26 ± 3
COD	mg/l	550 ± 123	306 ± 30	116 ± 9.6
TSS	mg/l	124 ± 24	34 ± 4	13 ± 2
NH_3	mg/l	44 ± 5.4	26 ± 3	14 ± 1.7
PO_4	mg/l	9 ± 1	7.4 ± 1	5 ± 1
Total coliform	MPN/100 ml	1,487 ± 138	747 ± 141	317 ± 105
DO	mg/l	0.58 ± 0.19	0.8 ± 0.39	1.63 ± 0.35
pH		7.5 ± 0.19	7.3 ± 0.24	7.28 ± 0.29

the national domestic wastewater discharge requirement, while the other parameter concentration was slightly higher than the standard (COD = 100 mg/l, TSS = 10 mg/l, NH_3 = 10 mg/l). The average PO_4^{3-} concentration was reduced to only about 4 mg/l.

7.5.2 Performance of the Hybrid System

Table 7.3 reveals organic pollutant removal efficiencies at a different stage in the combination of ABR and UAF reactor. The system shows excellent in reducing BOD and TSS, although the TSS removal efficiency decreased in UAF. Most of the ABR treatment conveys BOD, and TSS elimination results above 80% (Yulistyorini 2019a, b). In this study, the overall reduction of BOD and TSS was 88 and 90%, respectively. The first stage of the treatment occurred in several ABR compartments, leading to removing 72% solids particles from wastewater. The woven coconut fiber inserted in the third compartment help to reduce the velocity of the wastewater flow and enhance the settling of solids particle. This also occurred in a similar method for domestic wastewater using the addition of lamella in ABR. Yulistyorini and coworkers proved that the lamella increased the TSS settling of domestic wastewater up to 93% (Yulistyorini 2019c).

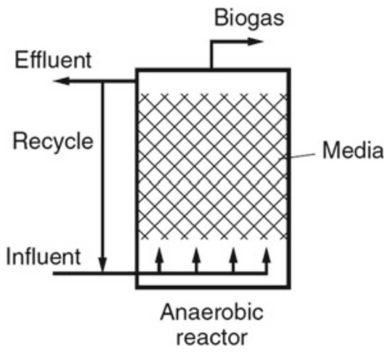
Additionally, TSS was also removed in filter media in which there were six UAF compartments filled with coconut fiber, gravel, and volcanic sand (Fig. 7.2). Solid particles were trapped in the filter media, and this treatment allowed a total reduction of 90% (Table 7.2, Fig. 7.6e). The high efficiency of solid removal in UAF was also proven by Igor et al. (Bodık et al. 2002), where they removed the TSS up to 93% (Table 7.3). The settling of the solids particle influences the elimination of BOD and COD from water as the higher suspended sediment triggers the organic material reduction (Jingsheng et al. 2006).

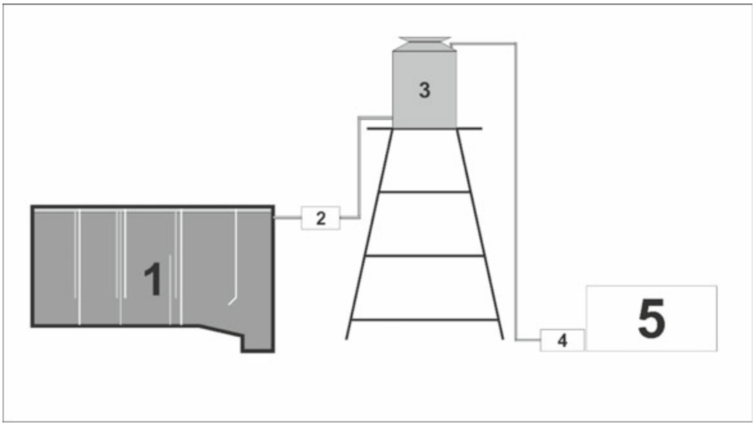
BOD and COD removals were 88–78%, respectively. These reductions are due to settling the solids particle and the high concentration of biodegradable organic material in the wastewater. The removal efficiency of BOD and COD in this study is higher than the treatment in ABR conducted by Nasr et al. (Nasr et al. 2009b).

Table 7.3 Pollutant removal efficiencies at a different stage

Parameters	First stage (ABR, %)	Second stage (UAF, %)	Overall (%)
BOD	61	69	88
COD	46	61	78
TSS	72	62	90
NH_3	40	48	70
PO_4	14	22	34
Total coliform	49	51	75

Fig. 7.2 Anaerobic filter configuration (Metcalf and Eddy 2014)



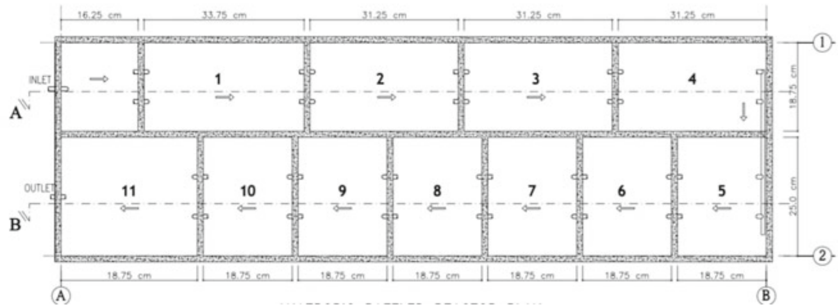


1.Hybrid ABR & UAF; 2. Peristaltic pump; 3. Wastewater tank; 4 Wastewater pump; 5. Wastewater treatment plant

Fig. 7.3 Setting-up lab-scale of the hybrid ABR-UAF

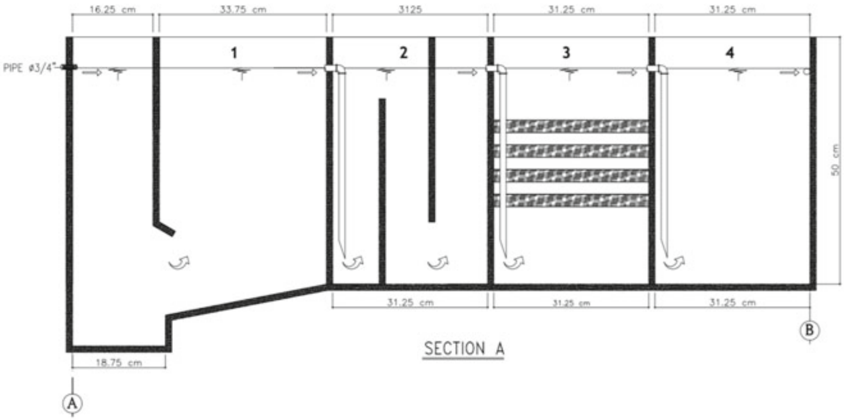
Organic matter in wastewater degraded faster from an average 218 mg/l to 26 mg/l and 550 mg/l to 116 mg/l, respectively (Table 7.1). Figures 7.6a and b showed that the concentration decreased faster in ABR and UAF. Although the concentration of untreated wastewater fluctuated, the final effluent of BOD meets the discharge consent, while the COD is just a bit higher. The ratio of BOD and COD of untreated wastewater and compartment four was 0.4 and 0.3, respectively (Fig. 7.7), and these values indicated that the wastewater is biodegradable (Kumar et al. 2010). Microorganisms in the attached biofilm in UAF can decompose organic matter in wastewater and cause the reduction of BOD and COD concentration (Peng et al. 2020).

Nutrient removal in the hybrid system showed higher NH_3 than PO_4, with a total removal efficiency of 70 and 34%, respectively. The average nutrient removal at three different sampling ports (e.g., inlet, compartment 4, outlet) was 44, 26, 14, and 9, 7, 5 $_{mg}$/l for NH_3 and PO_4. The chart (Fig. 7.6c, d) reveals that the concentration of

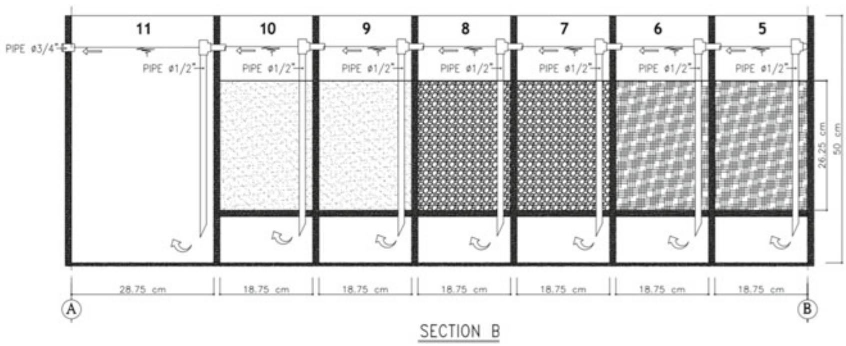


1. Sedimentation; 2. Baffled compartment; 3. Compartment with woven coconut fibre; 4. Baffled compartment; 5&6. UAF with coconut fibre; 7&8. UAF with gravel; 9&10. UAF with volcanic sand; 11. Final compartment

A. Top view



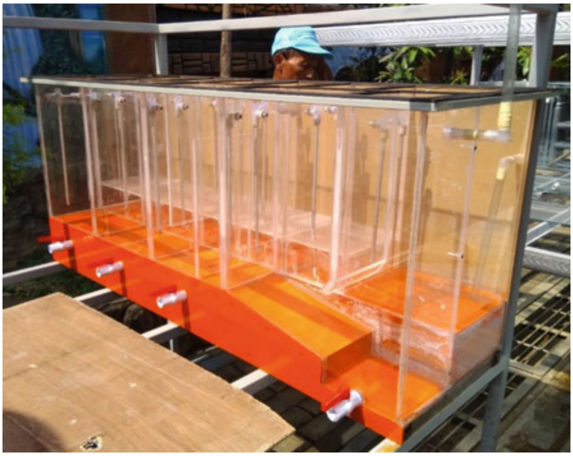
B. Section A



C. Section B

Fig. 7.4 Design of the hybrid ABR and UAF reactor

Fig. 7.5 Hybrid lab-scale



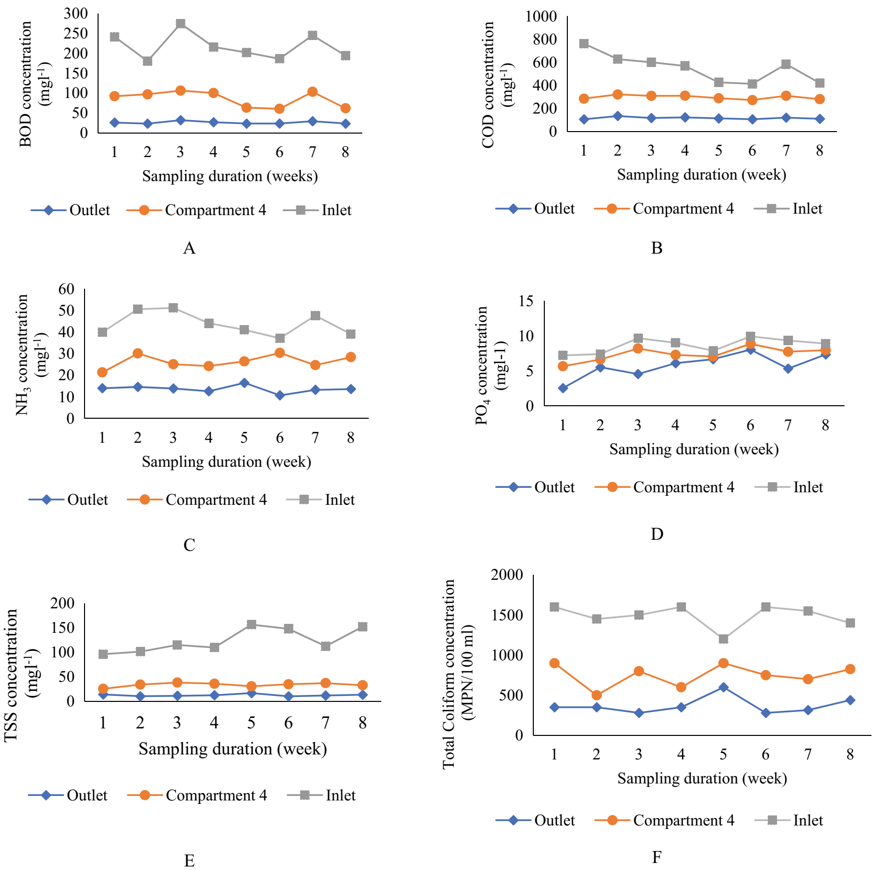


Fig. 7.6 Performance of the hybrid ABR and UAF on wastewater treatment

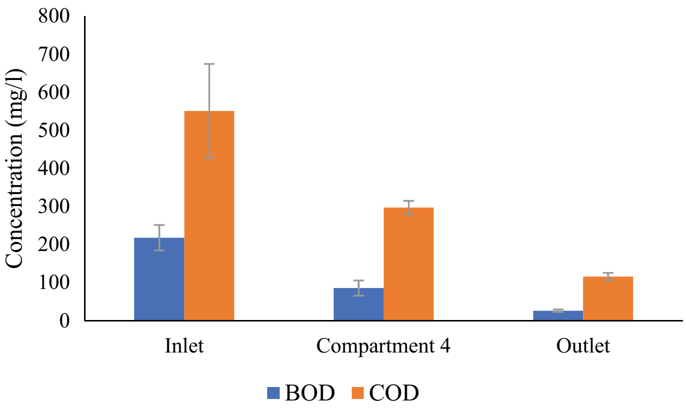


Fig. 7.7 BOD:COD ratio at the different sampling port

NH_3 in the effluent is quite stable, while the concentration of PO_4 relatively increased over time. Decreasing NH_3 in the hybrid system was caused by the nitrification and denitrification process (León-Becerril et al. 2016) and biomass (Peng et al. 2020). The optimal temperature will enhance the nitrogen removal process, in which the temperature in this study ranges from 25 °C to 31 °C. It was better for the nitrification and denitrification processes (Rodziewicz et al. 2019).

Furthermore, PO_4 concentration decreased from 9 to 5 mg/l, respectively, from inlet to outlet. However, the concentration of 5 mg/l PO_4 in the outlet is still categorized high for domestic wastewater. It is probably due to the use of detergent and soap for cleaning purposes in the boarding school. Phosphorus cannot be removed from either aerobic or anaerobic wastewater because it is generally eliminated by bacterial removal (active sludge) or phosphate fixing solids through sedimentation (Sasse 1998b). This is proven by the higher TSS removal at 90% and phosphorus fixation in the settlement biomass. Besides, enhanced biological phosphorus removal (EBPR) using polyphosphate-accumulating microorganisms (PAO) is responsible for PO_4 removal as PAOs consume biodegradable organic carbon and store it as polyhydroxyalkanoate (Yadav et al. 2014).

Total coliform (TC) consists of E. coli, salmonella, and coliforms, neutrophils microorganisms (Kumatse et al. 2020).In this study, the average TC concentration was very high in untreated wastewater (1,487 MPN/100 ml). However, after treatment, the concentration decreased up to 317 MPN/100 ml, meeting the Indonesian discharge wastewater effluent. As neutrophil microorganisms are grown at $pH > 7$, the alkaline condition could make the pathogens inactive. Additionally, the elimination of TC in wastewater was also triggered by the formation of biofilm in UAF.

7.6 Conclusion

It was possible to establish a detention time of 24 h for decentralized domestic wastewater treatment in the present work. The hybrid system has shown good performance in treating domestic wastewater from Islamic boarding schools. Removal efficiencies were 88, 78, 90, 70, 34, and 75% for parameters of BOD, COD, TSS, NH_3, PO_4, and total coliform. However, further tertiary treatment for phosphorus removal is required, or PAO can be added into the system to reduce phosphorus.

7.7 Recommendation

ABR is a low-cost technology suitable for various wastewater treatments for domestic and industrial wastewater. The ABR compartments and filter hybrid provide multi-function of the system to reduce the solids and organic matter in the wastewater and produce clean water that meets the discharge consent regulation.

The hybrid of the ABR and AF has potentially been implemented in developing countries for various wastewater types, particularly biodegradable wastewater. The technology offers low operational and maintenance costs and no energy requirement but efficiently removes organic matter and solids particles. Additionally, as the technology is anaerobic treatment, the hybrid system can generate methane for renewable energy. In the future, the system can be implemented in the community to treat the wastewater from several houses, particularly in a densely populated area.

The development of the ABR and AF as wastewater treatment will assist in realizing the sustainability of water and sanitation, ensure affordable, sustainable energy, and make a hygiene human settlement and resilient urban living. These efforts will contribute to SDG realization in developing countries, particularly in Indonesia.

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Chapter 8
Remediation of Heavy Metal Pollutants of Industrial Effluents and Environmental Impacts

Kavita Parmar, Vineeta Parmar, and Purabi Saikia

Abstract A variety of effectual, non-polluting, and economical nanomaterials have been developed, having special capabilities for the potential purification of industrial effluents. Improper disposal of effluent generated from different industries or mining activities affects the ecosystem through increased metal pollution and biodiversity loss. It has significant detrimental effects on the health of aquatic ecosystems through increased nutrient loads that can lead to eutrophication and temporary oxygen deficits and also a serious negative impact on ecosystems due to heavy metals (HMs) bioaccumulation in the food chains. Nano-metal silicate tubes (NMSTs) synthesized through the silica garden route are considered important materials for the removal of HMs from industrial effluents. The present chapter is emphasized on nano calcium silicate precipitation tubes (CaSPT) as HMsl (Zn(II), Cd(II), Cu(II), Pb(II), and Cr(III)) adsorbents in an aqueous medium to identify its application as water purifier after thorough physicochemical characterization. With the increase in initial metal ion concentration, the absorption process moved towards irreversibility. Adsorbent dose and its initial concentration has significant impacts on adsorption, and it varies non-linearly. CaSPT was identified as a superior adsorbent of HM ions as compared to the conventional non-tubular calcium silicate tube due to its high surface area. Nano CaSPT was successfully applied in an effluent sample collected from the electroplating industry to remove Cr(III), Zn(II), and Pb(II).

Keywords NMST · Silica Garden · Surface property · Adsorption · Heavy metals · Effluent · Environment

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8.1 Introduction

Heavy metals (HMs) are a group of inorganic chemical hazards that lead to the reduced ability of the environment to foster living beings and their health. Soils may become contaminated by the accumulation of HMs through emissions from the rapidly expanding industrial metallurgical and mining activities, disposal of high metal wastes, lead-based gasoline and paints, agricultural practices with application of inorganic fertilizers, animal manures, improper disposal of municipal solid wastes, sewage sludge, pesticides, wastewater irrigation, coal combustion residues, oil spills, and atmospheric deposition (Khan et al. 2008; Zhang et al. 2010). Various industrial activities and processes produce liquid effluents containing toxic HMs such as Cu(II), Pb(II), Zn(II), Cd(II), and Cr(III). Effluents from mining, metallurgical, electroplating, battery manufacturing, paints and pigments, chemical, ceramics, coating, electrical, and electronic large-scale industries are the major source of HM contamination of water (Sandhya and Tonni 2003). Zinc is a naturally occurring HM that acts a micronutrient for plants and the increased concentration of Zn(II) due to different human activities beyond the transmissible limits may cause serious health problems (Nriagu 2007). Cd(II) is an extremely toxic metal commonly found in industrial workplaces. The major sources of Cd contamination in wastewater include waste generated and discharged from metallurgical alloying, metal plating, photography, ceramics, pigment and colouring works, electroplating, textile printing, mining, and sewage sludge (Eckenfelder 1989). Cadmium is accumulated in the human body and creates a range of health issues including nausea, salivation, diarrhoea, muscular contraction and pain, renal degradation, skeleton malformation, erythrocyte demolition to pulmonary disorders (Dinesh and Singh 2002; Ozar and Pirincci 2006). Lead is a recognized pollutant (Gueu et al. 2007) that comes from different sources of industrial activities such as lead smelting, paints and pigments industries, coating, battery manufacturing, and storage. Permissible values of Pb in drinking water are 10(EU), 50(USEPA), and 10 μg/l(WHO) (Bhattacharjee et al. 2003). Pb(II) creates adverse effects on human health and also causes serious environmental problems beyond its acceptable limits. Chromium is a type of pollutant that enters in the form of Cr(III) and Cr(VI) in the air, water, and soil through natural processes and human activities. Steel, leather, electroplating, and textile manufacturing industries are the main sources that increase the concentrations of Cr(III) (Rafatullah et al. 2009). The recommended exposure limit for Cr(III) uptake is 0.5 m gm^{-3} and shortage may cause heart conditions, disruptions of metabolisms, and diabetes (Sandhya and Tonni 2003). Treatment of HMs from wastewater is required for quality control of soil, air, water, and human and animal health. Developed HM remediation technologies (physical, chemical, and conventional) are not feasible due to demanding costs, time-consuming, and polluted sludge discharge to the environment (Masini and Muedi 2018) that can cause serious bioaccumulation problems.

Self-organized tubular structures developed through precipitation reaction of metal salt crystals in aqueous sodium silicate are known as *silica gardens* (Coatman et al. 1980). The applicability of silicate compounds synthesized from more than three-centuries-old silica garden phenomenon has less been explored (Collins et al. 1999; Parmar et al. 2009, 2010, 2011, 2012). Nano calcium silicate precipitation tube (CaSPT) synthesized through the *silica garden* route exhibited adsorption potential for various HM ions through additional surface properties. Therefore, the present study aimed to explore the efficiency of nano CaSPT as a multi-functional water purifier and as an adsorbent for a wide range of HM ions with special emphasis on sludge disposal.

8.2 Materials and Methods

8.2.1 Adsorbent (Nano CaSPT)

The present study used a calcium silicate precipitation tube (CaSPT) as an adsorbent for the removal of HMs. Silicate precipitation tubes of Ca(II) used in the present research were synthesized in the laboratory.

8.2.1.1 Synthesis of Nano CaSPT

20 ml commercial sodium silicate was diluted with 60 ml ultrapure water in a 100 ml glass beaker that was stirred continuously to make a homogeneous solution. The pH of the solution was 11.9, and the silica content was 9.46%. Then, ~0.2 g solid $CaCl_2.2H_2O$ crystals were added to the solution and bristle-like tubular structures began to grow from the bottom of the beaker almost instantaneously. The growth of nano CaSPT tubes at different time intervals was photographed over a period of 30 min and kept the tubes overnight and then collected, washed, and preserved for detailed characterization and adsorption studies.

8.2.2 Adsorbate [Zn(II), Pb(II), Cd(II), Cu(II), and Cr(III)]

$ZnSO_4.7H_2O$, $Pb(NO_3)_2$, $CdCl_2$, $CuSO_4.5H_2O$, and $Cr(NO_3)_3.9H_2O$ of AR grade were used for the preparation of solutions of Zn(II), Pb(II), Cd(II), Cu(II), and Cr(III), respectively. Solutions were prepared from a stock solution of 1000 mg l^{-1} by the serial dilution process using 18 MΩ ASTM Grade 1 water.

8.2.3 Adsorption Experiments

All adsorption experiments were carried out in batches in stoppered conical flasks containing 50 ml of adsorbate solution of desired strength (initial concentration, C_0), pH, and known weight (mg) of the powdered nano CaSPT. For adsorbate–adsorbent contact, a horizontal orbital shaker was used with a contact time of 60 min. In selected cases, however, for detailed adsorption study, equilibrium contact time was determined. After adsorbate–adsorbent contact, the solution was kept aside for 60 min to settle down, then filtered and analysed for the final concentration of the adsorbate species (final concentration C_e).

Percentage of adsorbate (M) is calculated as,

$$\mathrm{Ad_M} = \frac{c_o - c_e}{c_o} \times 100\mathrm{Ad_M} = \frac{c_o - c_e}{c_o} \times 100 \tag{8.1}$$

Amount (mg) X of metal ion on adsorbate is calculated as,

$$X = \frac{c_o - c_e}{1000} \times 50X = \frac{c_o - c_e}{1000} \times 50 \tag{8.2}$$

8.3 Results and Discussion

The synthesized CaSPT tubes appeared bristle-like, brittle in nature and looked different from Co(II) and Fe(III) tubes. Its growth was also slower as compared to Co(II) and Fe(III) silicate tubes (Parmar et al. 2009, 2010). The photographs of nano CaSPT during synthesis over a period of 30 min are shown in Fig. 8.1.

8.3.1 Microscopic Study

The tubular structure is clearly visible in the SEM image of CaSPT ‘as grown’, while the SEM image of powdered form exhibited spherical globules with a porous network. The TEM image had a ladder-like appearance with longitudinally running intertwined rope-like strands of about 20 nm diameter connected transversely with similar strands. CaSPT ‘as synthesized’, scanning electron microscopy (SEM) image of CaSPT ‘as grown’, powdered SEM image of CaSPT, and powdered transmission electron microscopy (TEM) image of CaSPT are shown in Fig. 8.2a–d.

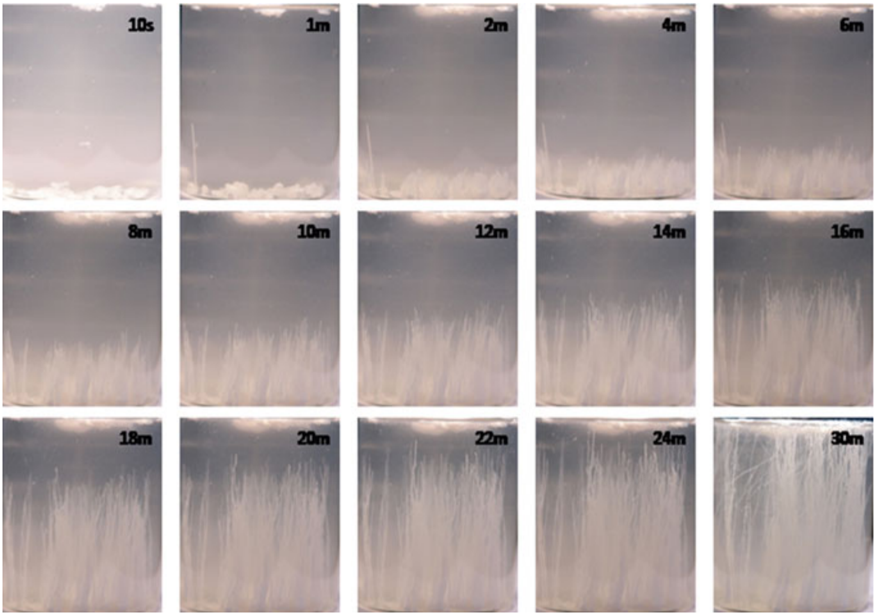

Fig. 8.1 Photographs of nano CaSPT during synthesis

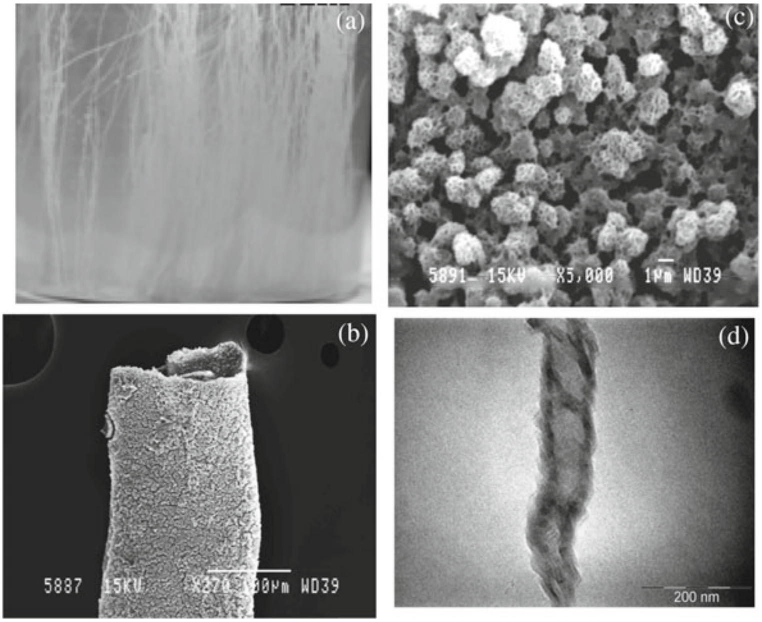

Fig. 8.2 **a** 'As synthesized', CaSPT, **b** SEM image of 'as grown' CaSPT, **c** SEM image of powdered CaSPT, and **d** TEM of powdered CaSPT

Table 8.1 Surface property of nano CaSPT

Surface property	CaSPT
BET surface area $\left(m^2\ g^{-1}\right)$	141.5
Pore volume $\left(cm^3\ g^{-1}\right)$	0.39
Pore radius (Å)	18.3
IEP	3.41
Surface charge	2.15×10^{-2} equivalence of H^+/g of CaSPT

8.3.2 *Surface Property Investigation*

BET surface area, pore volume, and pore radius of nano CaSPT were estimated using N_2 adsorption. The results along with isoelectric point (IEP) and surface charge have been listed in Table 8.1.

8.3.3 *Batch Adsorption Experiments*

Stoppered conical flasks containing 50 ml of HM ion solution of desired strength (initial concentration, C_0), pH, and known weight (m) of the synthesized CaSPT were carried out in batches for all adsorption experiments. Adsorbate–adsorbent contact time was consistently maintained at 60 min, followed by settling for 60 min, filtration, and analysis for final concentration (Ce). The amount of metal ion adsorbed on the CaSPT surface was calculated by subtraction (C_0-Ce). The absorption/ desorption envelope of Cd(II), Zn(II), Cu(II), Pb(II), and Cr(III) on the CaSPT surface was developed in the pH range of 2–9. Dilute NaOH and HCl were used for pH adjustments and the pH range was 2–9 in adsorption. On the other hand, in desorption, Cd(II), Zn(II), Cu(II), Pb(II), and Cr(III) were adsorbed over CaSPT without any pH adjustment for 60 min. This was followed by pH adjustment of the mixture in the range 2–9; another shaking time was 60 min in the horizontal shaker, settling for 30 min, filtration and analysis for final Cd(II), Zn(II), Cu(II), Pb(II), and Cr(III) concentration (C_e'). Amount of HM ions trapped on the CaSPT surface after desorption was calculated by subtraction (C_0-C_e'). For kinetic study, the contact time was varied from 5 to 180 min. Effect of temperature on Cd(II), Zn(II), Cu(II), Pb(II), and Cr(III) adsorption over CaSPT surface was studied at 25, 30, 40, and 50 °C with 50 ml of fixed Cd(II), Zn(II), Cu(II), Pb(II), and Cr(III) concentration and varying CaSPT weights. Except these, all other experiments were carried out at room temperature, 27 °C. Adsorption/desorption envelope of Cu(II) and Pb(II) on CaSPT surface was developed in the pH range of 2–7. For Zn(II), Cd(II), the pH range was 2.0–9.0, and for Cr(III), pH range was 2–8. Cd(II), Zn(II), Cu(II), Pb(II), and Cr(III) adsorption isotherms on CaSPT surface were developed at 0.01 g of CaSPT weight and metal ion concentrations.

Table 8.2 Adsorption screening of cations with Nano CaSPT as adsorbent

Adsorbate ion	Initial concentration (C_0) mg l^{-1}	Final concentration (C_e) mg l^{-1}	% Adsorption
Cu(II)	100.3	0.71	99.3
Co(II)	81.4	76.2	6.3
Ni(II)	98.7	91.1	7.8
Zn(II)	109.6	17.4	84.1
Cd(II)	7.6	0.16	97.9
Pb(II)	37.1	0	100.0
Cr(III)	90.1	0	100.0
Cr(VI)	98.6	95.4	3.2
Mn(II)	9.9	3.99	59.7
Hg(II)	0.14	0.07	

8.3.4 Adsorption Screening of HM Ions with CaSPT

'As synthesized' CaSPT was assessed as an adsorbent with reference to a number of cations including Cu(II), Ni(II), Zn(II), Pb(II), Co(II), Cd(II), and Cr(III) in the aqueous solution. 0.01 g of CaSPT and 50 ml of test solution were used in each case for the purpose of screening. It is interesting to observe that 'as synthesized' CaSPT exhibits positive affinity towards all the HM ions under consideration except Cr(VI), Co(II), and Ni(II) (Table 8.2). Based on these observations, Cu(II), Pb(II), Zn(II), Cd(II), and Cr(III) were picked up for a detailed adsorption study.

8.3.5 Metal Ion Adsorption on Nano CaSPT

8.3.5.1 Effect of Adsorbent Dose

Effect of adsorbent dose on individual uptake of Cd(II), Cu(II), Cr(III), Pb(II), and Zn(II) using nano CaSPT for a range of metal ion concentrations showed that metal uptake increases with an increase in adsorbent weight non-linearly in all the cases (Fig. 8.3). Complete removal could be achieved for all the metal ions at certain concentrations albeit with different CaSPT weights. For example, 0.07 g CaSPT could remove complete Cd(II) from 50 ml of 100 mg l^{-1} solution. It was 0.035 g CaSPT for 50 ml 99.4 mg l^{-1} Cu(II), 0.05 g CaSPT for 50 ml 50 mg l^{-1} Cr(III), 0.03 g CaSPT for 50 ml 300 mg l^{-1} Pb(II), and 0.07 g CaSPT for 50 ml 100 mg l^{-1} Zn(II). Prima facie shows that CaSPT have been found as the best medium for the removal of Pb(II) out of the all five studied HM ions.

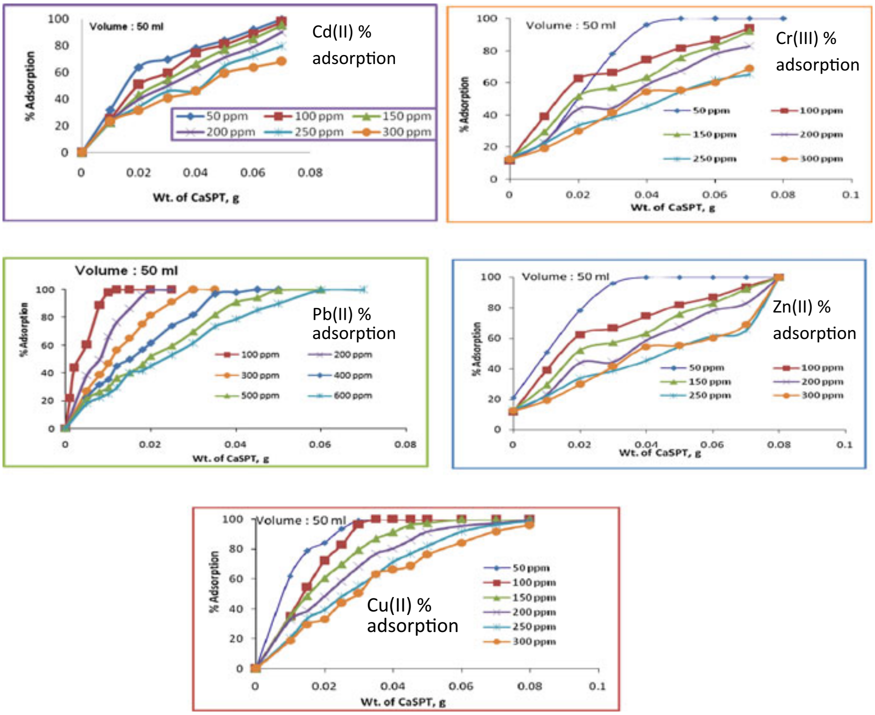

Fig. 8.3 Effect of adsorbent dose on Cd(II), Cu(II), Cr(III), Pb(II), and Zn(II) % adsorption by CaSPT

8.3.5.2 Effect of pH on Adsorption/Desorption

The pH range of the adsorption–desorption hysteresis curve of five metal ions on a nano CaSPT surface was different for different metal ions (Fig. 8.4). In the case of Cd(II), pH ranged from 2.0 to 9.0, while for Cu(II), Cr(III), Pb(II), and Zn(II), it was 2.0–7.0, 2.0–9.0, 2.0–7.0, and 2.0–9.0, respectively. For all the metal ions, desorption followed a different path from adsorption, and each metal ion was characterized by a desorption domain, i.e. a pH range within which desorption was likely to occur. This information may be useful for eco-friendly sludge disposal.

8.3.5.3 Adsorption Isotherms

Adsorption isotherms on nano CaSPT were developed for Cd(II), Cr(III), Cu(II), Pb(II), and Zn(II) at 0.01 g of adsorbent weight and Langmuir and Freundlich isotherm equations were used for interpreting the adsorption data. The detailed model and methodology were adopted to obtain model parameters based on earlier research (Parmar et al. 2011). Langmuir and Freundlich parameters for each metal

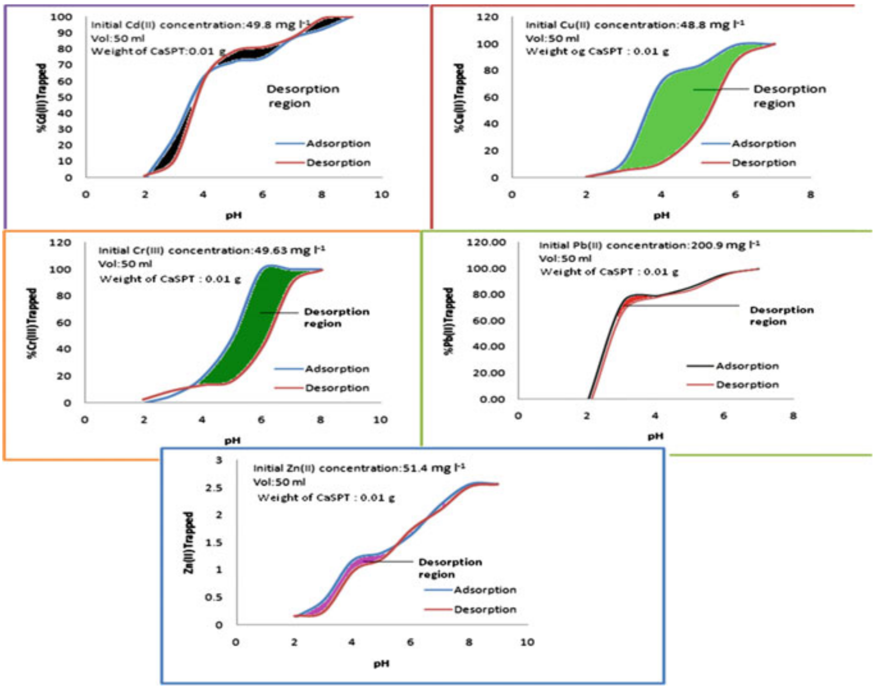

Fig. 8.4 Effect of pH on Cd(II), Cr(III), Cu(II), Pb(II), and Zn(II) adsorption and desorption

ion were determined through linearization and direct optimization (SOLVER) techniques (Table 8.3). The R^2 value indicates agreement between $\left(\frac{x}{m}\right)_{exp}$ and [illegible] using the

Table 8.3 Freundlich and Langmuir isotherm constants for Cd(II), Cu(II), Cr(III), Zn(II), and Pb(II) adsorption on 0.01 g of CaSPT weight

Adsorbate (0.01 g)	Model	Langmuir			Freundlich		
		b (ml mg^{-1})	V_m (mg g^{-1})	R^2	K_f (mg g^{-1})	n	R^2
Cd(II)	Solver	0.0159	331.9	0.998	31.02	2.52	0.998
	Linear	0.0193	312.5	0.991	27.1	2.36	0.981
Cu(II)	Solver	0.169	262.9	0.999	125.8	7.70	0.854
	Linear	1.69	263.1	0.999	114.8	6.66	0.850
Cr(III)	Solver	0.021	290.2	0.985	36.3	2.82	0.990
	Linear	0.026	333.3	0.990	40.4	3.02	0.981
Zn(II)	Solver	0.020	200.0	0.962	2.79	1.33	0.952
	Linear	0.014	250.0	0.774	5.33	2.11	0.901
Pb(II)	Solver	1.01	728.5	0.986	487.9	13.76	0.903
	Linear	1.02	729.9	0.990	476.4	13.15	0.918

corresponding isotherm parameters. For all the five HM ions, experimental adsorption data fit reasonably well in both Langmuir and Freundlich isotherm equations using direct optimization (SOLVER) and linearization techniques. However, between the two Langmuir's fit was consistently better than Freundlich's.

8.3.5.4 Comparison of Adsorption Loading Capacity

Nano CaSPT as an adsorbent ranks quite high amongst a range of adsorbents with high Cu(II), Pb(II), Cr(III), Cd(II), and Zn(II) loading capacity, as available in the literature (Table 8.4). The loading capacity of CaSPT reported for various metal ions is based on a single weight (0.01 g) of CaSPT which is testimony to the multi-functional nature of CaSPT as an adsorbent.

8.3.5.5 Adsorption Kinetics

Adsorption kinetics of five HM ions on the nano CaSPT surface was studied in the temperature range of 298–323 K, and the data were interpreted with Lagergren's first order (Lagergren 1898) and pseudo-second-order (Ho and McKay 2000) rate equations. Specific rate constants k_L and k_p for first- and second-order equations for each metal ion were calculated at 25°, 30°, 40°, and 50 °C from experimental data through regression analysis (Table 8.5), and the kinetic data of all the metal ions fitted better in pseudo-second-order model. Specific rate constants were calculated at four different temperatures (298, 303, 313, and 323 K) in both first- and second-order rate equations and the activation energy (E_a) of the adsorption process was calculated from the Arrhenius equation (Parmar et al. 2011). The activation energy was less in pseudo-second-order than in the first order in all the metal ions and clearly signifies that the adsorption of all the five metal ions on nano CaSPT was essentially physisorption as the activation energy is within the range of physisorption. The activation energy range for a physisorption process is 5–40 kJ mol^{-1}, while it is 40–800 KJ mol^{-1} for the chemisorption process (Nollet et al. 2003).

8.3.5.6 Adsorption with CaSPT, NT-CaSi(1), and NT-CaSi(2)

The adsorption efficacy in a mixed matrix of Cu(II), Cd(II), Cr(III), Pb(II), and Zn(II) by CaSPT along with additional NT-CaSi(1) and NT-CaSi(2) (Bhattamishra et al. 2008) has been tested after successful adsorption study of individual adsorbate as Cu(II), Cd(II), Cr(III), Pb(II), and Zn(II) by CaSPT. HM ion adsorption by CaSPT, NT-CaSi(1), and NT-CaSi(2) was studied separately with single and mixed matrices that have been summarized in Table 8.6 (Parmar et al. 2012). It is evident that CaSPT is a superior adsorbent compared to the non-tubular calcium silicate (NT-CaSi(1) and NT-CaSi(2)) in both single and mixed matrices.

Table 8.4 Comparison of Cu(II), Pb(II), Zn(II), Cd(II), and Cr(III) loading capacity of CaSPT with some high loading adsorbents

Adsorbent	Adsorption loading capacity (mg g^{-1})					Sources
	Cu(II)	Pb(II)	Zn(II)	Cd(II)	Cr(III)	
Newspaper pulp	27.7					Chakravarty et al. (2008)
Resin	85					Quanyuan et al. (2008)
Slag	26–88.5					Quanyuan et al. (2008)
Litter of poplar forest	30–200					Miranda et al. (20102010)
Fly ash	207.3					Shaobin et al. (2007)
Chitosan	222					Sandhya and Tonni (2003)
Potato peel charcoal	150–400					Miranda et al. (20102010)
CAM soybean straw	1271					Miranda et al. (20102010)
Sericitic Pyrophyllite(SP)		32.5				Prasad et al. (2000)
Red mud			14.5	13.0		Gupta and Sharma (2002)
Rice husk		11.0				Chuah (2005)
Chromite mine overburden		27.54		22.4		Mohapatra and Anand (2007)
Nickel laterite (low iron)		28.4		11.0		Mohapatra et al. (2009c)
Nickel laterite (high iron)		44.4		13.2		Mohapatra et al. (2009c)
Red bauxite		64.3	65.8	38.7		Rout et al. (2009a)
Iron ore slime		63.5	54.8	34.7		Mohapatra et al. (2009b)
Nalco Plant Sand		21.7	51.2	58.1		Mohapatra et al. (2009a)
Water washed clay			3.04	11.6		Samir (2008)
Chemically treated clay		48.1	15.2	12.6		Samir (2008)
Washed and treated clay		52.6	15.1	24.4		Samir (2008)
Low-grade manganese ore		142.8	98.0	59.1		Rout et al. (2009b)
Meranti sawdust	32.05	34.2			37.8	Rafatullah et al. (2009)
Chabazite-phillipsite	0.37				0.25	Li et al. (2007)
Clinoptilolite	25.4	124			2.4	Rout et al. (2009b)
Blast furnace sludge	16.1	64.2			9.6	Lopez-Delgado et al. (1998)
Peanut husk	10.15	29.1			7.67	Li et al. (2007)

(continued)

Table 8.4 (continued)

Adsorbent	Adsorption loading capacity (mg g^{-1})					Sources
	Cu(II)	Pb(II)	Zn(II)	Cd(II)	Cr(III)	
Nano CaSPT	262.9	728.5	200	331.9	290.2	Present work

Table 8.5 Specific rate constants k_L, k_P, activation energy E_a of different metal ions adsorption on CaSPT at different temperatures

Metal ion	Temp. (K)	Lagergren first order			Pseudo second order		
		k_L (min^{-1})	R^2	E_a (KJ mol^{-1})	$k_p \times 10^3$ (g mg ^{1} min^{-1})	R^2	E_a (KJ mol^{-1})
Cd(II)	298	0.014	0.934	28.12	0.22	0.979	9.18
	303	0.015	0.948		0.24	0.992	
	313	0.020	0.995		0.25	0.994	
	323	0.030	0.909		0.30	0.989	
Cu(II)	298	0.014	0.992	27.35	0.18	0.991	17.1
	303	0.016	0.940		0.19	0.995	
	313	0.023	0.992		0.23	0.998	
	323	0.032	0.920		0.31	0.997	
Cr(III)	298	0.021	0.931	25.6	0.11	0.939	7.18
	303	0.023	0.925		0.08	0.936	
	313	0.028	0.914		0.06	0.960	
	323	0.034	0.880		0.05	0.976	
Pb(II)	298	0.014	0.972	15.63	0.10	0.992	4.48
	303	0.014	0.994		0.09	0.992	
	313	0.015	0.961		0.12	0.997	
	323	0.024	0.937		0.11	0.995	
Zn(II)	298	0.016	0.949	22.47	0.15	0.982	20.1
	303	0.025	0.896		0.18	0.978	
	313	0.032	0.907		0.22	0.961	
	323	0.034	0.865		0.29	0.975	

8.3.5.7 Effluent Treatment

The nano CaSPT synthesized through the silica garden route as an adsorbent of Cu(II), Zn(II), Cd(II), Cr(III), and Pb(II) was applied on effluent samples collected from the electroplating industry. The pH of the effluent was 3.5 containing 51.19 mg l^{-1} of Zn(II), 50.17 $^{mg\,l-1}$ of Cr(III), and 50.61 $^{mg\,l-1}$ of Pb(II) (Table 8.7). At pH 6.5, more than 83% Zn(II), 100% Pb(II), and 90% Cr(III) adsorption were achieved. Other constituents of the effluent, i.e. Fe(II), was completely absorbed even at pH 3.5. These results increased the possibility of using CaSPT as a multi-cationic adsorbent.

Table 8.6 Percentage Adsorption data of CaSPT and two non-tubular calcium silicate samples NT-CaSi(1) and NT-CaSi(2) with HM ions in an aqueous medium

Metal ion [a]	Percentage (%) Adsorption in single matrix [b]			Metal ion [a]	Percentage (%) Adsorption in mixed matrix [b]		
	NT-CaSi (1)	NT-CaSi (2)	CaSPT		NT-CaSi (1)	NT-CaSi (2)	CaSPT
Cu(II)[49.5]	66.5	38.2	80.4	Cu(II)[50.8]	88.0	81.9	100.0
Zn(II)[20.2]	58.9	51.0	68.8	Zn(II)[25.2]	73.8	63.5	90.5
Cd(II)[45]	56.2	27.3	68.0	Cd(II)[44.8]	25.7	24.3	49.6
Cr(III)[45.2]	42.9	31.2	64.8	Cr(III)[40.5]	89.1	62.5	100.0
Pb(II)[99.5]	89.4	63.0	100.0	Pb(II)[41.5]	87.5	59.3	100.0

[a] The values within parentheses in column 1 and 5 represent initial concentration of the respective metal ion in mg l^{-1}
[b] Adsorbent weight in single and mixed matrix was 0.01 g and 0.05 g, respectively

Table 8.7 Corroboration of nano CaSPT with the effluent of the electroplating industry

Radical (mg l^{-1})	pH 3.5		pH 4.4		pH 5.5		pH 6.5	
	Before Ads	After Ads	Before Ads	After Ads	Before Ads	After Ads	Before Ads	After Ads
Zn(II)	51.19	45.2	51.19	25.6	51.19	20.1	51.19	9.6
Cr(III)	50.17	42.4	50.17	21.4	50.17	17.5	50.17	4.7
Pb(II)	50.61	38.4	50.61	15.2	50.61	9.6	50.61	n.f
Fe(II)	1.86	n.f	1.86	n.f	1.86	n.f	1.86	n.f

8.4 Recommendation and Future Research Prospects

Heavy metals are one of the most persistent pollutants in industrial effluents and wastewater, and its discharge without proper treatment causes several ecosystem and human health problems. It was observed that CaSPT as an adsorbent had a significant positive affinity towards more than one HM ion. Adsorption studies investigated in this research were with single adsorbate species in detail and with mixed matrix in short. However, multiple adsorbate species are present in a real-life contaminated water stream, in which all of them compete for the limited adsorbent sites. This complicates the adsorption process, and the net uptake of each adsorbate species by the adsorbent cannot be satisfactorily described by the existing formulations that warrant specially customized techniques. In the present study, an attempt was made to model competitive metal ion adsorption on CaSPT surfaces using multivariable linear regression models. Modelling of competitive adsorption may be investigated further with other algorithms, and artificial neural networks may be considered for this purpose. Besides, microbial bioremediation and phytoremediation processes are very much effective in the treatment of heavy metal pollutants in industrial effluents and wastewater and also to mitigate the problem of heavy metal pollution.

Although bioremediation is a time-taking process, its efficiency can be improved by proper selection of metal accumulating microorganisms, plant species and with the introduction of genetically modified microorganisms and transgenic plant species to degrade or accumulate toxic heavy metals, thereby leading to a reduction in the bioavailability of the metal contaminants in the environment.

8.5 Conclusions

The present study concludes that the nano CaSPT synthesized through the *chemical garden* route is a multi-functional adsorbent used in an aqueous medium. Nano CaSPT is porous, having excess negative sites at CaSPT surface that can absorb different HM ions including Zn(II), Cu(II), Cd(II), Cr(III), and Pb(II). CaSPT synthesized through *silica garden* route having potential for adsorption of Cd(II), Cu(II), Pb(II), Cr(III), and Zn(II) in an aqueous medium. Cu(II), Pb(II), Zn(II), Cd(II), and Cr(III) loading capacities of CaSPT as obtained from Langmuir isotherm were 262.9, 728.5, 200, 331.9, and 290.2 mg g^{-1} at 0.01 g CaSPT weight. Cu(II), Pb(II), Zn(II), Cd(II) and Cr(III) adsorption processes moved towards irreversibility as the initial metal ion concentration was increased. Cu(II), Pb(II), Zn(II), Cd(II), and Cr(III) adsorption kinetics on CaSPT followed a pseudo-second-order rate equation and the activation energy indicated physisorption process. Further, a detailed adsorption–desorption study with the effect of pH will be useful for sludge disposal. Nano CaSPT was a superior adsorbent for HM ions over conventional non-tubular calcium silicate due to its high surface area. Nano CaSPT was successfully applied on an effluent sample of the electroplating industry for the removal of Cr(III), Zn(II), and Pb(II).

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Chapter 9
Textile Dye Removal from Industrial Wastewater by Biological Methods and Impact on Environment

H. Gimhani Madhushika, Thilini U. Ariyadasa, and Sanja H. P. Gunawardena

Abstract Wet processing (dyeing) of textiles consumes large quantities of water and during processing, considerable quantities of dyes remain unfixed, thus generating coloured effluent. Textile industry is a major contributor to environmental pollution and the second-highest source of water pollution in the world. Thus, dye-containing textile effluents should be properly treated (decolourized) until they reach the regulatory discharge limits. Dye decolourization techniques can be classified into three main categories: physical (membrane-filtration, sorption techniques, etc.) chemical (coagulation or flocculation, electro flotation, electrokinetic coagulation, conventional oxidation methods, irradiation, or electrochemical processes, etc.) and biological methods (using microorganisms or their enzymes). Chemical and physical decolourization have shown efficient colour removal in certain dyes. However, generation of large quantities of sludge that requires further treatment or disposal and the high cost are the main drawbacks of these methods. On the contrary, biological techniques are considered as attractive solutions for textile effluent decolourization due to low-cost, sustainability, and public acceptability. Biological decolourization of dyes can be a result of either biosorption or biodegradation or both. Release of coloured effluents containing dyes into the environment may result in health issues and environmental pollution. When coloured effluents get into water bodies, light penetration through water is reduced and thus affects the photosynthetic activities of aquatic flora, thereby severely limiting the food sources for aquatic organisms. Dyes are toxic to flora, fauna and humans and further, degradation of dyes may deplete dissolved oxygen levels in water and consequently affect aquatic organisms.

Keywords Textile dyes · Coloured effluents · Decolourization · Biological treatment · Bioreactors

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9.1 Introduction

Textile wet processing includes singeing, desizing, kiering, bleaching, mercerizing, and dyeing where the dyeing individually contributes to 15–20% of wastewater generated in the total production flow (Kant 2011). Dyeing is the aqueous application of organic dyes on textiles to impart colour (Maria Drumond Chequer et al. 2013) and in this process, dyes that remains unfixed to fibres are washed out, producing coloured effluent. According to the United States' environmental protection agency (US EPA), 50–60% of reactive dyes, 10–20% acid dyes, 30% direct dyes and 5–25% amount of disperse dyes remain unfixed (Hessel et al. 2007).

Even at a lower concentration, dyes are highly visible in water and create problems when released to the aqueous ecosystem without proper treatment. Industrial effluents containing synthetic dyes reduce light penetration in rivers and consequently affect the photosynthetic activities of aquatic flora, severely affecting the food sources of aquatic organisms. Dyes are toxic to flora, fauna and humans and degradation of dyes may deplete dissolved oxygen levels in water. This would consequently affect the survival of aquatic organisms (Pereira and Alves 2012) as it increases the biochemical oxygen demand (BOD) in water. Furthermore, depending on the time of exposure and the concentration of dye, aquatic organisms may be subjected to acute or chronic toxicity.

Therefore, stringent government regulations have been imposed in most countries to avoid such negative consequences generated by the release of textile dyeing effluent to natural water bodies. Enforcement of law ensures that the coloured effluents are treated up to the discharge standards before releasing to the environment. Hence, to achieve the regulated discharge standards, textile-dyeing companies use different techniques to decolourize textile industry effluents.

These effluent decolourization techniques can be broadly categorized as physical, chemical and biological treatments. Adsorption, membrane-filtration (nanofiltration, reverse osmosis, electrodialysis), and irradiation are some examples of physical treatment techniques. Coagulation, flocculation, chemical oxidation (ozone or H_2O_2), advanced oxidation processes and electrochemical processes (electrokinetic coagulation, electro-oxidation) are some chemical treatment techniques used for effluent decolourization (Pereira and Alves 2012; Singh and Arora 2011; Popli and Patel 2015). In biological treatment living and non-living microorganisms and their enzymes (Pereira and Alves 2012; Singh and Arora 2011) are used for colour removal.

Even though chemical and physical dye decolourization techniques are commonly applied in textile industries, these methods have several drawbacks such as high cost (for chemicals, electricity, ultra-violet irradiation), difficulties associated with dewatering and disposing of generated sludge, and ineffective decolourization of some types of dyes (Pereira and Alves 2012; Anjaneyulu et al. 2005). Conversely, biological dye decolourization techniques are identified as environmentally friendly, economical and produce less sludge compared to physical and chemical treatments (Solís et al. 2012).

Various categories of microorganisms such as filamentous fungi (Senthilkumar et al. 2014; Taha et al. 2014), yeasts (Jadhav et al. 2007), bacteria (Deng et al. 2008; Olukanni et al. 2010) and algae (Lim et al. 2010) have exhibited potential in decolourization of synthetic dyes. Most of these biological dye decolourization studies have been conducted for model dyes with known structures such as Methyl red (Jadhav et al. 2007), Indigo and Congo red (Khelifi et al. 2009) and Malachite green (Deng et al. 2008). Application of such dyes in current industrial dyeing processes is limited, and recently developed dyes with enhanced properties are mostly used instead. Biological decolourization of these dyes and analysis of their degraded compounds are rarely reported. The main reason for this may be the unavailability of dye structures due to trade secrets.

Dye decolourization conducted in different types of reactors such as moving bed biofilm reactors (MBBR) (Francis and Sosamony 2016; Pratiwi et al. 2018; Gocer et al. 2017), up-flow anaerobic sludge blanket reactors (UASB) (Somasiri et al. 2008; Kumar Verma et al. 2015), rotating biological contactors (RBC) (Pakshirajan and Kheria 2012; Pakshirajan et al. 2011) and packed bed biofilm reactors (Madhushika 2021; Anjaneya et al. 2013) are reported in literature. Efficiency of dye decolourization varies depending on the type of reactor, operating conditions of the reactor, concentration of dyes and the microbial species utilized.

9.2 Textile Wastewater Characteristics

Textile dyeing and finishing industry is considered the second largest polluter of clean water globally (Kant 2011) and contaminate water bodies with large varieties of chemicals, such as surfactants, soaps, salts, dyes, softeners, organic solvents, resins, waxes, organic stabilizers and sizing agents (Yaseen and Scholz 2019).

Textile wastewater characterizes for its high COD, BOD, TDS, suspended solid and alkaline pH. Dyeing and washing processes introduce colour to the effluent which is a specific characteristic of textile effluent. Composition of textile effluent may vary from industry to industry depending on process conditions such as types of chemicals, fabrics and equipment used (Yaseen and Scholz 2019). The most common ranges of pH, COD, BOD and TSS for textile effluent can be identified, respectively, as 6–10 (Ghaly et al. 2014; Upadhye and Joshi 2012; Kalra et al. 2011), 150–10,000 mg/l (Hussein 2013; Upadhye and Joshi 2012; Kalra et al. 2011), 80–6000 mg/l (Ghaly et al. 2014; Al-Kdasi et al. 2004; Kehinde and Aziz 2014) and 15–800 mg/l (Ghaly et al. 2014; Al-Kdasi et al. 2004; Kehinde and Aziz 2014). Detailed reviews on the characteristics of textile effluent can be found in (Yaseen and Scholz 2019).

9.3 Textile Dyes

Dyes are coloured substances that absorb light in the visible range of the electromagnetic spectrum at a certain wavelength. The major structural element responsible for light absorption in dye molecules is the chromophore group. In addition, auxochromes such as $–NH_3$, –COOH, HSO_3 and –OH will enhance the colour of dyes (Pereira and Alves 2012). Annually, more than one million tons of dyes are produced globally, of which 50% are textile dyes (Singh and Arora 2011). Dyes can be mainly classified into two categories depending on the application and dye structure.

Based on the application/ usage, dyes can be classified as reactive, acid, direct, basic, mordant, disperse, sulphur and vat (Popli and Patel 2015). Dyes with their most compatible fibre types are given in Table 9.1.

9.3.1 Dye Structure and Properties

According to the chemical structure, the most widely used dye categories in the industry are azo, anthraquinone, indigoid, xanthene, arylmethane and phthalocyanine derivatives. It is estimated that azo dyes represent about 70% by weight of dyes produced in the world (dos Santos et al. 2007). Dyes that are representing azo category, should at least contain a single azo (–N = N–) bond in their structure (Fig. 9.1).

Anthraquinone dyes are the second most important group of dyes and are based on 9,10-anthraquinone structure (Fig. 9.2).

Indigoid dyes are one of the oldest groups of organic dyes and indigo dye is the most important and widely used dye in this category (Fig. 9.3).

Xanthene dyes contain xanthylium or dibenzo-γ-pryan nucleus (xanthene) as the chromophore of the dye structure. Due to rigid chromophoric nucleus, xanthenes are often fluorescent (Wight 2000). An example of xanthene dye is shown in Fig. 9.4.

Table 9.1 Classification of dyes according to usage (Ventura-Camargo and Marin-Morales 2013)

Dye class	Major substrates
Acid	nylon, wool, silk, paper, inks and leather
Azoic dyes	cotton, rayon, cellulose acetate and polyester
Basic	acrylic, modified nylon, polyester paper and inks
Direct	cotton, rayon, paper, leather and nylon
Disperse	polyester, polyamide, cellulose acetate, acrylic and plastics
Reactive	cotton, rayon, wool, silk and nylon
Sulfur	cotton and rayon
Vat	cotton, rayon and wool

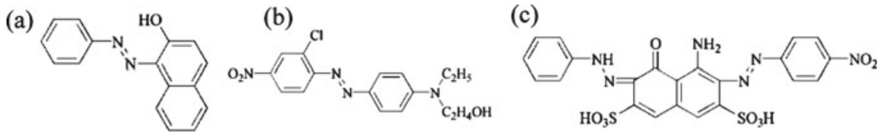


Fig. 9.1 Examples for azo dyes (Hunger et al. 2002), **a** C.I. Solvent Yellow 14, **b** C.I. Disperse Red 13 and **c** C.I. Acid Black 1

Fig. 9.2 C.I. Disperse Red 60 dye with anthraquinone structure (Hunger et al. 2002)

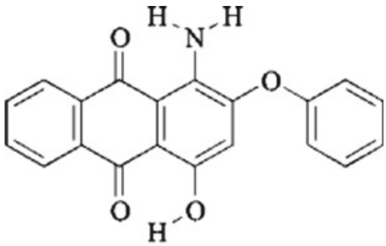


Fig. 9.3 Indigo dye with Indigoid structure (Hunger et al. 2002)

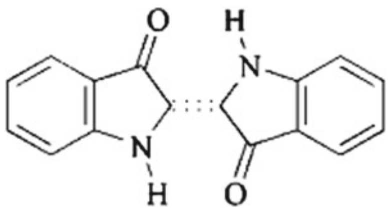
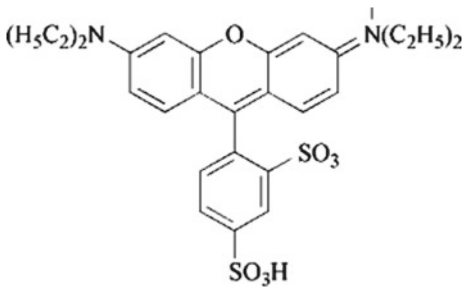


Fig. 9.4 Xanthene dye C.I. Acid Red 52 (Hunger et al. 2002)



Chromophoric system of triarylmethane dyes consist of a central carbon atom joined to three aromatic rings (Damant 2011) as shown in Fig. 9.5.

Out of large number of different textile dyes, some azo dyes have been identified as having the potential to form carcinogenic aromatic amines. To control the usage and discharge of such toxic dyes by textile industries, environmental legislation have been adopted by countries all over the world. The European Union banned the usage of azo dyes which produce 22 amines listed in the legislation, in a concentration higher than 30 ppm, by the directive 2002/61/EC, and reformulated by the directive 2004/21/CE

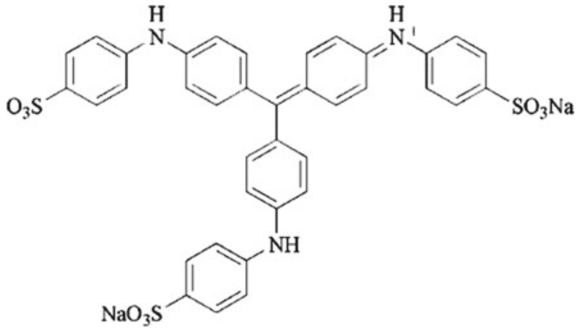


Fig. 9.5 Triarylmethane dye C.I. Acid Blue 93 (Hunger et al. 2002)

(Liikanen 2004; Ventura-Camargo and Marin-Morales 2013). To comply with the legislations, textile dyeing and finishing industries obtain written confirmations from dye suppliers to assure the purchased dyes are free of banned aromatic compounds. Global organic textile standards (GOTS) approval and zero discharge of hazardous chemicals manufacturing restricted substances list (ZDHC MRSL) conformance are examples of documents that are provided by dye manufacturers to assure quality of their dyes.

9.4 Environmental Impacts of Textile Dyes

9.4.1 Impact on Aquatic Environment

The presence of even trace quantities of dyes reduces the transparency and quality of water bodies. Dyes in water bodies may absorb or reflect sunlight which will lower the amount of sunlight obtained by the water hence affects the photosynthetic activities of aquatic vegetation and algae (Gita et al. 2017). A study conducted for toxicity evaluation of Optilan yellow, Drimarene blue and Lanasyn brown dyes using a green alga *Chlorella vulgaris* have revealed a significant reduction of algal pigment, chlorophyll, with the increase of dye concentration in water. Further, the reduction of specific growth rate, increase in generation time of algae was observed with increasing concentrations of the three dyes (Gita et al. 2019).

Different types of bioassays can be used to evaluate the toxic effect of textile dyes and effluents on aquatic organisms whereas conventional acute toxicity tests with fish and *Daphnia* are the most common. An acute toxicity study conducted using *Daphnia magna* as an aquatic experimental animal model has indicated minor acute toxicity in both dyes and in five textile and textile dyeing effluents (out of six effluents) used for the study (Verma 2008). Toxicity of textile dyes (reactive, vat and direct types) on zebrafish (Danio rerio) embryos have been studied and induction of malformations during embryonic and larval development of zebrafish have been observed (de Oliveira et al. 2016). Fish bioassay on textile effluents and their selected constituents conducted to evaluate mortality and erythrocyte disorders on a freshwater fish *Gambusia affinis* is reported (Sharma et al. 2009). According to the study textile effluents were toxic to fish and cause several internal and external injuries such as dyes deposition over the external (gills) and internal organs (lateral line and digestive system) and extensive mucous secretion.

9.4.2 Impact on Vegetation

Generally, water effluents produced in textile dyeing industries are released to natural water bodies with or without proper treatment. After entering the natural water bodies these dye-containing effluents may be introduced to irrigation systems so ultimately utilized in agricultural activities. Some textile dyes have been proven to have toxic effects on agricultural crops (Bilal et al. 2016). Large number of phytotoxicity analyses conducted on evaluating the toxicity effect of textile dyes and dye-containing effluents on various types of plants are reported in literature.

Phytotoxicity analysis on *Allium sativum* L., *Vicia faba* L. and *Lactuca sativa* L., conducted with wastewater obtained from the region Fez-Boulmane, Morocco has shown different levels of phytoxicity on selected three plant types (Giorgetti et al. 2011). In another study conducted on phytotoxicity of textile effluent collected from industrial cluster in Tamil Nadu, South India, using two agriculturally important plants, *Vigna unguiculata* (Cow pea) and *Cicer arietinum* (Bengal gram) showed that the untreated textile effluent has negative effect on seed germination and plant growth, however, plants were unhealthy and died after 15 days of growth due to toxicity of dyes (Valli Nachiyar et al. 2014).

9.4.3 Impact on Human Health

Effect of textile dyes on human health can be identified under three categories as dermatological effect, toxicological effect and respiratory effect (Tang et al. 2018). Dermatological effects such as allergies, urticaria and/or dermatitis can cause when dyes migrate and penetrate the skin (Lazarov et al. 2003; Ryberg et al. 2006; Moreau and Goossens 2005). Employees in dye manufacturing and processing plants are in direct contact with dyes and hence they can be considered as the highest risk group. Studies conducted on textile dyeing industry workers suggest the potential to develop acute and chronic respiratory diseases in workers due to the exposure to dyes (Ozkurt et al. 2012; Zuskin et al. 1997). Further, research revealed that some textile dyes can migrate from fabrics to the human skin during perspiration as clothes are directly in contact with human body (Tang et al. 2018) and hence all the wearers of such textiles are at risk.

Some of the textile dyes are known carcinogens and mutagens hence have the ability to change DNA structure of cells and to cause diseases such as cancer (Tang et al. 2018; Lodi et al. 1998; Guin et al. 1999). Studies conducted to evaluate genotoxicity or mutagenicity of textile dyes are reported in literature. Ames *Salmonella* reversion assay conducted for 12 randomly selected textile dyes showed that 11 dyes were positively mutagenic (Mathur and Bhatnagar 2007). Ames test conducted using five "his" *Salmonella typhimurium* strains to evaluate the mutagenic effect of eight textile dyes has revealed that almost all dyes tested were mutagenic to all the strains (Moawad et al. 2003). Textile effluent obtained from Fez-Boulmane region in Morocco has been used for genotoxicity evaluation and reported that it showed cytotoxic and genotoxic effects on *S. cerevisiae* D7 strain (Giorgetti et al. 2011).

Considering the aforementioned negative effects, utilization, handling and disposing of textile dyes should be done with extreme care to mitigate possible threats on humans and the environment.

9.5 Textile Dye Decolourization Techniques

To meet standard discharge limits, textile dyeing and finishing companies are using different decolourization techniques to eliminate unwanted colour from effluents. These dye decolourization techniques can be mainly classified into three categories as physical (membrane-filtration, sorption techniques, etc.) chemical (coagulation or flocculation, electro flotation, electrokinetic coagulation, conventional oxidation methods, irradiation or electrochemical processes, etc.) and biological methods (using microorganisms or their enzymes) (Pereira and Alves 2012).

9.5.1 Physical Treatment Techniques

Adsorption

Adsorption can be considered an effective method of separating textile dyes from wastewater by concentrating dye molecules on the surface of an adsorbent. Based on the affinity of dyes towards the adsorbent, effectiveness of the treatment process may vary. Further, the effectiveness of the decolourization process may influenced by the factors such as particle size, temperature, adsorbent surface area, pH, contact time and dye-adsorbent interactions (dos Santos et al. 2007).

Different types of adsorbents such as activated carbon, peat, wood chips, fly ash and coal, natural clay, corn cobs and rice hulls have the ability to decolourize textile dyes. Out of these different adsorbents, activated carbon is the most common type of adsorbent used and has the ability to decolourize cationic, mordant, and acid dyes effectively (Robinson et al. 2001). However, due to the high cost and requirement of regeneration of adsorbent after each cycle the industrial applicability of this adsorbent is limited (Nasipude et al. 2016). Even though there are low-cost adsorbents, their effectiveness in dye removal is less compared to activated carbon and therefore requires long retention times (Robinson et al. 2001).

Membrane filtration

Membrane filtration utilizes semipermeable barriers to separate components in a mixture using a driving force such as pressure difference, concentration difference and potential difference. This technique can effectively be used to separate dye particles from textile effluent. Based on the pore size of the membranes utilized for the separation, this filtration technique can be sub-divided as reverse osmosis, ultrafiltration and nanofiltration (Pereira and Alves 2012).

Membrane filtration method has positive features such as resistance to temperature and removal of all types of dyes. However, the drawbacks such as residue disposal problems, high capital cost and the possibility of membrane clogging limit its application in the industry (Verma et al. 2012).

9.5.2 Chemical Treatment Techniques

Coagulation and flocculation technique

Coagulation and flocculation technique utilizes chemical substances to destabilize particles in wastewater and induce them to come together, make contact and thereby form large agglomerates (Bratby 1980). The most commonly applied coagulants in wastewater treatment are aluminium sulfate or alum ($Al_2(SO_4)3.18H_2O$), lime ($Ca(OH)_2$) and ferric salt such as ferric sulfate ($Fe_2(SO_4)3.7H_2O$) or ferric chloride ($FeCl_3$ $0.7H_2O$) [42]. This is one of the most widely used methods in textile industries to decolourize effluents in countries including France, Germany (dos Santos et al. 2007) and Sri Lanka (Madhushika 2021).

Although coagulation and flocculation technique has shown efficient colour removal in certain dyes, for example, sulphur and disperse dyes, this method is not efficient with effluents that contain acid, direct, reactive and vat dyes (Marmagne and Coste 1996). Further, the generation of large quantities of secondary sludge and difficulties in disposing the generated sludge has been identified as the main drawbacks of this method (Verma et al. 2012).

Oxidative processes

In chemical oxidation, oxidizing agents such as permanganate (MnO_4), chlorine (Cl_2) or (HOCl) hydrogen peroxide (H_2O_2) and ozone (O_3) are utilized to alter the chemical composition of a compound or a group of compounds (Metcalf et al. 1972). Ozone is a popular agent in wastewater treatment processes due to its high oxidation potential compared to other oxidizing agents (Robinson et al. 2001). Further, ozone is the most widely used oxidizing agent in decolourizing textile effluents due to its high reactivity with many dyes and high colour removals (Alaton et al. 2002; dos Santos et al. 2007). Short half-life of oxygen, ineffectiveness in removing water-insoluble disperse dyes and high cost are the drawbacks of this method (Anjaneyulu et al. 2005).

In order to overcome the drawbacks in conventional oxidative processes, advanced oxidation processes (AOP) have been introduced which typically involves the generation and usage of hydroxyl radical ($HO^{\bullet}$) as the oxidizing agent. O_3 and H_2O_2 are utilized as oxidizing agents in AOP's in the presence or the absence of catalysts; Fe, Mn and TiO_2 and irradiation source to generate hydroxyl radical (Metcalf et al. 1972). Fenton reagent is one such AOP where H_2O_2 is added to an acidic medium of pH 2–3 containing Fe^{2+} ions. This method is considered as low-cost method and has the capability to decolourize large variety of dyes (Kuo 1992; Khan et al. 2019). However, the main drawback of the Fenton method is the generation of excess sludge which require disposal (Robinson et al. 2001).

H_2O_2/UV process has been successfully utilized in decolourization of different dyes such as blue sulfur dye (Amin et al. 2008), reactive dyes (Rosa et al. 2020) and the efficiency of this treatment mainly depends on the H_2O_2 concentration (Arslan et al. 1999). This method is effective in removal of acid, direct, basic, and reactive dyes using H_2O_2/UV process, however, it is ineffective for the decolourization of disperse and vat dyes (Yang et al. 1998). Negligible sludge formation and high COD removal within short retention times are benefits of this method (dos Santos et al. 2007; Safarzadeh-Amiri et al. 1997).

9.5.3 Biological Treatments

Compared to chemical and physical methods, biological techniques are considered an attractive solution for textile effluent decolourization due to its reputation as a low-cost, sustainable and publicly acceptable technology (Pereira and Alves 2012). Microorganisms such as bacteria, filamentous fungi, algae and yeast or their enzymes have the potential in decolourization of textile dyes (Tables 9.2 and 9.3). Decolourization of textile dyes using these living organisms or substances produced by them is termed as biological dye decolourization. Figure 9.6 shows four different dye solutions decolourized using isolated strain of *Proteus mirabilis* and control dye solutions (Madhushika et al. 2019a).

Biological decolourization of dyes can be due to either biosorption or biodegradation or both. In biosorption, the original structure of the dye particle may not be destroyed but it will be entrapped into the living or dead microbial cells (Pereira and Alves 2012). The potential of a microorganism for biosorption depends on the heteropolysaccharide and lipid components of the cell wall, which contain different functional groups, including amino, carboxyl, hydroxyl, phosphate and other charged groups, resulting in strong attractive forces between the azo dye and the cell wall (Solís et al. 2012). Further, functional groups present in the dye molecule affect biosorption; hydroxyl, nitro and azo groups have the potential to enhance biosorption while sulfonic acid groups result in the reduction of biosorption (Srinivasan and Viraraghavan 2010).

Compared to biosorption, biodegradation can be considered as an environmentally friendly technique as it mineralizes toxic dye compounds into non-toxic substances

Table 9.2 Decolourization of textile dyes using bacteria and algae

Organism	Dyes	% decolourization	Comments	References
Enterococcus gallinarum	Direct Black 38	53–63% within 24 h	25, 50, 75, and 100 ppm dye concentrations in minimal medium	Bafana et al. (2008)
		71–85% within 24 h	20, 50, 100, 200, and 250 ppm dye concentrations in minimal medium	
Bacillus cereus	Acid Blue 25	96% within 6 h	100 mM concentration	Deng et al. (2008)
	Malachite Green	96% within 4 h	55 mM concentration	
	Basic Blue X-GRRL	98% within 2 h	750 mM concentration	
Paenibacillus polymyxa, Micrococcus luteus and Micrococcus sp.	Reactive Violet 5R	93% within 38 h	100 ppm concentration	Moosvi et al. (2007)
Bacillus sp.	Metanil Yellow	100% within 27 h	200 mg /l concentration	Anjaneya et al. (2011)
Lysinibacillus sp.		100% within 12 h	200 mg /l concentration	
Kerstersia sp.	Amaranth, Fast Red E, Congo Red and Ponceau S	100% within 24 h	100 mg/l concentration	Vijaykumar et al. (2007)
	Orange II	84% within 24 h		
	Acid Orange 12	73% within 24 h		
	Acid Red 151	44% within 24 h		
Oscillatoria curviceps	Acid Black 1	84% within 8 days	100 mg/l concentration, marine cyanobacteria	Priya et al. (2011)
Chlorella vulgaris, Lyngbya lagerlerimi, Nostoc lincki, Oscillatoria rubescens, Elkatothrix viridis and Volvox aureus	Methyl Red, Orange II, G-Red (FN-3G), Basic Cationic and Basic Fuchsin	~4 to 95% within 7 days (individual dye decolourization with individual microorganisms)	Some green algae and cyanobacteria	El-Sheekh et al. (2009)

(continued)

Table 9.2 (continued)

Organism	Dyes	% decolourization	Comments	References
Proteus mirabilis	Sumifix Supra Yellow EXF	96% within 72 h	50 mg/l concentration stationary condition	Madhushika et al. (2019a)
	Sumifix Supra Blue EXF	83% within 72 h		
	Cibacron Black WNN	95% within 72 h		
Moraxella osloensis	Mordant Black 17	87% within 48 h	100 mg/l concentration shake condition	Karunya et al. (2014a)
		92% within 48 h	100 mg/l concentration stationary condition	
Micrococcus glutamicus	Reactive Green 19A	100% within 42 h	50 mg/l concentration	Saratale et al. (2009)
Galactomyces geotrichum and Bacillus sp.	Brilliant Blue G	100% within 5 h	50 mg/l concentration stationary condition	Jadhav et al. (2008)
Proteus mirabilis	Reactive Red EXF	94% within 72 h	50 mg/l concentration stationary condition	Madhushika et al. (2018)

such as CO_2 and H_2O. Biodegradation of textile dyes has been reported under aerobic, anaerobic or facultative anaerobic conditions by different microbial species.

Bacterial dye degradation under aerobic conditions by mono and di-oxygenase enzymes is quite difficult, especially when dyes contain nitro and sulfonic groups. However, some bacterial strains such as *Pseudomonas* species have been reported to degrade textile dyes under aerobic conditions by aerobic azo reductase enzymes (Zimmermann et al. 1984; dos Santos et al. 2007).

Fungal dye degradation is more efficient in aerobic conditions than anaerobic conditions and is attributed to the functions of exoenzymes such as peroxidases and phenoloxidases. Lignin and manganese peroxidases degrade textile dyes starting from enzyme oxidation in the presence of H_2O_2 where azo dyes then reduce enzymes into their original form. Tyrosinases and laccases are the two types of phenoloxidases which are oxidoreductase enzymes that can catalyze the oxidation of aromatic compounds without the use of cofactors (Solís et al. 2012; dos Santos et al. 2007). Fungal dye degradation is mostly reported with wood-rot fungi (*Phanerochaete chrysosporium, Pleurotus ostreatus* etc.) whereas biosorption of dyes are commonly reported with fungal species other than wood-rot fungi (*Aspergillus niger, Rhizopus stolonifer* etc.) (Kaushik and Malik 2009).

Table 9.3 Decolourization of textile dyes by fungi and yeast

Organism	Dyes	% decolourization	Comments	References
Saccharomyces cerevisiae	Methyl Red	100% within 16 min	100 mg /l dye concentration using 2 g cells	Jadhav et al. (2007)
Aspergillus alliaceus	Indigo	98.6% within 9 days	150 mg/l dye concentration	Khelifi et al. (2009)
	Congo red	98% within 9 days	150 mg/l dye concentration	
Phanerochaete chrysosporium	Reactive Yellow MERL	~98% within 11 days	10 mg/l dye concentration, wood rot fungi	Koyani et al. (2013)
	Reactive Red ME4BL			
Phanerochaete chrysosporium	Amido Black 10B	98% within 72 h	White-rot fungi	Senthilkumar et al. (2014)
Candida albicans	Direct Violet 51	73.2% in 96 h non-autoclaved conditions	100 mg/l dye concentration decolourized by yeast cells by biosorption and biodegradation	Vitor and Corso (2008)
		87.26% in 96 h autoclaved conditions		
Thermomucor indicae-seudaticae	Azure B, Congo Red, Trypan Blue and Remazol Brilliant Blue R	90.42%	100 mg/l concentration (dye mixture)	Taha et al. (2014)
		67.99%	1000 mg/l concentration (dye mixture)	

Anaerobic or oxygen-limited conditions are reported to be more favourable for the degradation of azo dyes by bacteria. Generally, anaerobic degradation of azo dyes occurs in two steps involving transfer of four electrons with the help of azoreductase enzymes. During the initial step, Hydrazo intermediate is formed by the transfer of two electrons to the azo dye (Eq. 9.1). Then this intermediate accepts two more electrons and be reductively cleaved into the respective aromatic amines (Eq. 9.2). In both steps, dye behaves as the final electron acceptor (dos Santos et al. 2007). Due to the breakage of the azo bond, colour will be removed from the solution. Some of the aromatic amines formed by the breakage of azo dyes are reported to be toxic. However, these aromatic amines can be further mineralized into non-toxic products under aerobic or anaerobic biological treatments (Saratale et al. 2011).

$$R_1 - N = N - R_2 + 2e^- + 2H^+ \rightarrow R_1 - NH - NH - R_2 \tag{9.1}$$

$$R_1 - NH - NH - R_2 + 2e^- + 2H^+ \rightarrow R_1 - NH_2 + R_2 - NH_2 \tag{9.2}$$

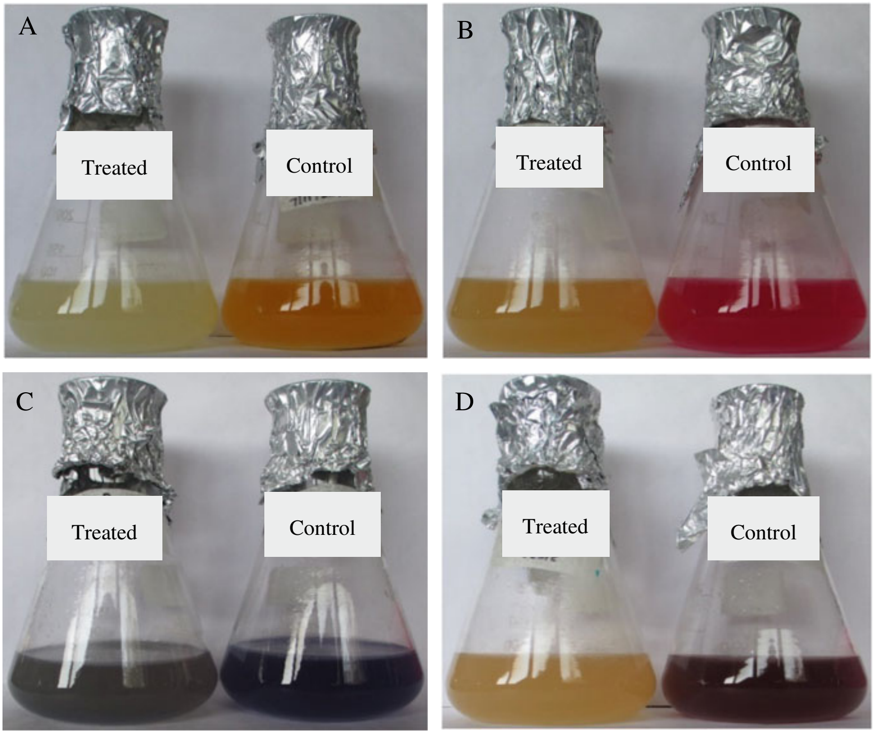


Fig. 9.6 Dye solutions biologically treated with *Proteus mirabilis* (after 72 h) and control samples of A-Yellow EXF, B-Red EXF, and C-Blue EXF D- Nova Black WNN (Madhushika et al. 2019a)

Transfer of electrons between the extracellular dye and the intracellular reductases are accelerated by the redox mediator which acts as an electron shuttle during anaerobic dye degradation. The presence of reducing equivalents such as FADH (reduced form of flavin adenine dinucleotide), NADH (reduced form of nicotinamide adenine dinucleotide) and NADPH (reduced form of nicotinamide adenine dinucleotide phosphate) are essential for azoreductases to catalyze this reaction (Solís et al. 2012). Quinone-based compounds (riboflavin (vitamin B2), anthraquinone-2,6-disulfonate (AQDS), cyanocobalamin (vitamin B12), anthraquinone-2-sulfonate (AQS), lawsone (2-hydroxy-1,4-naphthoquinone), etc.) and flavin-based compounds (flavin adenide mononucleotide (FMN), flavin adenide dinucleotide (FAD), etc.) have been reported as redox mediators (Saratale et al. 2011).

Some species of algae have the ability to decolourize textile dyes either by biodegradation or biosorption (Singh and Arora 2011). Comparable to bacterial dye degradation, several algal species can reductively cleavage azo dyes via azo reductase enzymes forming aromatic amines. In addition, some algal species have abilities to further degrade aromatic amines formed, resulting in complete mineralization of dyes (El-Sheekh et al. 2009).

Textile dyes can effectively be removed by utilization of microbial consortium rather than individual species (Phugare et al. 2011; Madhushika et al. 2019b; Samuchiwal et al. 2021). Microbial consortium could consist of any number of microorganisms which represents the same category such as bacterial consortium (Tony et al. 2009; Nachiyar 2012) or different categories of microorganisms such bacterial-fungal consortium (Lade et al. 2016; Mani and Hameed 2019). It is reported that synergistic metabolic activities of microbial community in a consortium result in high dye decolourization and mineralization effect than by individual bacteria (Karunya et al. 2014b). As different microorganisms have abilities to degrade dissimilar functional groups in dye particles, microbial consortium is more appropriate in decolourizing mixture of dyes and textile effluents containing large number of dyes.

In addition to whole cells (microorganisms), dye decolourization can be carried out using enzymes isolated from microorganisms (Zouari-Mechichi et al. 2006; Dawkar et al. 2009)**.** Peroxidase, laccase, polyphenol oxidase, lignin peroxidase, catalase, veratryl alcohol oxidase, NADH–DCIP reductase and azoreductase are some of the enzymes that have the ability to decolourize textile dyes and produced by different plant and microbial species (Mishra and Maiti 2019). Utilization of isolated enzymes in dye decolourization has some benefits over the usage of whole microbial cells such as the ability to withstand shock loads, absence of sludge disposal issues and the ease of process control and standardization. When isolated enzymes are used for dye decolourization, they should be delivered in immobilized form to enhance the stability, reusability, and localization. However, in industrial effluent decolourization, various chemicals present in effluent may result in the deactivation of these enzymes. Further, high cost of isolation, purification and production of enzymes have constrained the direct usage of enzymes in textile effluent decolourization (Pereira and Alves 2012).

9.5.4 Decolourization of Textile Dyes in Reactors

Industrial-scale biological dye decolourization is rarely reported even though laboratory-scale research has been done and reported in literature. Table 9.4 summarizes dye decolourization conducted using various types of lab-scale biological reactors; submerged anaerobic membrane bioreactors (SAMBRs), air-lift bioreactors, sequencing batch reactors (SBR), moving-bed biofilm reactors (MBBR), upflow anaerobic sludge blanket (UASB—Fig. 9.7) and rotating biological contactor (RBC—Fig. 9.8).

General configurations of some commonly used bioreactors are discussed here. UASB reactors with anaerobic granular sludge have been commonly employed in dye decolourization. Granular sludge in UASB is generally composed of different layers of bacteria such as acidogenic bacteria, methanothrix-like bacteria and H_2-producing and H_2-utilizing bacteria (Liu et al. 2002). In a UASB reactor, wastewater enters from the bottom of the reactor and moves upwards through the activated granular sludge and gets treated due to the activity of microorganisms in sludge beds (Daud et al.

Table 9.4 Dye decolourization conducted using different biological reactors

Reactor	Dyes	Microorganisms	Reactor working volume (L)	Hydraulic retention time (HRT)	Mode of operation	Decolourization (%) and remarks	Reference
RBC	Diluted textile effluent	*Phanerochaete chrysosporium* white-rot fungus	3 L	48 h	Continuous	64% decolourization when 50% diluted with media containing glucose	Pakshirajan and Kheria (2012)
UASB	Acid Red 131 Acid Yellow 79 Acid Blue 204	Anaerobic granular sludge	1.25 L	24 h	Continuous	Over 85% of decolourization with all dye concentrations of 10, 25, 50, 100, 150, 300 mg/L	Wijetunga et al. (2010)
SAMBR	Reactive Orange 16	Anaerobic granular sludge	11.4 L	2.5 d	Continuous	Over 99% of decolourization, methane production was inhibited when dye concentration increased	Spagni et al. (2012)
Air-lift bioreactor	Acid dyes and reactive dyes	*Bjerkandera adusta* white-rot fungus	2 L	72 h	Batch	Decolourized 91–99% of 200 mg/l of each dye (except acid orange 7)	Sodaneath et al. (2017)
Anaerobic reactors	Reactive Red 2	Anaerobic sludge	NA	96 h	Semi-continuous	Above 76% decolourization	Maas and Chaudhari (2005)

(continued)

Table 9.4 (continued)

Reactor	Dyes	Microorganisms	Reactor working volume (L)	Hydraulic retention time (HRT)	Mode of operation	Decolourization (%) and remarks	Reference
SBR	Remazol Brilliant Violet 5	Activated sludge	1 L	Cycle time 24 h	Sequencing batch	90% colour removal, aerated reaction phase of 10 h	Lourenco et al. (2001)
	Remazol Black B					75% colour, aerated reaction phase of 10 h	
RBC	Direct Red-80 Mordant Blue-9	*Phanerochaete chrysosporium*	3 L	24 h	Batch	77–89% decolourization with 200 ppm dye concentration	Pakshirajan and Singh (2010)
MBBR	Remazol Brilliant Violet 5R	Bacteria enriched with anaerobic sludge	4 L	Cycle time 8 h	Sequencing batch	94.4% colour removal but colour removal rate decreased after first 5 h of anaerobic stages	Gocer et al. (2017)
MBBR	Remazol Black 5	Mixed culture	5 L	24–6 h	Continuous	76–81% colour removal at 24–6 h retention times	Pratiwi et al. (2018)
UASB	textile wastewater	anaerobic granular sludge	1.25 L	24 h	Continuous	Over 92% colour removal	Somasiri et al. (2008)
UASB-CSTR	Direct Black 38	Partially granulated anaerobic sludge	UASB-1.8 L	3.6 d	Continuous	81% in UASB and overall 94% colour removal	Işik and Sponza (2004)
		activated sludge	CSTR-9 L	18 d			

(continued)

Table 9.4 (continued)

Reactor	Dyes	Microorganisms	Reactor working volume (L)	Hydraulic retention time (HRT)	Mode of operation	Decolourization (%) and remarks	Reference
Up-flow packed bed bioreactor	textile wastewater	*Aspergillus carbonarius* and *Penicillium glabrum*	0.4 L	40 min	Continuous 3 d operation time	78.8% colour removal. Macro porous polymeric support has been used for the growth of filamentus fungi	Arikan et al. (2019)
UASB	Congo Red	anaerobic sludge	5.2 L	24 h	Continuous	95–98% colour removal	Firmino et al. (2010)
	textile wastewater					57% colour removal	
Anaerobic packed bed reactor	dye mixture	Anaerobic digesting domestic sewage sludge	15 L	5 d	Continuous	98% colour removal with 250 mg/l dye concentration. Pall rings have been used as the packing material	Talarposhti et al. (2001)

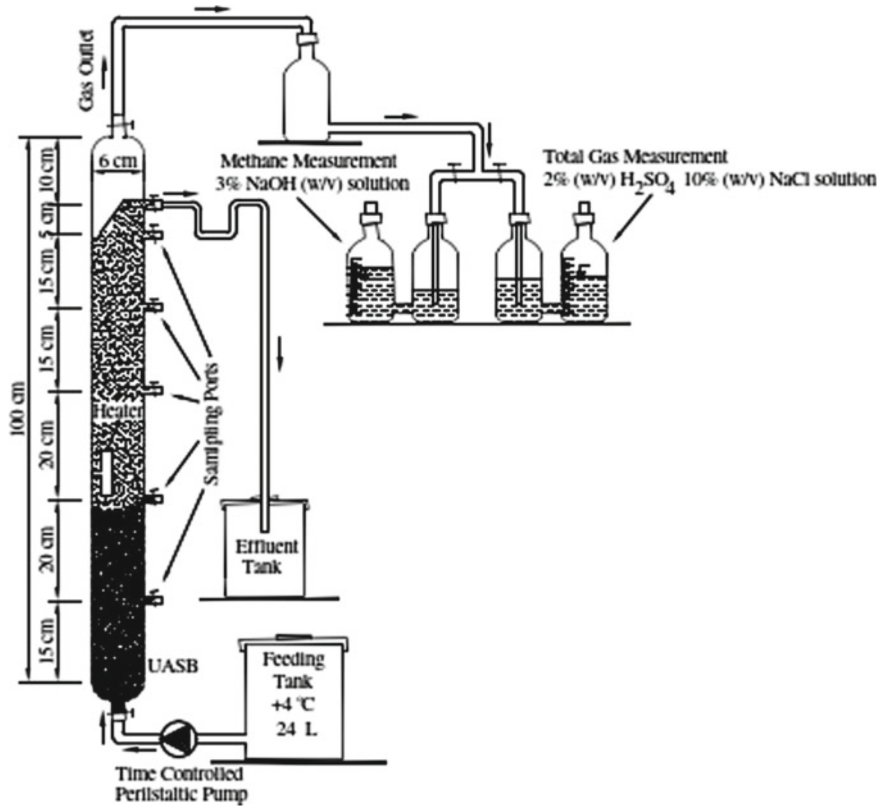


Fig. 9.7 Schematic configuration of a UASB reactor used to decolourize Congo red dye (Işık and Sponza 2005)

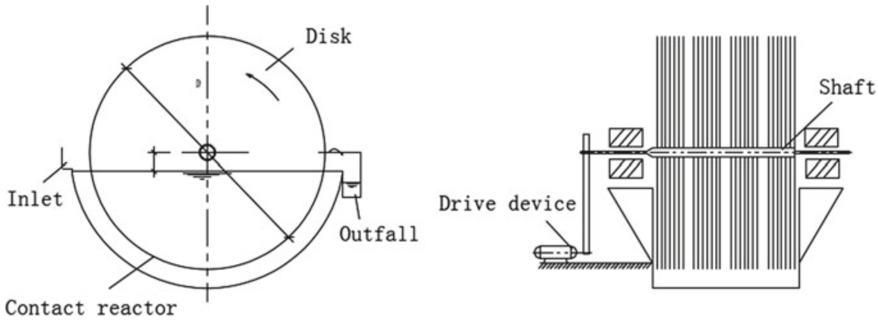


Fig. 9.8 Schematic diagram of biological rotating disk (Wang et al. 2011)

2018). Treated water moves through a three-phase separator (air, liquid and solid) and is taken out from the top of the UASB.

Anaerobic up-flow packed bed reactors, anaerobic expanded bed reactors (AEBR) and anaerobic fluidized bed reactors (FBR) are the most commonly utilized bioreactors with attached microbial growth for industrial wastewater treatment processes (Metcalf et al. 1972). However, utilization of these bioreactors for textile effluent decolourization is not yet reported.

Upflow anaerobic packed bed reactors can be cylindrical or rectangular in shape and packing material is placed in entire depth or in the upper 50–70% of the reactor volume. Corrugated plastic cross flow or tubular modules and plastic pall rings are the most used packing materials in industrial applications. Biomass is retained in the void spaces of the packing materials and attached to the surfaces. Low up-flow velocities are generally maintained to prevent the wash-out of biomass from the reactors (Metcalf et al. 1972).

Up-flow anaerobic expanded bed reactors generally utilize silica sand as the packing material. Bed expansion is achieved by controlling the up-flow liquid velocity. Silica sand is small but provides high surface area per unit volume and consequently enhances the growth of biomass.

Anaerobic fluidized bed reactors are similar to up-flow anaerobic expanded bed reactors in physical design and utilize sand as the packing material. However, FBR reactors are operated at higher up-flow liquid velocities to provide about 100% bed expansion. Besides sand, other packing materials such as diatomaceous earth, activated carbon and anion and cation exchange resins have been utilized in FBR reactors (Metcalf et al. 1972).

Anaerobic or aerobic sludge directly obtained from existing wastewater treatment plants have been used in some lab-scale bioreactors such as UASB, SBR, and CSTR for biological dye decolourization. Therefore, precise identification of microorganisms specifically involved in decolourization has not been possible. However, reactors with attached growth (biofilm) systems mostly utilized isolated microorganisms for dye decolourization (Table 9.4). Out of these different anaerobic attached growth reactor systems, packed bed reactors are most widely used in lab-scale dye decolourization due to its operational simplicity.

9.5.5 Biofilms

Biofilm can be defined as an assemblage of microbial cells that are irreversibly attached to a surface and surrounded by a matrix of primarily polysaccharide material (Donlan 2002). Naturally grown biofilms may contain a single species of a microorganism or extensively a combination of several species. During the formation of biofilms, microorganisms may change from the planktonic stage to sessile growth conditions with limited mobility. Formation of biofilm structures allows microorganisms to survive extreme conditions such as nutrient deprivation, pH changes and the presence of oxygen radicals and withstand physical forces such as shear stresses created by liquid flow (Jefferson 2004). Formation of a biofilm on a surface is a process that can be expressed in few steps. Initially, inorganic, and organic molecules are secreted by microorganisms on to a surface to make it more favourable for cell settlement. Then the planktonic cells will interact with the conditioned surface followed by the attachment of cells to the surface reversibly and later irreversibly. Thereafter, attached cells will be multiplied and simultaneously secrete extracellular polymeric substances (EPS) which attach cells to the surface as well as to each other. EPS are mainly composed of polysaccharides, nucleic acids, lipids and proteins which will contribute to the mechanical stability of biofilms (Shukla et al. 2014). Biofilm structure is then gradually developed (maturation) and forms a cohesive, three-dimensional polymeric network that interconnects microbial cells. Finally, matured biofilms get dispersed either by shedding of daughter cells from actively growing cells or detach due to different reasons such as nutrient depletion, shear force on biofilms owing to flow effects and quorum sensing (Donlan 2002). As matured biofilm structures are exposed to strong mechanical and hydrodynamic forces, their potential for detachment is high. Detached biofilm sections can re-adhere to the substratum to form new biofilms or can be washed-out from the system (Sekhar et al. 2011).

The formation of biofilms on a surface mainly depends on several factors such as surface properties, microbial cell properties and environmental conditions (Morgan-Sagastume 2018). Microbial cell components such as flagella, fimbriae and type IV pili-mediated motilities are important in the initial attachment stage of biofilm formation (Renner and Weibel 2011). Interactions between cells and surface are initiated by flagella while the aggregation of cells for the formation of microcolonies is enhanced by pili-mediated twitching motilities (Rabin et al. 2015). Further, the surface properties such as roughness, wettability, or hydrophobicity influence the ability of microorganisms to attach to particular surface (Lee et al. 2015). Different types of natural materials (pumice, woodchips, etc.) and synthetic materials (polyurethane (PU), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), nylon, glass, stainless steel, etc.) have been tested and proven to have biofilm formation ability (Morgan-Sagastume 2018; Lee et al. 2015). Some researchers have observed high microbial activity rates and good biomass attachment with relatively hydrophobic materials such as PP, PVC and high-density polystyrene (HDPS) (Sousa et al. 1997). Contradictorily, another study reported high biofilm formation in less hydrophobic materials such as nylon and melamine (Mao et al. 2017; Kim et al. 1997). Hence, it can be assumed that the biofilm formation ability on different surfaces is moreover microbial strain-specific and rely on other conditions such as external environment and electrostatic interactions of the surfaces (Sousa et al. 1997).

9.5.6 Decolourization of Textile Dyes in Fixed (Packed) Bed Biofilm Reactors

Most dye decolourization studies in packed bed reactors have utilized natural packing materials such as brick pieces (Sharma et al. 2004a), sheep bone chips (Anjaneya et al. 2013), gravel (Oxspring et al. 1996), granular activated carbon (Ong et al. 2008), laterite pebbles (Senan et al. 2003) and seashells (Sharma et al. 2004b). Further, these studies were limited to reactors with volumes less than 1 L (Table 9.5).

Although these natural carrier materials support biofilm formations, their usage in industrial-scale reactors is challenging due to number of practical reasons. Heavy weight of packing materials such as brick pieces and gravel may result in tightly packed columns which ultimately lead to reactor clogging and requirement of high-pressure effluent pumping. Furthermore, degradation of these natural carrier materials can interfere with the reactor operation. Hence, for successful reactor operation, biofilm support material should be chemically inert, easily degradable, should have high surface to volume ratio and lightweight (Spagni et al. 2012). Lightweight plastic carriers developed with high surface to volume ratio are in line with the above requirements and are considered to be more beneficial than natural support materials in large-scale biofilm reactor operations.

Figure 9.9 shows a fixed bed biofilm reactor filled with polypropylene carrier materials used to decolourize both synthetic dye mixture and textile industry effluent (Madhushika 2021). In this work the biofilm consisted of isolated bacterial strains; *Proteus mirabilis*, *Morganella morganii* and *Enterobacter cloacae*.

Table 9.5 Dye decolourization in packed bed biofilm reactors with natural support materials

Microorganisms used	Dyes used	Biofilm support material	Reactor volume	References
Bacterial consortium	Amaranth dye	Sheep bone chips	65 ml	Anjaneya et al. (2013)
Bacterial consortium	Remazol Black B	Gravel	125 ml	Oxspring et al. (1996)
Bacterial consortium	Acid Blue-15	Brick pieces	148 ml	Sharma et al. (2004a)
Bacterial consortium	Acid Violet-17	Seashells	138 ml	Sharma et al. (2004b)
Microbial consortium	Dye mixture	Laterite pebbles	850 ml	Senan et al. (2003)
Dye degrading bacteria	Acid Orange 7	Granular activated carbon	2.3 l	Ong et al. (2008)

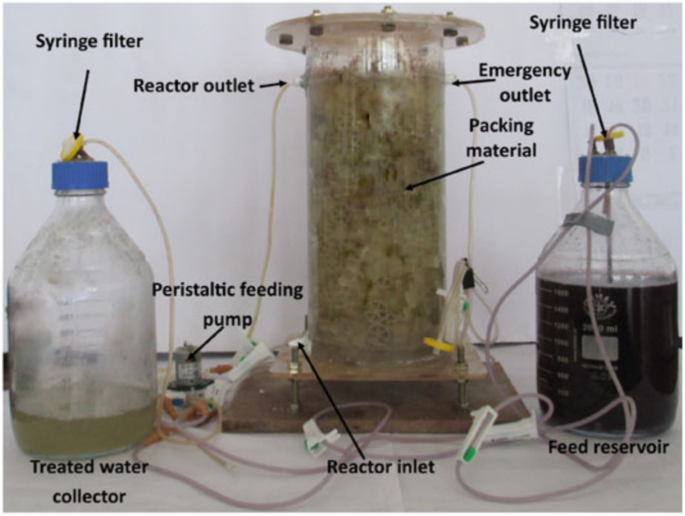


Fig. 9.9 Fixed bed biofilm reactor

9.6 Conclusions

Textile dyes in industry effluents can be removed by adsorption, degradation or both using various types of algae, bacteria, yeast, and filamentous fungi. Functional groups available in the dry structure as well as on the microbial cell wall determine the potential of colour removal by adsorption. Dye degradation is due to breakage of different bonds in the dye structure and aerobic, anaerobic, or facultative conditions must be maintained for this degradation depending on the type of dye and the microbial species used. Studies show that mixed cultures are better in colour reduction compared to monocultures since different microbes have the capability to degrade different functional groups in dye molecules. Various types of biological reactors operated in batch and continuous modes have been tested for decolourization of textile dyes. The level of colour reduction depends on the type of dye, microbial species used, type of reactor used, operating conditions of the reactor and the mode of operation.

9.7 Recommendations

Biodegradation of dyes shows great potential in decolourization of textile industry effluents. However, studies reported so far are mostly limited to laboratory scale and hence in-depth investigations should be directed to identify suitable microbes for specific dyes and their growth conditions, identify and develop suitable reactor systems that can be scalable and investigate strategies for cost-effective operations.

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Chapter 10
Environmental Remediation Technologies

Richa Singh and Kirpa Ram

Abstract The rapid increase in uncontrolled anthropogenic activities, human population, industrialization, and deforestation etc., has created a huge pressure on our environment and natural resources. These have caused environmental degradation (i.e., the deterioration of the various aspects of environment including soil, water, and air) through exploitation of natural resources involving both biotic and abiotic aspects. At present, the deterioration of the environment has touched almost every corner of the earth in one way or the other. The effect of such degradation can be seen on the air and water quality, health of plants, animals, human beings, etc. Therefore, we need to promote sustainable usage of our existing natural resources without further exploitation. In addition, alternative technologies (e.g., bioremediation, nanoremediation, thermal oxidation, phytoremediation, etc.) should be encouraged which will not only help in restoring the deteriorated resources but also avoid further damages to the ecosystems. In this chapter, we have discussed various aspects of pollution resulting to environmental degradation, and have highlighted the possible remediation technologies that can be used to minimize environmental degradation. Thus, the purpose of this chapter is to provide an overview of the ongoing remediation technologies along with their applicability, efficiency and, limitations that should be improved.

Keywords Environmental degradation · Remediation technologies · In situ · Ex situ remediation

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10.1 Introduction

Environmental degradation is one of the ten threats officially cautioned by the High-level Panel on Threats, Challenges and Change of the United Nations which has become a global problem, and all most every country is facing serious intimidations from environmental deterioration. It can be defined as "exhaustion of natural resources such as land, water, air and the destruction of ecosystem and extinction of wild life" (Batool and Jamil 2017). The United Nations International Strategy for Disaster Reduction defines environmental degradation as "The reduction of the capacity of the environment to meet social and ecological objectives, and needs" (Choudhary et al. 2015). It embraces multiple environmental issues including pollution, biodiversity loss, animal extinction, desertification, and deforestation etc. One of the main reasons for environmental degradation is uncontrolled and excessive exploitation of our natural resources resulting from extensive urbanization, deforestation, industrialization, etc. (Urushigawa 1995). The unplanned urbanization and industrialization have already caused significant damage to the environment. The advent of industrial revolution led to the introduction of heavy equipped machines, thereby increasing the production and manufacturing of goods surplusly. However, the modern production technologies based on application of heavy equipped machines involve substantial consumption of fuel as a source of energy (Choudhary 2015) that can potentially deteriorate the environment. If these activities are not checked on time, they can cause irreversible and permanent degradation of various aspects of the environment for instance biodiversity, ecosystems, natural resources, and habitats.

The repercussions of environmental degradation are becoming more and more serious, particularly for the people living in developing countries, resulting in ill-health, death, disabilities among millions of people. Environmental degradation can lead to a shortage of resources, such as water and farmable land. Huge amount of waste is being generated on daily basis, resulting in the increase of landfills. These landfills/dumping yards increase the risk of hazardous material making their way to the food chain, creating various kinds of chronic diseases (Earth Eclipse). To cope with the arising situation, proper management of resources should be done. Sustainable ways for the resource application should be encouraged. Along with this, different types of environmental remediation technology have been developed in past few years such as soil vapor extraction, nanoremediation, phytoremediation, bioremediation, thermal desorption, and in situ oxidation to combat environment degradation. The basic premise behind these technologies is to move pollutants from contaminated soils or ground water to other locations for eventual treatment or disposal or to confine and destroy pollutants at a specific location (Zhang 2009).

The current section provides an overview of various commonly available remediation technologies. Although a thorough discussion on each of the technologies discussed is beyond the scope of this chapter, the author has concentrated on their processes, application, advantages, limitations, site-specific characteristics, and economic status in various environments. Despite this, if the reader wants to explore any certain technology, a comprehensive list of references is provided to conduct their further research.

10.2 Remediation Technologies and Their Application

Contaminated sites have always been a reason of public concern because their potential to harm living organisms, ecology, the environment, and property value. They can cause considerable damage to public health and environment (Urushigawa 1995). Therefore, remediation technologies are implemented to reduce the concentration of contaminants at the site and further to restore the ecosystem. Physical, chemical, and biological procedures are used in remediation methods, and they are either applied directly to the contaminated site (in situ remediation), or the contaminants are excavated from the original site for treatment (ex situ remediation). Remediation is usually achieved through extraction of contaminants from the site, transformation of contaminant into less toxic form or through stabilization and solidification. These technologies have been found to be very effective in treating soil, wastewater, ground water, industrial leachates, etc.

10.2.1 NanoRemediation Technology

Nanomaterial offers possibilities for the efficient removal of pollutants and biological contaminant in the field of environmental remediation. Nanotechnology has gained a lot of attention in the past decades due to its unique physical properties of nanoscale materials. Nanomaterials show a better performance in environmental remediation than other conventional techniques because of their high surface area (surface-to-volume ratio) and their associated high reactivity (Khan et al. 2019). They are available in various shapes/morphologies, such as nanoparticles, tubes, wires, and fibers, function as adsorbents and catalysts, and their composites with polymers are used for the detection and removal of gases (SO_2, CO, NO_x, etc.), contaminated chemicals (arsenic, iron, manganese, nitrate, heavy metals, etc.), organic pollutants (aliphatic and aromatic hydrocarbons), and biological substances, such as viruses, bacteria, parasites, and antibiotics (Khin et al. 2012).

Over the time, new nanomaterials have been explored for the purpose of remediation such as, nanoscale zeolites, carbon-nanotubes, chitosan, graphene sheet, zinc oxide, and metal oxide (Guerra et al. 2018). Because of the high surface area to volume ratio and the presence of a larger number of reactive sites, these materials can be extremely reactive; nevertheless, they may also display changed reaction rates that surface area alone cannot account for. Nanomaterials are often covered with extra-reactive materials with appropriate charges and functional groups to improve their efficiency. These coatings enable them to increase interaction with contaminants, resulting in rapid pollutant concentration reduction. Nanoscale materials may also be able to enter very small areas in the subsurface and remain suspended in ground water if they are coated appropriately. Appropriate coating may allow particles to go further than macro-sized particles, resulting in a broader dispersion and, as a result, better pollutant removal. The major process involved in nanoremediation technologys is as shown in Fig. (10.1).

Amendments in Nonmaterial

Depending upon the type of contaminants, nanomaterials can be manipulated for specific application to construct novel properties that are not usually present in particles of the same material at micro- or macro-scales. They offer the potential to influence unique surface chemistry as compared to traditional approaches such that they can be functionalized or grafted with functional groups that can target specific molecules of interest (pollutants) for efficient remediation. Further, the intentional

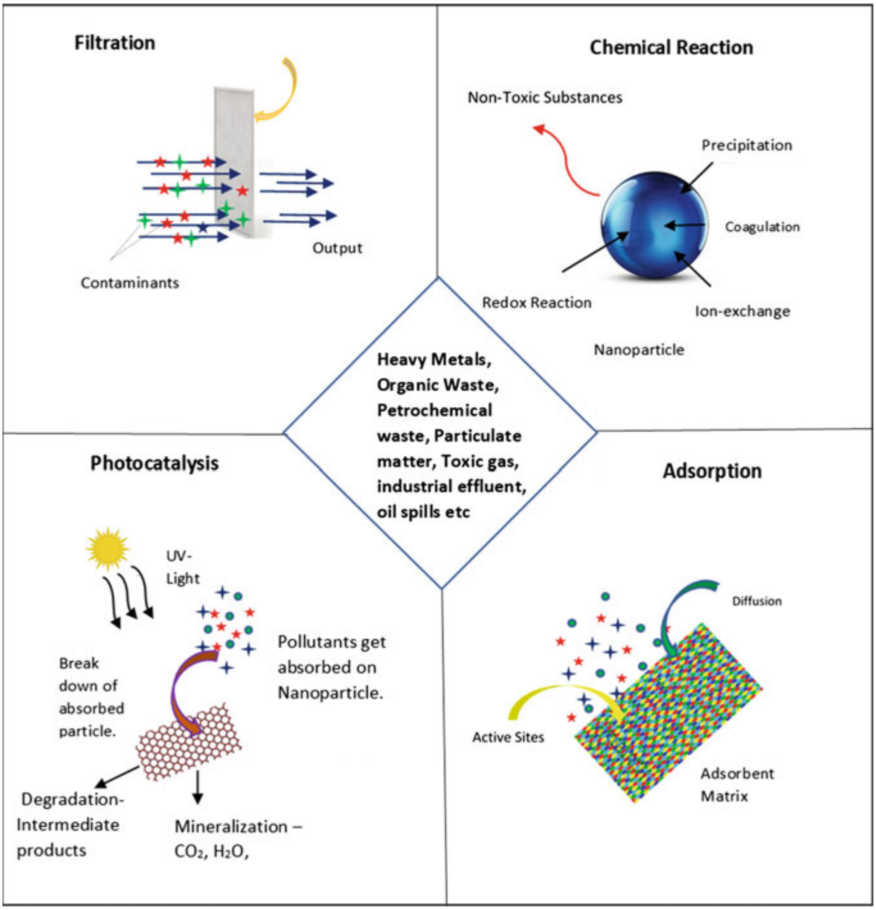

Fig. 10.1 Major processes involved in nanoremediation technology

modification in the physical properties of the nanomaterials (e.g., size, morphology, porosity, and chemical composition etc.) confer additional advantageous characteristics that directly affect the performance of the material for contaminant remediation. The resulting material formed from such modifications is more versatile than the original ones. For example, iron nanoparticles are frequently utilized in environmental remediation due to their unique physicochemical properties resulting from their extremely small size, high surface area to volume ratio, and cost-effectiveness (Abdelbasir and Shalan 2019). Iron-based nanoparticles can be successfully applied to eliminate wide range of contaminates from the waste such as DDT, lindane, arsenic, cadmium, chlorobenzene, and dichlorobenzene (Li et al. 2006). Literature is filled with studies based on nanoparticles and their application in removal of environmental contaminants. Table 10.1 summarizes the application of nanomaterials in successful removal of the contaminates from different environmental matrices.

Recent advancement made in the field of nanotechnology has opened a new opportunity into the realm of environment protection and remediation. The global demand for nanoscale material tool and devices has been increased. Nanotechnology research programs have a significant economic influence in recent years. It has a broad range

Table 10.1 Application of nanomaterials in removal of environmental contaminants

Material	Application	References
Magnetic γ-Fe_2O_3 nanoparticle	Elimination of As (III) and As (V) from aqueous solution	Lin et al. (2012)
Solar-nano-TiO_2	Photocatalytic destruction Cu, Zn, Fe, S, S-ethylenediamine-*N*,*N*-di-succinic acid	Clarizia et al. (2017)
Silver-based nanoparticle (AgNPs)	Nutrient removal from wastewater	Alito and Gunsch (2013)
Iron oxide/activated carbon nanoparticle	Cd (II), Cr (VI), Cu (II) from aqueous solution	Jain et al. (2018)
ZnO–FeO_4 base nanoparticles	Removal of methyl blue dye	Goyal et al. (2018)
α-Fe_2O_3 nanoparticles	Removal of rhodamine B (RhB) dye	Umar et al. (2013)
Graphene oxide	Filters levoflavin and Pb from aqueous solution	Dong et al. (2016)
Graphene-based nanoparticle	Removal of antibiotic via adsorption and oxidation process	Wang et al. (2019)
Carbon-based nanomaterial	Adsorptive removal of Pb^{+2} from aqueous solution	Kabbashi et al. (2009)
Layered double hydroxide-based (LDH) nanomaterial	Removal of radionuclides from aqueous solution	Gu et al. (2018)
Exfoliated graphene oxide (EGO) and reduced graphene oxide (RGO)	Adsorption of a cationic and anionic dyes	Ramesha et al. (2011)

of environmental applications, including sensor manufacturing, treatment, remediation, and green synthesis. As a result, the technological advantages of NMs/NPs provide a vision for conveying new discoveries in terms of a variety of products.

10.2.2 Solidification and Stabilization

It is a soil remediation process that prevents the movement of contaminants from the waste such as sediments, soil, and sludge. It not only limits down the solubility of hazardous waste, but also decreases, the surface area of the waste mass through which leakage can likely occur (Sharma and Reddy 2004). Solidification is a more specific process that fixes material to increase its solidity and structural integrity. Stabilization is a general term for a procedure that turns pollutants into a less mobile or harmful state. However, solidification does not eliminate or degrade pollutants; rather, it stops them from being transported to other locations by reducing or eliminating their mobility (United States Environmental Protection Agency 2012). The technology is quite effective in treating waste having contaminants such as metals, radionuclides, volatile organic compounds, and pesticides. It involves mixing of the waste with a binding agent; it fixes the loose waste material into a compact form. Common binding agent includes cements, asphalts, fly ash, and clay. Water is then added to the mixture to ensure appropriate binding. After that the mixture is then allowed to cure and harden into a solid block (Fig. 10.2).

Based on the application of reagent, stabilization/solidification can be grouped into following type

- *Cement-based S/S*: In this process, Portland cement along with the water is mixed with the waste. It initiates the hydration reaction with the waste resulting in its compaction. It is more likely applicable for PCBs, oils, and other organic compounds.

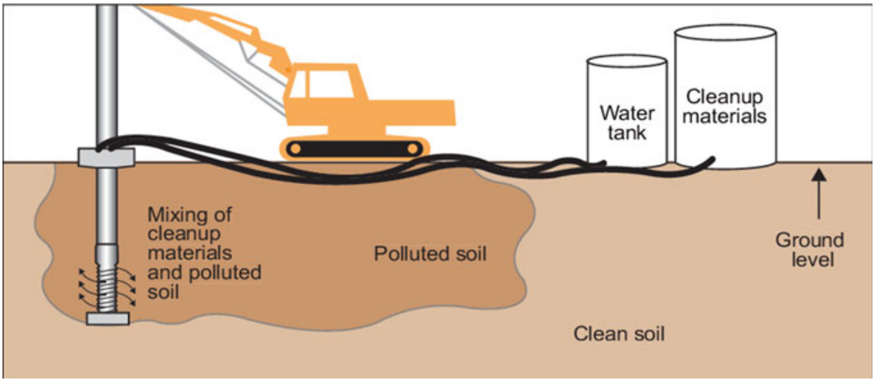

Fig. 10.2 In situ solidification/stabilization of contaminated soil (USEPA 2012)

- *Thermoplastic based S/S*: In this process, thermoplastic material such as asphalt or polythene is used to cover the contaminants. It basically encapsulates the waste material within an impermeable layer. This process is best suited for radionuclides, metals.
- *Organic polymerization S/S*: Urea–formaldehyde is the most common binding agent used in this process. It is mainly applicable for radioactive wastes.
- *Pozzolanic S/S*: It involves the application of salicaceous and aluminosilicate material such as fly ash, lime kiln, and blast furnace slag to bind the waste. It is primarily used for the waste containing waste metal, waste acid, and creosotes.

Limitations

- It does not remove or destroy the contaminants.
- In situ solidification may prevent the site from being used in the future.
- If it is not done in a proper way, leakage of waste materials can take place.

10.2.3 Thermal Desorption

Thermal desorption is a physical separation method that involves, heating of contaminated soil to a specific temperature for efficient removal of impurities. The basic principle is to apply heat to the parent material such as soil, sediments, sludge, or filter cake in order to vaporize the contaminants. By applying heat to the contaminated soil, the waste with low boiling points is converted into vapor which can be further collected, followed by treatment in off-gas treatment unit.

The effectiveness of this technique is governed by three major factors:

1. Volatilization
2. Adsorption
3. Diffusion.

Here, adsorption is the property of soil that describes the ability of soil particle to accumulate the contaminant on their surface. As the temperature increases, the rate of volatilization also increases, due to which the contaminants present in the soil start to lose their hold on soil particle surface resulting in their removal.

Thermal desorption technology is found very effective in removing broad range of soil contaminants such as diesel range organics (DROs), petroleum range organics (PROs), volatile organic compounds (VOCs), semi-volatile organic compound (SMVOCs), poly-chlorinated biphenyls, pesticides, and dioxins-furans. Soil texture and temperature of thermal desorption unit play a very important role in overall working of the process. The soil matrices that are composed predominately of course particle such as sand will desorb contaminates easier than finer particles like silt and clay (Sharma and Reddy 2004) Further, several studies have reported that increasing the temperature significantly decreases the concentration of contaminants in the treated waste.

A typical thermal desorption system is divided into following three units—the pre-treatment unit, the desorption unit, and post-treatment unit. The latter one is for both, i.e., gas contaminants and remaining soil after which the soil is sent back to excavation site (Geoengineering 2013).

Pre-treatment or material handling unit: Once the excavation of the contaminated material is done, it undergoes screening procedure. It basically removes the large particles present in the material. If the contaminated material is wet or has a significant amount of moisture, it is dried off or mixed with sand to make it viable.

Desorption unit: It is intended to heat the contaminates, to a certain temperature until it completely gets vaporized (Sharma and Reddy 2004) Based on the application of heat, the American Academy of Environmental Engineering has identified three distinct classes of thermal desorption unit.

Direct fired rotatory disrobers (DFRD): It consists of a cylindrical metal drum that is slightly inclined; the contaminated material passes through the drum where it gets heated with flame or combustion gas.

Indirect fired rotatory disrobers (IDFRD): Unlike DRFD in IDFRD, the combustion gas does not come in direct contact with waste being treated. A metal rotatory shell is heated from outside; it indirectly heats the waste present inside the shell.

Indirect fired heated conveyor system (IFCS): The heat is generated in a separate chamber situated outside the main processing chamber, which is then, conveyed to the desorber via different medias such as steam, special heat transfer fluid, or electric salts.

Post-treatment Unit

The gas that is released from the desorber unit still contain some contaminants and particulate matter. Hence, it becomes necessary to treat the released gases. Depending upon the type of and amount of contaminant present, different techniques such as cyclone filters, bag house, wet scrubbers, venturi scrubber, carbon units are used to treat the off-gas. Similarly, the treated soil from the desorber unit is also tested to check the level of reduction in contaminates level. If the treated soil is proven to be non-toxic, it is either returned to the excavation site or taken somewhere else to be used as a refill. However, if in any case if the soil needs further treatment, it may be treated using another method, or taken off-site for disposal.

Limitations

- The treatment and management of air emissions from thermal desorption activities is a critical factor to address. Metals, some polycyclic aromatic hydrocarbons (PAHs), and dioxins/furans should not be leaked.
- Treated soil may no longer be able to support microbiological activity.

10.2.4 Gas-Based Techniques

The basic principle behind this technology is that vapor/air is applied directly to the contaminated area. The principal gas-based processes utilized for clean-up include soil surface extraction, bioventing, and air sparging.

Soil vapor extraction (SVE) Soil vapor extraction (SVE) is a physical process used to remove chemicals from the soil's vadose zone of a subsurface environment. It is also known as vacuum extraction, aeration, in situ volatilization, soil venting, etc. It is based on the application of vacuum to the soil matrix to create an airflow that takes contaminants to extraction wells and air treatment units before they are released into the atmosphere (Greene and Pimie 2003). The movement of vapor in the subsurface zone is primarily caused by advection; this is due to the influence of pressure gradients that occur during the operation of vapor extraction wells. Extraction wells are typically used at depths of 5 ft or greater, and it has been successfully applied as deep as 91 m (300 ft). SVE is typically used to clean up contaminants with a Henry's Law constant of >0.01 or a vapor pressure of >0.5 mm Hg. The passage of gas air in the unsaturated zone is induced by a pressure gradient (Framework 2018), for example, petroleum range hydrocarbon, (PRO), diesel range hydrocarbon (DRO), vinyl chloride, BETX, pesticides, and herbicides.

Bioventing It is based on bioremediation principle which involve soil microbes to degrade the toxic contaminants present in unsaturated zone of soil. This technique involves controlled stimulation of airflow by delivering oxygen to unsaturated (vadose) zone in order to increase bioremediation, thereby increasing the actions of indigenous microbes (Rodríguez et al. 1989). Bioventing systems are unique in that they are designed to biodegrade gasoline compounds instead of just volatilize them for disposal. Bioventing can be used to treat any aerobically biodegradable ingredient. Bioventing, in particular, has proven to be particularly successful at removing petroleum pollutants such as gasoline, jet fuels, kerosene, and diesel fuel from the environment.

Air-sparging It is an in situ remediation technique that relies on the usage of native micro-organisms that can biodegrade organic compounds present in the saturated zone. This method is similar to bioventing in that air is injected into the subsurface of the soil to encourage microbial activity and increase contaminant removal from contaminated sites. Unlike bioventing, however, air is injected at the saturated zone, which can accelerate biodegradation by causing upward migration of volatile organic molecules to the unsaturated zone (Khan et al. 2004). It is found very effective in treating aquifers contaminated with the petroleum wastes.

Limitations of Gas-Based Technologies

- In low permeability soils, stratified soils, and soils with a high humic content, SVE is proven to be inefficient (Sharma and Reddy 2004).
- Aeration is likely to be difficult in saturated soil.
- It is necessary to monitor vapor at the soil surface.

10.2.5 Phytoremediation

It is a plant-assisted bioremediation technique. It is based on application of different kinds of plants and their associated microbes that have ability to remove, transfer, stabilize, or extract the contaminants in the soil (https://cope.org). Certain plants are very effective in absorbing ionic compound that are present in soil even at very low concentration. Plants extend their root systems into the soil matrix, forming a rhizosphere ecosystem, which accumulates heavy metals and modulates their bioavailability, reclaiming damaged soil, and restoring soil fertility (Ralinda and Miller 1996).

Based on the mechanism involved in the contamination removal, following phytoremediation techniques have been developed (Barceló and Poschenrieder 2003):

Phytoextraction It is also called phytoaccumulation. It involves the application of plants that can accumulate/uptake the contaminants directly in their tissues. The most common route of chemical uptake into plant is through their roots. The contaminates move from soil to plant root with the help of transpiration, diffusive transpiration, or microbial-facilitated transportation. Phytoextraction plants have the ability to collect and withstand high concentrations of metals in their harvestable tissues; as well as, a quick growth rate and high biomass production are considered suitable for phytoextraction.

Phytovolatilization This approach involved the application of plants with the potential to absorb volatile chemicals through their roots. Plants absorb volatile substances through their roots and then release the same compounds, or their metabolites, into the environment through their leaves. The phytovolatilization is found very effective compared to other remediation technology by the fact that it removes the contaminates from the site and dispersed it as a gaseous compound, without any further need for harvesting.

Phytodegradation It is also termed as phytotransformation. Plants degrade the contaminants into simpler forms as part of their metabolic process. Contaminants are degraded either within the plant body or in the surrounding of plants through the action of enzymes produced by plants.

Phytostabilization It is also called phytosequestration. It relies on the application of plant species to contaminated site, which reduces the mobility of the pollutants. Contaminants are sequestered by transpiration and root growth, which reduces leaching, controls erosion, creates an aerobic environment in the rhizosphere; it also supplies organic matter to the substrate that binds the contaminant. This technique can be used to re-establish a vegetative cover at sites where natural vegetation has been lost due to high metal concentrations in surface soils. Plants having high tolerance level against the contaminants and possess high production of root biomass are considered effective for phytostabilization.

Limitations

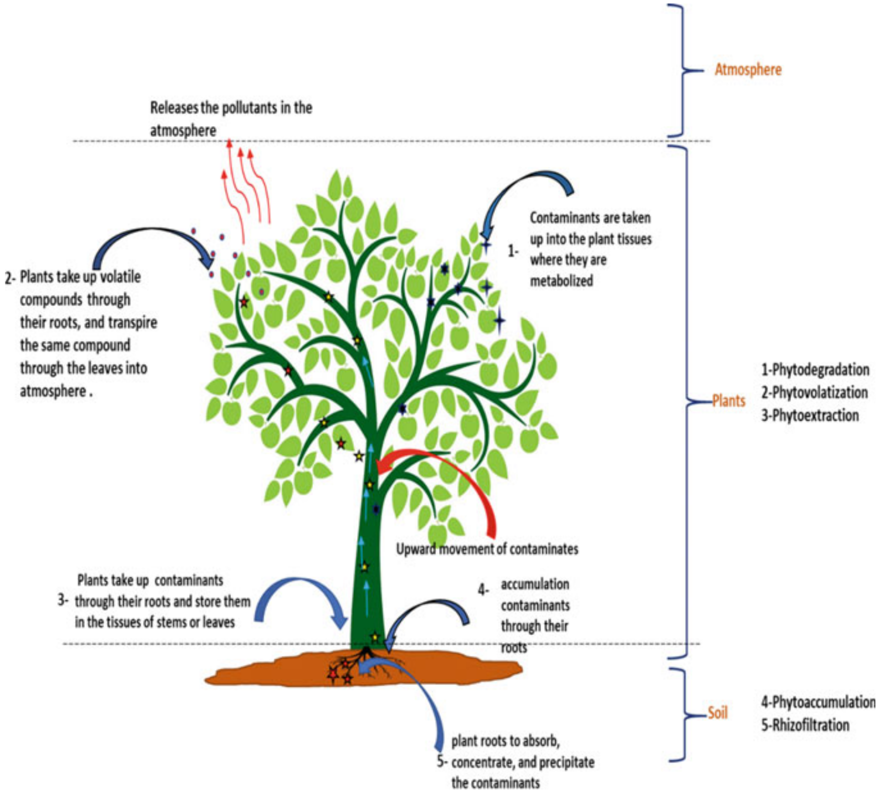

Fig. 10.3 Overview of different phytoremediation processes

- Plants can be destroyed by high concentrations of toxic substances.
- Phytoremediation products may bioaccumulate in animals or be mobilized into groundwater.
- It may be seasonal, depending upon the location.

10.3 Selection of Relevant Remediation Technology

The physical (e.g., density, viscosity, solubility, melting/boiling point, etc.) as well chemical properties of a pollutant as well as their molecular qualities determine the success of any remediation approach. Because no two pollutants are the same, the effective restoration requires a unique remediation procedure based on their qualities. Furthermore, the polluted matrix plays a critical function in defining a technology's overall efficiency. As a result, selecting a superior technology necessitates a thorough grasp of the pollutants' physicochemical properties, as well as their molecular properties such as shapes and sizes, the site's geological and stratigraphic contexts, and the depth of the contamination (Henshaw 2009).

Besides this, the US Environmental Protection Agency (USEPA 1994) devised a remediation technology screening matrix to evaluate the overall performance of the technology. The screening matrix has 13 elements that address cost, performance, technical development, and institutional concerns. Five of the 13 criteria in the system are concerned with performance, while the remaining eight are concerned with overall cost, commercial availability, minimum pollutant concentration availability, time to finish clean-up, system dependability, and awareness remediation community, etc. Technologies are assigned one of four possible ratings—better, average, worse, or inadequate information (USEPA 1994). It is important to note that matrix provides basic and representative information about the technology.

10.4 Conclusions

Contaminants as well as contaminated site pose a serious harm to public health as well as surrounding environment of an ecosystem, and therefore, remediation techniques are essential to reduce level of contaminants at the site to restore the ecosystem. In this chapter, we have summarized a variety of remediation technologies, including their theories, current status and advanced development, applicability and suitability of a technology as well as their limitations. Among all the existing technologies, remediation through nanotechnology has emerged as one of the promising technologies because nanomaterials have higher surface-to-volume ratio, which increases reactivity, adsorption, and effectiveness of contaminant removal. In addition, compared to traditional approaches, the ability of nanomaterials to exploit their unique surface chemistry by allowing them to be functionalized or grafted with more than one functional group that can be used to target specific contaminant, resulting in an effective remediation. Nonetheless, despite the abovementioned potential benefits of nanomaterials, some nanomaterials are intrinsically unstable in typical conditions. As a result, nanoscale creation necessitates the development of specialized procedures. Moreover, some technologies perform better when they are used in tandem with other remediation technologies. For example, biological treatment followed by physical or thermal treatment of petroleum waste becomes more effective than either treatment alone. Therefore, a comprehensive knowledge about the contamination distribution, soil and ground water characteristics is necessary in order to choose the best remediation mechanism or a combination of them to meet the project's environmental expectation.

10.5 Recommendations

Given the staggering number of contaminated sites that require clean-up activities, particularly when financial resources are limited, developing efficient and cost-effective environmental remediation technologies remains an important research field. The lack of quantifiable risk, benefit, and cost statistics associated with emerging technologies poses a substantial problem to researchers, decision-makers, industrial experts, and stockholders. Despite the fact that various technologies in the field of environmental restoration have previously been developed and proven to be effective, specific applicability, and efficiency of new technologies such as nanoremediation, phytotechnology, thermal desorption, soil vapor extraction, and others need to be investigated. Furthermore, while the mechanisms involved in the remediation process are well understood, the fate of the treated contaminants after they have been removed from the locations remains a concern. Given these conditions, future research should focus on enhancing the efficiency, efficacy as well as suitability of remediation technologies involved in treatment and disposal of toxins released during the remediation process. It will help the scientists, researchers, and developers to comprehend and forecast the behavior of contaminants in the environment for mitigation of pollutants.

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Chapter 11
Wastewater Remediation: Emerging Technologies and Future Prospects

Pallabi Das and K. K. K. Singh

Abstract Treatment of industrial effluent combining sustainability and high efficiency is the need of the hour. Conventional effluent treatment techniques suffer from energy-intensiveness, low output efficiency, risks of secondary contamination apart from bearing an array of treatment steps. This makes it imperative for a paradigm shift in the process development and design of wastewater treatment plants to cater to the stringent environmental conditions and challenges of the future. Novel technology solutions like integrated membrane separation, photocatalysis, nanotechnology focusing on complete pollutant degradation without generation of toxic residues and scoring high on the eco-friendliness aspect offers promising options to deliver broad-spectrum effluent remediation. This chapter explores novel green alternatives. The chapter also studies the pros and the cons of conventional ETP and evaluates their newage modifications. This is followed by an in-depth discussion of the crux of emerging novel technology solutions, scope of their application and possible integration with prevailing separation techniques. Finally, strategies like waste valorization patterns of process intensification in design were discussed for sustainable and cost-effective technology development.

Keywords Sustainable · Effluent treatment · Process intensification · Waste to wealth · Membrane separation · Photocatalysis

11.1 Introduction

Remediation of wastewater and its reclamation represent one of the most pressing research challenges in today's world, at the backdrop of water scarcity in different regions coupled with an increase in the environmental hazards associated with the

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discharge of toxic industrial effluents. There is a dire need to treat and recycle industrial effluent to decrease freshwater consumption and prevent depletion of water resources. This can be achieved by purification of effluents and grey water recycling. Wastewater treatment (WWT) is often perceived as a necessary expenditure towards the environment. The emergence of the waste to wealth techniques, incentivising the treatment process by the formation of value-added products is one of the approaches towards greater implementation of the wastewater remediation guidelines and standards by all and sundry.

While understanding the process of wastewater remediation, it is very important to understand that industrial effluents are a highly variable matrix with widely varying characteristics. The parameters of BOD, COD, heavy metal loading, total dissolved solids, total suspended solids, microbial content are present in varying concentrations apart from the contaminants particular to the production processes particular to the respective industries. For example, steel plants effluent apart from high loadings of the aforesaid contaminants also contain toxic ammonia, cyanide, phenol in high concentrations produced during coke quenching and water scrubbing of the coke oven gases (Das et al. 2018). Similarly, effluents emanating from tanneries contain high of toxic hexavalent chromium used during chrome tanning, or pharmaceutical effluents contain active pharmaceutical ingredients (API's, drug residues) (Gadipelly et al. 2014). This makes selection of the right removal technique critical for degrading the specific and generalized components. Hence, any Wastewater Treatment Plant (WWTP) is often a blend of different separation processes to handle varied categories of contaminants. The most common unit operations found in any Effluent Treatment Plant (ETP) include aerators, clarifiers, screens, chemical dosing and disinfectant. Some of the units are described in the schematic in Fig. 11.1.

The conventional wastewater treatment plants include bulky infrastructure comprising of primary, secondary and tertiary stages. This makes the capital and operating costs expensive. These large installations are often tailor-made for a narrow range of operating conditions making them unsuitable for handling fluctuating contaminant loadings. Hence undesirable phenomenon like washout of the microbial columns takes place. The conventional WWT plants are often highly energy-intensive

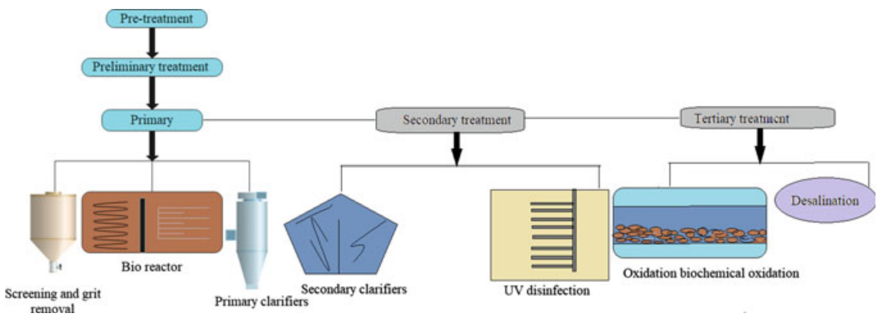


Fig. 11.1 WWT treatment stages in conventional treatment plants

which increases the cost of production of clean water. This puts budget constraints for moving towards the zero liquid discharge techniques. The design strategies to meet the most stringent environmental norms also necessitate provision of sludge disposal, concentrate management, prevention of generation of toxic residues, minimization of any form of secondary contamination. The curent techniques cannot cater to all of the aforesaid requirements.

This calls for a paradigm shift in the process design and WWT plant operation perspectives. There is a worldwide focus on the selection of sustainable, environment-friendly techniques that also guarantee high treatment efficiency. This has led to the development of operationally flexible, modular process intensified systems that integrate sustainability and high output efficacy. Novel technological developments in the field of advanced separation techniques like membrane separation, photocatalysis and nanotechnology are constantly changing the conventional mindsets in wastewater remediation. Integration of the novel technologies with conventional technologies are also being researched upon to prevent scraping of existing infrastructure for implementation of new treatment options. Hybrid technologies like membrane adsorption or photo-Fenton's are being developed to ameliorate the drawbacks of the conventional WWT methods while cutting down cost of the advanced WWT options. Process intensification is also being explored to develop multi-functional systems like the nano-bubbler ozonators that perform multifarious functions of disinfection oxidation, precipitation, aeration in one single assembly. The research in this domain is crucial for development of remediation techniques keeping in mind the future constraints of water and energy that are bound to arise.

In this chapter, a step by step discussion of the crux of different conventional WWT techniques which forms the core of any WWTP has been undertaken. The process fundamentals, merits and demerits of various conventional and novel techniques have been discussed. The future research perspectives for each technique have been evaluated along with discourse on the newer technological modifications. The novel and emerging separation technique, their areas of application, innovation and sustainability quotient and research perspectives for implementation was studied in detail followed by a discussion of the integrated options for complete WWT technology development. Finally, the possibility of value-added product recovery and process intensification in WWTP design as tools for sustainable technology development was also briefly evaluated.

11.2 Conventional Effluent Treatment Techniques

The conventional effluent treatment techniques can be broadly divided into physico-chemical and biological processes. Each class can be further subdivided depending on the mechanism, applicability and raw materials used.

11.2.1 Physico-chemical Treatment Processes

The conventionally applied techniques represent distinct classes that can be broadly grouped under the physico-chemical treatment processes.

11.2.1.1 Adsorption

Adsorption is perhaps the most ubiquitously used and researched technology option in the domain of wastewater treatment. The crux of the process is based on the selective mass transfer of the target contaminants from the bulk phase to the surface of the adsorbents, based on their relative affinity. The term adsorption loosely refers to the accumulation on the surface and is often used in conjunction with sorption which indicates the ability of the compound to load adsorbate in its entire internal structural matrix.The adsorbents have a3D porous surface structure which imparts a high degree of interfacial mass transport and accumulation characteristics. They are characterized by interstices and capillary-like micro-channels which enables rapid accumulation of the selected ions/components on the surface.

The most widely used adsorbent is activated carbon and its analogous forms like activated carbon, charcoal due to its large surface area and porous structure. Both powdered and activated variants are used to treat different contaminants present in wastewater like heavy metals, toxic anions like fluoride, cyanide and also dissolved organics (Mavrov et al. 2003; Demirbas 2008). Activated carbons are used in two variants: Powdered activated carbon (PAC) and Granular Activated Carbon (GAC). The former is commonly used to treat low volumes of wastewater while the latter is preferred in packed beds and activated carbon filters (Johnson 2014). The important factors that govern the adsorptive removal of contaminants include solution pH, adsorbent dosage, adsorbate concentration and physical state, interfering ions present in the feed, and hydrophobicity of the adsorbate. The optimum performance of the adsorbent is determined by attainment of the equilibrium, which in turns depends upon the adsorption kinetics and isotherm.

Different classes of adsorbents have been developed for removal of different contaminants like chitosan complexes, activated alumina, and also polymeric adsorbents. The biggest USP of the process is the simplicity and the cost-effectiveness of the operation. However, one problem faced in this process is that of sludge disposal after the exhaustion of the adsorbent beds. While using adsorption process for the mitigation of heavy metals and other toxic contaminants, the passivation of sludge is of utmost priority to prevent any secondary contamination. Nevertheless, the process of adsorption and adsorption integrated with filtration has proven to be efficacious for treatment of waters catering to the domestic sector and also small industrial installations.

11.2.1.2 Coagulation–Flocculation

The key focus of these treatment techniques is to precipitate/settle the contaminants by dispersing their surface charge.

In the process of coagulation, chemical compounds are added to introduce opposite charges into the medium. This dispelling of surface charges aids in the coalescence of smaller particles. Subsequently, their weight increases and they precipitate at the bottom due to the difference in the densities. Coagulation is often accompanied by mixing which promotes the interparticle collision and quick growth of the microflocs (Prakash et al. 2014). Commonly available chemicals like ferric chloride, aluminum sulfate (alum) act as coagulants binding ions, organics and also colloidal sols from feedstreams (Zhanpeng and Yuntao 2006; Bratby 2015).

In the process of flocculation, modification of surface tension and particle density is induced by flocculent dosing. Here growth of the microflocs takes place resulting in the formation of visible flocs. This growth process continues till a particular floc size is attained before it can be separated by filtration, floatation or sedimentation. Flocculants are more often polymeric in their chemical structure than coagulants which adsorb small particles on its surface (Otsuka and Ohishi 2013). In comparison to the sludge generated by inorganic flocculants, polymeric flocculants generate lesser sludge volume sinc ethey are driven by ionic solvation. In fact chemical modification by grafting of naturally available polymers like starch, guar gum, has yielded efficacious flocculants for wastewater treatment. They act by a bridging mechanism where the polymer binds the particles by forming a loop or a bridge. Ionic charges are also incorporated into the synthetic flocculants for increasing the celerity of the separation process. Some commonly used cationic flocculants include quaternary ammonium compounds, while the anionic polyelectrolyte flocculants comprising of carboxylic or sulfonic groups are also used for the pupose. (Brostow et al. 2009).

Coagulation and flocculation are techniques that are commonly used in conjuction. The mode of action includes charge destabilization, interparticle collision and floc formation which occurs simultaneously for speeding up the process of wastewater treatment. The coagulant also in many cases serves as flocculation promoters strengthening the flocs. This enhances the ease of separation (Zhanpeng and Yuntao 2006). Inorganic coagulants bearing aluminum or iron forms multi-charged polynuclear complex in solution. This is a function of the solution pH. These hydrolyzed species bind with the contaminants. These are also polymeric and pre-polymerized class of coagulants which have a higher resistance to solution pH and temperatures (Bratby 2016).

While coagulation-flocculation represents a relatively simple and efficacious technique for water treatment, it is often not sufficient to be used as a standalone option. There are also considerations of sludge disposal, cost (especially for polymeric coagulants flocculants), secondary contamination which needs to be weighed upon to ascertain technological feasibility in the long run. Research and development focusing on biodegradable, non-toxic natural polymeric coagulants flocculants are a right step in this direction and merits more pilot trials for long term applications.

11.2.1.3 Ion-Exchange

Ion-exchange is a physico-chemical treatment process that commonly finds usage in water softening applications. As the name suggests, the process functions by replacing ions from the contaminated water with an ion of the same charge. The replaced ion gets incorporated onto the ion exchange resin matrix and can be released on regeneration. The ion-exchange resins are available in the form of microbeads, columns or porous ion-exchange membranes, wherein the loosely bounded ions are replaced (Figueiredo et al. 2017).

The resins can be broadly categorized into 2 categories; cation exchange resins and anion exchange resins for removal of cationic and anionic species respectively. The ion-exchangers may be of polymeric (resin) composition or of inorganic, zeolite origin. The microporous beads of ion exchange resins that are synthesized industrially usually consist of polystyrene or polyacrylate as base materials. Into that gel matrix, water and the resin are dispersed in a 1:1 ratio (Neumann and Fatula 2009).

The charged functional groups present in the monomers are the key building blocks for the ion-exchange process. The binding forces between the functional groups and ions are relatively weak and can be reversed by ionic interactions with a stronger electropositive or electronegative potential in the electrochemical series. This allows for the regeneration of the ion exchange resins or zeolite columns. However, it is observed that the ion exchange capacity diminishes progressively with each regeneration cycle (Das et al. 2017).

The most common example of application of ion exchange and its regeneration is found in water softening when supersaturated polystyrene beads are used to remove calcium and magnesium ions. The exhausted resin beds are subsequently flushed with brine when sodium ions once again replace the loosely bound Mg^{2+}/Ca^{2+} cations and regenerate the resin (Leonard 2000). One of the drawbacks faced in the conventional gel-based ion-exchange polymeric beads is the relatively lesser surface area, and fouling propensity. To counteract these shortcomings, macroreticular resins with a large porous structure have been developed which are resistant to organic fouling. The cross-linked structure gives rise to a 3D maze with increased surface area. Furthermore, cross-linked structure of polystyrene divinylbenzene offers chemical resistance. The chemical structural formations are demonstrated in Fig. 11.2 below:

In the domain of industrial wastewater treatment, the ion exchange resins are broadly divided into four categories depending upon the application:

(a) Strong acid cation
(b) Weak acid cation
(c) Strong base anion
(d) Weak base anion.

In recent years there has been commercial level implementation of resin technology for treating wastewater as well as saline water. However, their ionic specificity is often a hurdle which increases the cost and necessitates different ion exchanger formulations for separate ionic species.

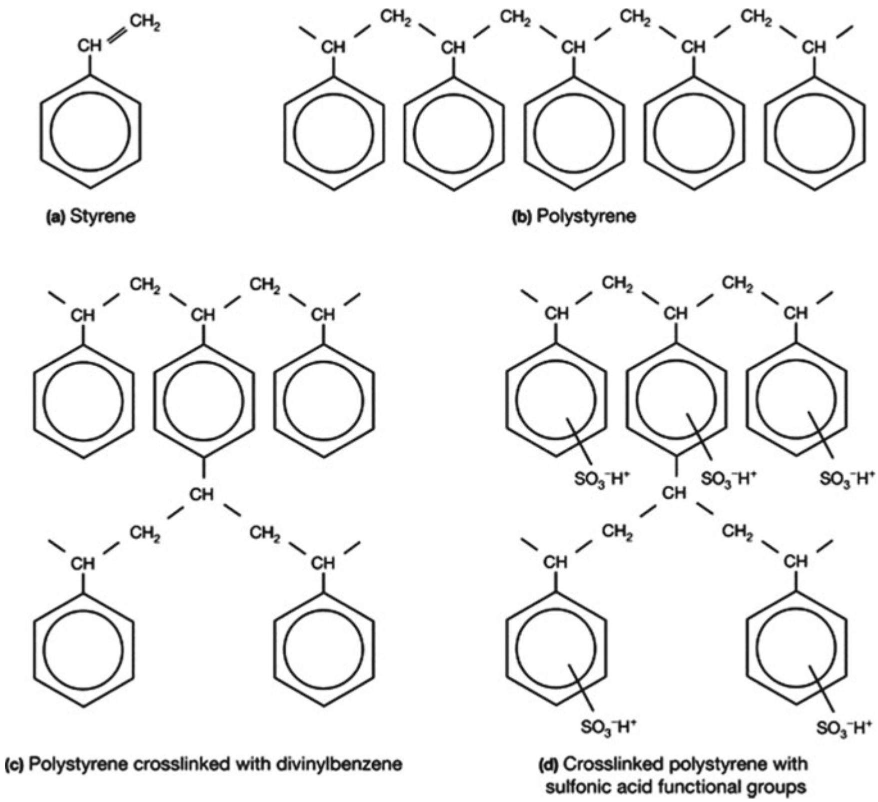


Fig. 11.2 Porous cross-linked resin structure (Schönbächler and Fehr 2014)

11.2.1.4 Advanced Oxidation Processes (AOP)

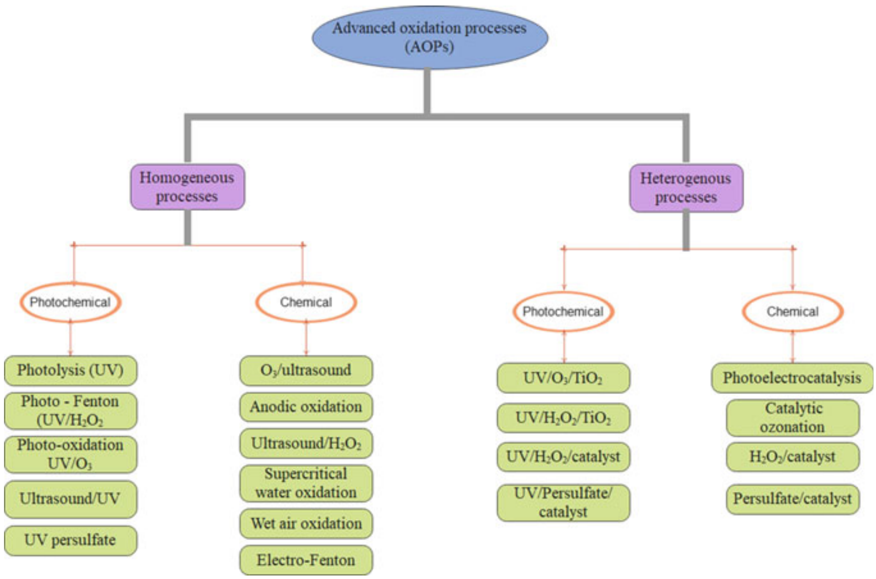
The class of treatments is a group of accelerated, contaminant degrading techniques that are used for the removal of hazardous chemicals, dissolved organics and micropollutants from effluents. There are different classes of AOP's like Ultra-violet oxidation, H_2O_2—Fenton's, photocatalysis, ozonation, chemical oxidation via ferric or titania and their hybrid variations. Other variants include microwave and other electromagnetic wave-based wastewater treatments. Infact UV based treatments due to their efficacy in hydrolyzing the microbial content have become a common household name (Babuponnusami and Muthukumar 2014; Liu et al. 2006; Wang and Chen 2020). Common industrial AOP'S include wet air oxidation, photolysis, UV treatment. Their common pathway of action is oxidation and hydrolysis through free radical formation (Kaur et al. 2020).

The AOP'S have demonstrated successful mitigation of hazardous water pollutants like microbes, API'S such as diclofenac, carbamazepine, dissolved organics like polyaromatic hydrocarbons and heavy metals (Oh et al. 2014; Kowalska et al.

2020; Du et al. 2020). The other benefits include in-situ treatment, no or very less, benign residue generation; and fast reaction times (Singh and Garg 2021). AOP's also include innovative and greener options like sonolysis where soundwaves of different frequencies are used to generate the reactive oxygen species (ROS) without the use of any additional chemicals. Sonolysis harnesses a physical phenomenon called acoustic cavitation where the growth and adiabatic collapse of bubbles are involved that generates heat to split the water molecules into reactive $O^{\cdot}$ species (Balachandran et al. 2016; Rayaroth et al. 2020).

$$H_2O \rightarrow O^{\cdot}H + H^{\cdot}$$
$$O^{\cdot}H + H^{\cdot} \rightarrow H_2O$$
$$2O^{\cdot}H \rightarrow H_2O_2$$
$$2^{\cdot}H \rightarrow H_2$$
$$^{\cdot}H + O_2 \rightarrow HO_2^{\cdot}$$

The AOP'S are divided into photochemical and non-photochemical process based on the reaction pathway. The photochemical AOP'S can be further subdivided into homogenous and heterogenous categories based on physico-chemical mechanisms. Hybrid options like electro fenton's or electro photo-fentons are usually classified in the heterogenous photochemical AOP category (Verma et al. 2021). The different classes of AOP'S are shown in figure below.



Apart from acting as standalone options, AOP'S have also demonstrated increased efficiency when integrated with other treatment options like biochemical degradation or fluidization (Ghime and Ghosh 2020).

Despite the overwhelming high removal efficiencies demonstrated by AOP'S, novel processes like sonolysis, electro photo-fentons has still not been implemented industrially. In recent years research in the process intensified system developments such ozonation with nanobubbles targeting broad-spectrum contaminant removal are finding industrial applications. Another impedicament is the high cost associated with fabrication and installation of such systems. The cost economic analysis and design intensification are required for commercial level implementaion.

11.2.2 Biological Treatments

Bioremediation techniques can be broadly categorized into three groups:

(i) Aerobic processes,
(ii) Anaerobic processes,
(iii) Phytoremediation.

Each of the categories have been serially described below.

11.2.2.1 Aerobic Effluent Treatment Processes

In the simplest terms, aerobic bioremediation is the use of oxygen to treat effluents in the presence of oxygen. As such most of the common substrates on which microorganisms act include dissolved organics. The organic compounds serve as sources of carbon and electrons that can be harnessed for the growth of the microbes. The molecular oxygen acting as electron acceptors are used to oxidize the carbon into CO_2 and new cell mass. The combined processes of oxidation–reduction where the microbe acts as electron receptors and the contaminant as a source of electron donors break down the organic foulants and colloidal matter present in the effluents.

Oxidation

COHNS (Organic matter) + O_2 + Bacteria → CO_{2+} NH_3 + Other end products + Energy (Samer 2015).

The microbes are also capable of degrading inorganic constituents including heavy metals (Fernandes et al. 2008). Aerobic degradation technology focuses on introducing microbe culture in the form of columns of sludge or sludge blankets in which the effluent is fed for the biological remediation processes to take place. In such systems, stoichiometric ratio of 1:3 of hydrocarbon: oxygen is maintained. The rate-controlling step is the O_2 transport to the microbial cells. Based on the location of the sludge blanket and the mechanism of O_2 transport and associated reaction, aerobic treatments are classified into in-situ and ex-situ technologies. The growth kinetics of those microbial enzymes catalyzed reaction can be described with the help of Monod's equation (Russel 2006).

$$\mu = \frac{\lambda S}{K_s + S}$$

μ Specific growth rate coefficient
λ Maximum growth rate coefficient
S Concentration of the limiting nutrient
K_S Monod coefficient.

In terms of process design, the aerobic bioremediation technologies can be segmented into aeration lagoons, oxidation ponds, trickling filters. In these systems different forms of bioventing are used for oxygen supply into the unsaturated zone by using oxygen sparger, aerators or oxygen radical generating compounds like ozone, hydrogen peroxide to increase the speed of the process. One of the side reactions that are observed especially in oxidation ponds is the growth of the algae due to the conducive environment. The selection of the appropriate technology depends upon the organic loading of the effluent volume, interfering ions present and solution pH. For example, effluents originating from food processing industries are treated in aeration lagoons while activated sludge reactors are widely used for the treatment of municipal sewage and allied effluents (Tenore et al. 2018; Khazaei et al. 2009) The design parameters include hydraulic retention time, aeration and/or bubble generation rates, microbial biomass growth, BOD and COD of the effluents. The advantage of the aerobic process is that it can treat a wide range of biodegradable contaminants. It also demonstrates higher biomass yields than anaerobic processes and relatively low CAPEX. However, there are drawbacks like low temperature and pH tolerances, operational difficulties like sludge overflow, BOD and COD overload, necessity of larger reactor size which entails higher energy experience. These trade off's need to be carefully addressed for cost-effective treatment technology development.

11.2.2.2 Anaerobic Bioremediation

This class of treatments utilize anaerobic bacteria to degrade the contaminants in the absence of oxygen. They are typically used for systems with a BOD > 500 mg/L (Samer 2015). The two principal bacterial classes that are used for the anaerobic digestion process are acidogenic bacteria and methanognic bacteria using thermophilic or mesophilic pathways (Stams 1994; Moset et al. 2015). These bacteria and chemosynthetic autotrophs or semi-autotrophs and are more resistant to feed pH, temperature and toxicity levels (Lin and Chen 1999).

The efficacy of these processes can be determined by plotting biosorption isotherms which helps ascertain optimum removal rates under equilibrium conditions. The chief sources of inorganic nutrients are nitrate, phosphates and sulfates which get converted to ammonia and nitrogen, hydrogen sulfide and ATP + H_2O

respectively (Russel 2006). The systems that are used for this purpose include anaerobic lagoons, anaerobic sludge blanket reactors anerobic methane reactors which function by development of an anaerobic biofilm driven by co-metabolism and fermentative pathways. The process does not need any external energy source like oxygen requirement in the aerobic counterparts. Moreover, the calorific values of the gases that are released like methane, hydrogen sulfide are utilized as energy sources. The residual sludge from the process can also be used as a fertilizer or soil conditioner leading to a win–win situation (Nriagu 2011).

The anaerobic reactors are capable of treating large effluent volumes in shorter residence time. Apart from treatment of complex industrial wastewater like dye processing effluents, dairy processing wastewater, steel plant effluents the anaerobic processes are particularly effective for lipid breakdown which is not possible in the aerobic reactors due to inhibitory lipid kinetics (Ma et al. 2015). However, one fundamental drawback of the anaerobic reactor system is the failure to completely stabilize the contaminants. This necessitates a secondary treatment step or combination with aerobic reactors. Despite this shortcoming, anaerobic bioremediation techniques find multifarious applications due to their low reactor volume, lower energy consumption and lesser sludge generation. The energy yield from the evolved gases serves as additional value addition to the process.

11.2.2.3 Phytoremediation

Phytoremediation encompasses different processes of phytoextraction, phytostabilization, phytodegradation, phytodesalination, phytovolatilization all of which uses different plant species for contaminated effluent treatment. As the name indicates, this process offers a sustainable green treatment option that minimizes the production of toxic residues or any forms of secondary contamination. Primarily plant roots are utilized for biosorption of nutrients, heavy metals and other contaminants from wastewater. The different phytoremediation techniques discussed above often use aquatic plants like free-floating *azollapinnata*, *spirodelapolyrhiza, eichhorniacrassipes*, submerged (*hydrophilla corymbesa, vallisneria americana, hyriophylum aquaticum* as well as emergent plants like *nuphurlutea*, *Nymphaea* species) (Mustafa and Hayder 2021). Plant species have demonstrated particularly high efficiency for uptake of heavy metals such as lead, chromium, among others (Chanu and Gupta 2016; Kassaye et al. 2017).

The aquatic plants have shown heavy metal removal from complex systems like municipal wastewater, textile industry effluents which contain high BOD, COD, heavy metals, organic and inorganic nutrients, pathogens and a host of other contaminants (Mojiri 2012; Dulawat 2017). The heavy metal uptake by the plants can also be recovered using hyperaccumulator plant species that yield a large amount of biomass such as *Alyssum bertolenii* (Robinson et al. 1997). This has given rise to an entire new research domain called phytomining which is being used to clean up metal contaminated sites, old abandoned heavy metal mine sites by bio-harvesting of metals (Sheoran et al. 2009). The process of phytoremediation can be used for simultaneous remediation of contaminated water and soil with very less or no energy inputs. Here also, removal techniques can be divided into ex-situ and in-situ subcategories both of which offers the scope of utilization of the produced biomass. Interestingly, it is seen that the mechanisms of phyttoremediation processes often resemble their physico-chemical counterparts (such as ion-exchange, hydroxide condensation, precipitation and ionic complexation) (Gardea-Torresdey et al. 2004).

The plant body exhibits two distinct defence mechanisms of avoidance and tolerance to cope with the toxicity of the heavy metals (Hall 2002). Interestingly certain species of plants display broad-spectrum heavy metal sorption like *Sedum alfredii* which has demonstrated uptake of Zn^{2+}, Pb^{2+} and Cr^{3+}species (Yang et al. 2004). This can help in practical application by reducing the surface area requirements for plant growth. Through this process. the toxic microbial content can be minimized. Studies have shown the complete removal of faecal*Streptocci*and *pseudomonas* after receipt of algae treatments (Rajhi et al. 2020). Apart from contaminant mitigation, nutrient recovery of $NO_3^{(-)}$ and $PO_4^{(3-)}$ compounds are also possible resulting in the formation of slow-release fertilizers like struvite. A crucial factor is the uptake time and resistance of the plant species to fluctuating levels of pH, toxicity which will decide the viability of the phytotoremediation process.

11.3 Advanced Effluent Treatment Techniques

These represent the emerging technological developments in the field of wastewater treatment. In recent years membrane separation techniques have been touted as a panacea for WWT. Apart from the widely studied pressure-driven membrane processes, there are also interesting developments in terms of utilization of thermal and concentration gradients. Photocatalysts and nanotechnology also offer very rapid degradation of contaminants and have garnered widespread research focus. Some of the interesting and promising technologies are described below.

11.3.1 Membrane Distillation (MD)

It is an innovative application of membrane separation technique combining distillation with membrane separation and has been used for radioactive wastes resistant contaminants like arsenic and chromium. Here, nonporous hydrophobic membranes are used that allow preferential vapour transport. The contaminated feed solution is heated, to generate vapours which are transported through the hydrophobic membrane impervious to any solvent flow in the liquid state. Resultantly the contaminant remains behind in the residual concentrate while the vapours containing pure solvent undergo separation. In order to ensure rapid separation of the vapours and to condense them to yield pure water, a coolant is circulated in the permeate side. This creates a thermal gradient between the feed and the permeate sides, enhancing the driving force for the separation and providing a medium for impingement of the vapour molecules. Mechanisms such as air gap, sweep gas or vacuum are also increased to further enhance the separation flux.

Membrane distillation technologies have demonstrated 90% removal of contaminants like arsenic, phenols, (Kiai et al. 2014; El-abbassi et al. 2012) and has also been applied for seawater desalination (Alobaidani et al. 2008). MD offers advantages over conventional thermal separation techniques by reducing the temperature requirements and also by initiating vapour transport at temperature less than the boiling point temperature. This allows the flexibility of coupling renewable energy sources like solar energy, geothermal energy sources and also low-grade waste heat to power the energy requirements of the process (Wang et al. 2019; Sarbatly and Chiam 2013). Compared to the other membrane-based processes, the use of hydrophobic membranes entails lower fouling propensity than the hydrophilic counterparts. This also decreases the stringent pre-treatment conditions needed for the maintenance of the membrane (Alobaidani et al. 2008). MD systems equipped with the provision of heat recovery demonstrates high-performance ratio of 8 due to the short diffusion path traversed by the vapour molecules through the compact, dense MD membrane (Schneider et al. 1988). In terms of process design, membranes module and template selection affect the process performance. Depending upon the operating conditions, plate and frame tubular shell and tube or spiral wound modules are used with flat sheet or hollow fibre hydrophobic membranes. PVDF (Poly Vinylidene Fluoride) and PTFE (Poly Tetra Fluoro Ethylene) are the mostly used membrane material for MD followed by composite membranes (Adnan et al. 2012; Boo et al. 2016). The distribution of pore size, tortuosity, selectively governs the separation and results in near-complete exclusion of different contaminants.

However, notwithstanding all the benefits of the process, there are several challenges faced by the MD membranes. The principal among them are membrane wetting resulting in the gradual loss of the hydrophobic character of the membranes and the low flux associated with the process (Rezaei et al. 2018). Another operational difficulty experienced in real-life condition is temperature polarization, analogous to the concentration polarization due to the imposition of the temperature gradient. Dedicated research efforts in this direction are needed to address the problems. The benefit of high separation efficiency can also offset the operating cost involved in counteracting the operational difficulties. MD has the potential to be developed into an ambitious technology for converting industrial effluents into potable water.

11.3.2 Forward Osmosis

Forward osmosis represents a nascent, highly promising technological niche where concentration gradient is used as a driving force for separation. It is a direct opposite of its popular counterpart Reverse Osmosis (RO). In this process, an additional synthetic solution termed as the draw solution (DS) at a higher concentration than the feed (WW) is circulated on one side of the membrane. These two solutions are separated by a semi-permeable membrane which allows selective solvent transport. The difference in the feed and DS concentrations creates a concentration gradient along the length of the membrane surface. Under the influence of the concentration gradient, the solvent moves from the feed side to the DS side and a dilute DS is produced. This DS is then subsequently treated to get pure water. Recovery of the DS is also possible further incentivising the process. The ideal forward osmosis process is driven solely by concentration gradient without the requirement of any external energy expenditure. However, to increase the speed a small amount of external pressure is applied in a popular variant of the process called pressure assisted osmosis. This technology has proven to be particularly efficacious for drawing clean water from complex industrial effluents.

The operating principle is analogous to MD where the focus is on drawing the clean solvent while the contaminants remain behind in the feed. Owing to the simplicity, high separation efficiency and competitive flux values from the process, numerous hybrid options like integrated RO-FO, FO-MD, FO-NF and other possible process combinations are being researched upon (Kim et al. 2019; Bamaga et al. 2011) Application of osmotic membrane separation in conjugation with RO is helpful for managing the problem of highly saline concentrates. It has also demonstrated efficacious hypersaline brine treatment by cutting down energy expenditure by reducing the external pressure requirements (Das and Singh 2021).

The membrane selection and the draw solution selection are key factors affecting the FO process dynamics. Cellulose acetate thin-film composites with a thinner support layer are mostly used for the FO processes (Das et al. 2020). A critical literature review reveals the exploration of different classes of draw solute and their regeneration strategies. These range from commonly used ionic salts like NaCl and $MgCl_2$, polyelectrolytes, chelating ligands like EDTA, stimuli-responsive hydrogels, magnetic draw solutes (Koetting et al. 2015; Ge et al. 2012). Direct reduction of the secondary draw solute purification step occurs when edible macromolecular draw solutes are used. In this case, there is a yield of dilute draw solution containng nutrients instead of water. This can also be drunk as a nutrient supplement. Similarly, research has also been undertaken for the use of the dilute DS as fertilizers using nutrient concentrates as draw solutions (Phuntsho et al. 2012).

The successful exploitation of the concentration gradient has also yielded several interesting spin-off's like osmotic pumps, pressure retarded osmosis, osmotic bays, osmotic evaporators (Das et al. 2019a). Though they are challenges like internal and external concentration polarization, reverse salt diffusion, requirement of secondary purification step, FO is largely touted as the new-big thing in the domain of wastewater treatment possesing broad spectrum applicability.

11.3.3 Photocatalysis

It is a nascent technology that combines the efficacy of catalytic contaminant degradation with renewable solar energy as a source of energy. Broadly it can be classified as an advanced oxidation technology that is used to breakdown persistent organics like pesticides, textile dyes, oil as well as inorganic components like nitrates and heavy metals (Mboula et al. 2013; Prieto et al. 2005). Photocatalysis has also been used to breakdown pathogens like bacteria and viruses from contaminated wastewater (Martín-Sómer et al. 2019). The process of photocatalytic effluent treatment can be broadly divided into two parts homogeneous photocatalysis and heterogenous photocatalysis. The homogenous photocatalysis relies on the action of UV light to generate hydroxyl free radicals from water which in turn hydrolyze and breakdown metal ions and are accompanied by a formation of hydrogen peroxide.

$$\begin{aligned}
&\mathrm{MeOH^{n+} + h\upsilon \rightarrow Me^{(n-1)+} + OH^{\cdot}} \\
&\mathrm{MeL^{n+} + h\upsilon \rightarrow Me^{(n-1)+} + L^{\cdot}}
\end{aligned}$$

(Prihodko and Soboleva 2013).

The heterogeneous photolysis as its name suggests includes composite phased materials, and also offer the flexibility of using visible light sources apart from UV waves. Critical analysis of research literature in this arena reveals large number of research dedicated to crystalline modification for improved catalytic material synthesis and the application of integrated photocatalytic systems with other advanced oxidation technologies. The fundamental principle of photocatalytic effluent treatment is derived from quantum chemistry where absorption of photonic packets equivalent to one quantum energy generates an electron-hole pair. The photogenerated holes drive thermodynamically spontaneous reactions catalyzed by hydroxyl cationic free radicals, by adsorptive mechanism on the surface of the photocatalysts.

$$\begin{aligned}
&\mathrm{H_2O_{ads} + h^+ \rightarrow HO^{\cdot}_{ads} + H^+} \\
&\mathrm{OH^-_{ads} + h^+ \rightarrow HO^{\cdot}_{ads}OH^-_{ads} + h^+ \rightarrow HO^{\cdot}_{ads}} \\
&\mathrm{R_{ads} + h^+ \rightarrow R^{\cdot +}_{ads}}
\end{aligned}$$

Similarly, spontaneous oxidative pathways are also catalyzed

$$\begin{aligned}
&\mathrm{O_{2ads} + e^{(-)} \rightarrow O_2^{\cdot -}ads} \\
&\mathrm{O_2^{\cdot}ads + H^+ \rightarrow HO^{\cdot}_{2ads}} \\
&\mathrm{O_{2ads} + 2e^{(-)} + 2H^+ \rightarrow H_2O_2ads}
\end{aligned}$$

The oxidative mechanisms follows Langmuir-Hinselwood and Eley–Rideal pathways.

There are different classes of photocatalysts being researched upon. However, the vast majority of research publications as well as limited number of commercial ventures focused on using TiO_2anatase phase. TiO_2 nanomaterials are generally preferred due to the higher surface area of these processes (Hussain et al. 2010). Some of the process developments include nanosized TiO_2 embedded on zeolites or mesoporous supports for simultaneous oxidation and ion-exchange utilizing the molecular sieving properties. The TiO_2 is used as colloidal suspensions, solid nanoinjections or dispersed in carries suspended specially in the photoreactors.

However, while evaluating the market competitiveness of photocatalytic processes, their cost and photonic conversion efficiency are areas that demand further research before the competitiveness with other separation processes can be established. In a photocatalytic reactor one of the important design considerations is the depth of penetration, and depth of catalyst bed, which in turn depend upon catalyst synthesis and life of the active catalyst components. Application in real wastewater treatments often mandates pre-treatments to remove interfering ions which might poison the catalyst. Light storage and supply also poses veritable challenge. Comprehensive life cycle analysis covering catalyst synthesis, WWT efficiency and catalyst regeneration is necessary for cost-benefit assessment.

11.3.4 Nanomaterial and Nanotechnology

In recent years considerable research space in the domain of environmental technology in general and effluent treatment has been occupied by nanotechnology which represents a scaling down of the process to the nanolevel for increased speed, surface area and higher reaction efficiency. The nanomaterials that are used for wastewater treatment can be divided into metallic nanomaterials, metal oxides, carbon nanotubes and nanofibers and nanocomposites. The zero valent metal nanoparticle is the simplest to synthesize and widely used in the arena of effluent treatment. Silver nanoparticles are especially, used to degrade microbial contaminants due to the antibacterial and fungicidal properties of silver (Borrego et al. 2016; Kalhapure et al. 2015). Silver nanoparticles have also been combined with plant extracts in several green synthesis studies which have proven to be effective in the remediation of heavy metals (Shittu and Ihebunna 2017). Other prominent metal nanoparticles used in WWT include iron nanoparticles. Zero valent aluminium nanoparticles are also being researched upon due to their rapid surface reactions forming hydroxides and/or oxides (Rivero-Huguet and Marshall 2009).

The metal oxide nanoparticles include compounds that can also act as semiconductors for possible integration with photocatalyst TiO_2 nanoparticles which are widely used as a photocatalyst for effluent remediation falls under this category. Iron oxide nanoparticles doped with graphene is also an interesting technological development that intensifies process performance. The nanoparticles are potent scavengers breaking down radioactive elements, halogenated organic compounds, nitroaromatic compounds and other persistent pollutants (Ling and Zhang 2015; Liang et al. 2014; Xiong et al. 2015). Another novel development credited to advanced material science research is the discovery of carbon nanotubes. These are single layers of graphene bundled in a cylindrical shape which can be single-walled or multiwalled with interconnecting nanotubes. The multiwalled CNI'S can also be arranged in a hexagonal pattern forming a honeycomb structure. This greatly enhances the surface area and the fine diameters impart high selectivity to the nanoparticles. Their fast reaction kinetics and organic separation potential has been utilized in the area of pharmaceutical effluent management.

The contaminant mitigation mechanisms of the nanoparticles include adsorption and in some cases biosorption, oxidation and hydrolysis, ion-exchange. Due to the capability to exhibit more than one removal mechanism, nanoparticles can be used for broad-spectrum contaminant removal from complex industrial wastewaters like oil industry wastewater (He et al. 2021). Their fast kinetics and the nanolevel separation characteristics have been harnessed in the treatment of high salinity containing produced water (Kunduru et al. 2017). Another interesting class of heterogeneous nanomaterials are the nanocomposites. Nanoparticles embedded on polymeric membranes or ceramic/zeolite membranes have been used for the mitigation of particularly recalcitrant substances from effluents like catalysts residues, drug residues, volatile organic compounds (Zou et al. 2019; Li et al. 2019). Nanocomposites are multiphase substances consisting of porous media, gels, colloids and polymers (Rane et al. 2018). The nanomaterials are one fast-emerging technology that has the potential to develop as a standalone WWToption.

11.4 Sustainability and Value Addition in WWT

11.4.1 Recovery of Value Added Products from Effluent Streams

One of the important avenues of research in the domain of WWT is the recovery of value-added products from effluents streams this approach is a sustainable research perspective that considers wastewater as a rich source of underutilized compounds from which value addition may be derived. In recent years due to shrinkage of resources and implementation of stronger environmental norms, wastes to wealth technologies are receiving heightened research attention. Membrane separation techniques have been particularly studied for the recovery of value-added products, like brine and soda ash recovery, extraction of metallic values, chemical recovery and others. Niche areas of sustainable technology such as membrane-based crystallization have been harnessed for nutrient recovery (Das et al. 2019b).

While focussing on value-added product recovery from effluents, it is imperative to understand the compositions of the wastewaters and what are the products that can be recovered from it. Membrane crystallization and membrane extraction techniques have been successfully harnessed to recover organic acids like succinic acid, lactic acid and also pure lactose crystals from cheese whey (Wan et al. 2007; Guimarães et al. 2010; Tejayadi and Cheryan 1995). Ammonium and phosphate containing effluent streams have been reacted with magnesium dosing to isolate a slow release fertilizer magnesium ammonium phosphate; commonly known as struvite (Çelen and Türker 2001; Diwani et al. 2007). Several integrated membrane separation techniques have been utilized for struvite recovery (Diwani et al. 2007).

Biochemical and electrochemical technologies have also been studied for recovery of value-added products. For example, selective microbial action has been used for fumaric acid production or oven biogas production from organic effluents (Sebastian et al. 2019; Pogaku et al. 2015). Similarly, fruit and oil industry effluents have been exploited for bioethanol production via the bioreactor route. Physico-chemical techniques like accelerated carbonation, selective leaching have also demonstrated the potential of extraction of valuable components from effluent streams.

11.4.2 Process Intensification

The newer challenges of zero liquid discharge, highly toxic contaminants like emerging micropollutants necessitate a paradigm shift in the design of ETP units. It is imperative for the WWT techniques to be sustainable and environment friendly. In terms of design, these requirements translate into optimum raw material consumption, minimum energy expenditure, coupling with renewable energy resources, sludge management and high WWT efficiency. Process intensification is one research avenue that can meet those requirements. Process intensified systems are highly efficient, modular design units that are the product of compact process development, which aims to merge several unit operations into one. Another parallel focus is to make the systems sustainable without compromising on energy efficiency.

Research in the domain of advanced separation techniques has led to the advent of process intensified systems incorporating membrane separation, photocatalysis, and nanotechnology. All of these systems aim to replace the bulky, multicomponent traditional effluents systems with single staged multipass units that are essentially simple and highly efficient. The process complexity diminishes with scaling down of the process. The single membrane assembly/membrane bioreactor also allows operational flexibility of coupling and decoupling of additional membrane module to treat fluctuating feedstocks and variable contaminant loadings.

Integration of process intensification technologies with conventional treatment options and value-added product recovery will enhance the sustainability quotient and economic viability of the processes leading to more large-scale implementation.

11.5 Conclusion and Future Work

(1) There are a host of different classes of wastewater treatment techniques. It is imperative to select the technologies based on the contaminants, toxicity levels, concentration, effluent volume and overall process economics.

(2) The conventional effluents options often lack the operational flexibility to handle new age contaminants as well as fluctuating contaminant loadings. Research options to integrate these techniques or combine them with novel

techniques are needed for their applicability in the current effluent treatment scenario.

(3) Membrane separation techniques are being widely researched upon and practically implemented as a broad spectrum effluent treatment option. They can be easily coupled with nanomaterials or catalysts or with the conventional techniques leading to a win–win situation.

(4) In recent years, process intensification, recovery of value-added products and process sustainability are important attributes that are being increasingly incorporated in the new age effluents treatment techniques.

(5) Advanced novel techniques like photocatalytic membrane reactor, solar-driven membrane distillation are being explored to couple renewable energy sources thereby increasing the environmental friendliness quotients.

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Part IV
Impacts of Degradation

Chapter 12
Microbial Diversity and Physio-Chemical Characterization and Treatment of Textiles Effluents

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Abstract Water is crucial component that determines living forms including plants and animals as well as human beings and its availability and quality is one of the major factors for domestic, agriculture, industries, transportation and other activities. Thus, the water quality becomes as a central concern on determining the life quality and the economy any country. Besides, urbanization, mechanization and waste disposals including industrial effluents are essential factors usually influence the water quality in a specified area. Present environmental problems are mainly encountered due to the disposal of unprocessed, and raw industrial effluents containing various toxic chemical to the environment specially water bodies (rivers).

Keywords Toxic chemicals · Microorganisms · Industrial effluent · Water pollution

12.1 Introduction

Water is an essential component that is required for all kinds of life and it is contributes approximately 50–97% of the total mass of plants and animals including the human body. Water is also an energetic reserve for agricultural processes and other industrial applications. The range of water quality determines the eminence of life forms and predominately linked with its usage. It is an essential element for the economic development of any nation (Ramamurthy et al. 2014; Zhang 2020; Sharif et al. 2021). There are different types of water sources including rain water, ground water, salt water and surface water, etc. However, the major contribution comes from the

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surface and ground water any activity related to the biological or non- biological purposes in day today life. Meanwhile, the ground and surface waters are more prone for contamination by several sources and the industries play a prominent role in determining the range of their contamination. Unethical clearance of such industrial wastes and their effluents to nearby water bodies is one of the major contributors for poor water quality in urban areas (Ramamurthy et al. 2015; Talabi and Kayode 2019). Today, the improper handling of the by-products from toxic chemical manufacturing and their disposal pose a dangerous threat worldwide and the public water bodies such as city sewage systems, the lakes and the rivers become an illegal place for discharge. In addition to, the cottage industries also generate and dispose their waste products in to such water bodies. As mentioned above, the rubbish products such as cafeteria garbage, masonry, concretes, metallic scraps, trashes, contaminated soils from automobile industries, various solvents, chemicals, weed grasses, haw mill dirt's are few examples for the industrial wastes. Those could be dirt and gravel wood and scrap lumber and similar wastes. Similarly, those wastes are classified based on their physical nature viz., solid, liquid and gases; in addition to, they could be of hazardous and non-hazardous waste depending upon their chemical components and their biological effects (Rajasulochana and Preethy 2016; Velvizhi et al. 2020).

Whilst their exact impacts on the human health and environment are largely unknown, the pile up of scientific research have shown that those chemicals have contaminated almost of all biological systems in the world human' living hold (Bradney et al. 2019). The industrial waste water discharge contributes majorly for water pollution because of the high voluminous identifiable chemical compounds and the workers such as from farms; oil and gas processing units are having higher exposure probability for those chemicals. Nonetheless, most of the major industries have their waste processing units by their own, but the level industries need to contribute higher proportion of their income for maintaining their waste processing units. As a result, due to high burden of the investment, equipment and labours, those small-scale industries do not firmly adopt the environmental pollution rules in many major cities worldwide (Guttikunda et al. 2019).

The toxic effects of such water pollution are reported from any of the ecological niche and predominately affecting the physiology of the living systems irrespective of the phyla viz., animals, fish, and birds. Firstly, the polluted water is unsuitable for drinking purpose, recreation, agriculture, and also for further industrial applications. Particularly, the water pollution highly reduces the aquatic biodiversity and further, their reproductive ability (Bashir et al. 2020).

12.2 Pollutants and Aquatic Environment

Discharge of industrial effluent directly to the aquatic system due to green revolution and rapid urbanizations severely affects the water quality (Arif et al. 2021). Every industry discharges their own kin kind of waste water and the recent reports highly classify them based on their physical, chemical and biological nature. In

India, raw sewage and industrial effluents from distilleries, tanneries, pulp factories, paper mills, sugar factories and chemical industries are falsely considered and not processed by their kind of systems. This indiscriminate discharge systems contribute an environmental chaos and resulting in severe impact on ecological imbalances and deterioration. The aquatic organisms especially, the fishes are predominately affected by the polluted waters and face a critical risk in their behavioural, biochemical and pathological aspects (Wolf 2021; Ali et al. 2019). The effluents released from such industrial wastes have been reported to cause chronic physiological paralysis in fishes and occasionally, also the immediate death (Chowdhary et al. 2020).

Effluent discharged from distilleries affects the physico-chemical nature of aquatic medium (Ray and Ghangrekar 2019). The turbidity of water is increased by the dark brown colour of the distillery effluent. Presence of high organic and inorganic compounds in the effluent, increase the production of algal blooms leads to severe oxygen reduction in the freshwater bodies affects the aquatic flora and fauna (Bhateria and Jain 2016).

Most of the unprocessed waste waters contain serious level of heavy metals and their presence in such aquatic systems render substantial adverse effects on aquatic communities. The industrial wastes, mining, agricultural development and fossil fuel combustion are few examples for the major heavy metal introducers in to the environments (Adakole 2000; Jeevanantham et al. 2019). Such metal contamination in aquatic life becomes a dangerous threat and their elevated levels may lead to inhibition of vital enzymes in the animal and plants. Further, the fishes in the contaminated environments considered as a pollution source for bio-magnification and suffer as the direct victims in such environmental scenario (Adakole and Abolude 2009). Heavy metal contaminations such as Poly aromatic hydrocarbons (PAH), Organo chlorines, Organo sulphur derivatives are few examples for such devastating chemical pollutants (Rani and Shanker 2020).

12.3 Effects of Industrial Effluents in Aquatic Environment

The aquatic organisms are affected by industrial effluents directly or indirectly in different ways and are as follow;

Higher contamination of water bodies affects the survivability and population of aquatic animal especially fish population. Since water contamination reduces the utilization of food and oxygen consumption of fish. Food composition such as protein, carbohydrate and lipid is also changed in fish.

The rate of oxygen consumption of fish is affected, when the fish is exposed to industrial effluents, (Javed and Usmani 2019).The oxygen content in the environment and its consumption is a critical life process and considered to be a vital biomarker for indicating the presence of such pollutants due to it has higher tendency to affect the respiratory process directly many researchers viz., have reported that the oxygen consumption decreased with the pollutant exposure (Gurusamy and Ramadas 2000; Dwivedi et al. 2018; Barbieri et al. 2019; Alaguprathana and Poonkothai 2021).

Malachite green is one of the food colouring agents usually served as an additive in food- processing units and as a disinfectant in anthelminthic preparations. Its usage is extended to many industries such as, dyes, jute, wool, silk, cotton, paper, leather and acrylic processing. Conversely, as a pollutant, the malachite green reported to cause severe respiratory distress in variegated trout fish (Ross et al. 1985) and Nile tilapia (Omoregie et al. 1998).

12.4 Textile Colorants

Textile dyes are the mixtures of chemicals and it composed of salts, calcium stearate, carboxy methyl cellulose and other unknown chemicals. It is estimated that India uses approximately, 64,000 tonnes of different types of dyes in a year for various industrial applications including textile, leather, paint and even the food processing. Among them, the textile industry alone consumes nearly 80% and those exhibits high toxicity even at their lower concentrations due to their ability to make covalent bonds with a number of environmental components (Katheresan et al. 2018). Most of the dyes used by textile industries are producing carcinogens and teratogens. About 40% of global colouring agents contain organically bound chlorine with carcinogenic effect. Mordant dyes contain chromium which is toxic and has high impact on the environmental pollution.

Azo dyes are very popular in textile industry due its high stability in light and resistant capacity to the microbial attack. These dyes are environmental persistent and slowly degradable at normal circumstances. Because of their strong, covalent nature these dyes make a hard challenge in waste water treatments and the conventional treatments face a hardship on their treatment. A variety of azo derivatives of anthraquinone, polycyclic and tri phenyl methane dyes are used as colouring agents in textile industries and occupy major portion on their waste water discharge (Kishor et al. 2021).

Dyes that utilized by the textiles industries giving toxic effects at cell and gene levels that can cause mutations and cancers in aquatic animals like fishes, algal species, bacteria, fungi and as well as animals. The entry of textile effluents that enter in to the food chains those aquatic organisms certainly cause different physiological imbalances such as syndromes such as high blood pressure, periodic fever, renal damage and pains (Koul and Taak 2018; Mehta et al. 2020).

The effluents from the textile industries are greatly affect the environment by a number of ways including their oxygen reducing ability (the presence of hydro sulphide group compounds oxygen concentration in waters), blocking the light penetration are few reasons that bring unfavourable effects to the water ecosystem (Kumar and Joshiba 2018).

12.5 Study of Textile Effluents

Besides, many bioassay assays were developed to display and measure the waste water toxicity of domestic and industrial effluents (Hader et al. 2018). The proficiency of such assays can be monitored at each step of the waste water treatment processing based on the physical, chemical and biological evaluations (Bourgin et al. 2018; Bhatia et al. 2018).

Abbas et al. (Abbas et al. 2018) and Iqbal (Iqbal 2016) reported that *Vibrio fischeri*-based bioluminescence inhibiting (VFBIA) and *Vicia faba* growth inhibition were simple model systems to monitor the sensitivity and to detect the poisonous load, respectively (Giorgetti et al. 2011; Ahkola et al. 2021).

Many researches proved that the unprocessed raw textile effluents greatly show the cytogenic and mutagenic effects compared with the treated wastes. The hazard valuation of textile industrial areas reported by many authors and recently, Noreen et al. (Noreen et al. 2017) detailed the waste water risk assessment around the Faisalabad city.

The groundwater quality is one of the main methods for evaluating the susceptibility potential to landfill site pollution based on the DRASTIC test model (Majolagbe et al. 2016, 2017). Their study demonstrated that a DRASTIC is one of the useful methods in assessing the environmental sustainability against the pollutants. Further, the mathematical model based on the equations as proposed by Ukpaka (Ukpaka 2016) is used to determine the effect of the contaminant in ecosystems and groundwater quality.

12.6 Physico-Chemical Characteristics of Effluent

The environmental factors namely, temperature, salinity, hardness and total dissolved substances, etc., have the capacity to change the nature and the modifying effect of temperature on the toxicity of chemicals to fishes has been documented by Vieira ("Removal of endocrine disruptors in waters by adsorption, membrane filtration and biodegradation. 2020; Lead et al. 2018).

Water temperature is one of the main factors because it is significant role in the determination of distribution, survival, growth, metabolism and reproduction of organisms (Azra et al. 2020). Verma and Mathur (Verma and Mathur 1974) have stated that the distillery effluent is more toxic than mixed paper and pulp mill effluent. Arokiasamy (Arokiasamy 1982) has stated that the toxic effects of distillery effluent must be due to its very high COD, BOD, total dissolved solids. The chromium contamination leads to the onset of anaemia in fishes when treated with chromium. Similar findings were also supported from several authors in recent analysis (Alaguprathana and Poonkothai 2021; Sivakumar et al. 2020).

Tekade et al. (2011) collected soap industry effluents from Wardha and analyzed the important factors such as colour, temperature, odour, viscosity, surface tension, acidity, chloride, hardness, alkalinity, total suspended solid, Chemical Oxygen Demand (COD), total dissolved solids, conductance, pH, sulphate, Biological Oxygen Demand (BOD) and pathogens. BOD and COD values are the primary parameters that are generally used to detect organic strength of any waste water.

12.7 Bioremediation

Bioremediation is a recent biological technique applied in the field of pollution control, where microbes are used to catalyze the reactions to reduce the harmful effects or it may use to transform the toxic compounds into non-toxic (Bhatia et al. 2018; Darwesh et al. 2019). This technique is very useful for the treatment of various industrial effluents (Darwesh et al. 2019).

The concern about fast industrialization and increasing interest for clean environment enforcing the industrialist, environmentalist and the government to search and alternate option and it should be effective, low cost and long-term solutions for waste treatment and recycling (Bennett 2020; Pritchard and Zimring 2020). Because, physico-chemical methods adopted for waste water treatment is very expensive, and hence it is not followed by many industries especially in developing countries like India (Jasmin et al. 2020). Hence, in recent years, biological waste water treatment or bioremediation process getting more attention at global level due to its low investment.

The successes of bioremediation of waste water have been proved by many studies using algal culture to remove nitrogen and phosphorous compounds (Vitti et al. 2021). So, bioremediation is the best alternative process for waste water treatment which will minimize the costly physico-chemical treatment systems and it also offer high potential for waste management (Rahman et al. 2020). The algal systems, mainly cyanobacteria are widely used for waste water treatment along with the various useful by-product from their biomass (Mackereth 1963).

12.7.1 Oscillatoria

Oscillatoria sp. is a filamentous cyanobacteria found in fresh and marine waters. It is common in fresh water ponds and plays a prominent role in neutralizing the nutrients on municipal waste water systems. Due to their photoautotrophic and eutrophic nature, they are highly used in removing the wastes from textile effluents. The systematic position of cyanobacterial strain used for removal of waste from the textile industries are given below.

- Kingdom: Bacteria
- Phylum: Cyanobacteria
- Class: Cyanophyceae

- Order: Oscillatoriales
- Family: Oscillatoriaceae
- Genus: Oscillatoria

12.8 Materials and Methods

12.8.1 Collection of Samples

Textile effluent was collected from textile industries of Tirupur Dist., Tamilnadu. The effluent was filtered with cotton cloth to discharge the suspended particles present in it. The physical, chemical characters of the sample were done on the same day of collection. Glassware's for analytical study was procured from Borosil and standard laboratory procedure was adopted throughout the study. The free carbon-dioxide; carbonate and bicarbonate alkalinities in the samples were determined titre metrically and expressed as mg l-1 (Strickland and Parsons 1972).The Dissolved Oxygen (DO) of textile effluent was estimated by Winkler's method and improved by Strickland and Parsons (APHA 1991) following necessary safeguards and it found that the result is mg O_2 l-1.TSS, TDS, BOD and COD were assessed as per the standard methods (Solorzano 1969). Nitrates and nitrites were determined according to the method of Strickland and Parsons (APHA 1991) and the values are expressed as mg NO_2-N l-1 and mg NO_3-N l-1, respectively. Ammonia nitrogen was appraised following the method of Solorzano (Menzel and Corwin 1965) and expressed as mg NH_3-N l-1.

The total amount of phosphorus present in the sample was measured by Menzel and Corwin (Murphy and Riley 1962) method and expressed as mg P l-1. Inorganic phosphate was determined by the method of Murphy and Riley (Mackereth 1963) and expressed as mg PO_4-P l-1.

Calcium and magnesium values are estimated titre metrically (Bergey's Manual. 1984) and expressed as mg l-1. Chloride was determined titre metrically (APHA 1991) and expressed as mg l-1.

12.8.2 Study of Microbial Diversity

The effluent sample was collected aseptically in sterilized containers for the bacterial and fungal isolation. The same place was selected for cyanobacterial study also. The bacteria were isolated using the nutrient agar medium and identified by adopting the previous methods with minor modifications (Bergey's manual, (Gillman 1957)). The fungi were isolated from the samples using potato dextrose agar (PDA) medium with pH 5.6. The fungal growth was stained using lacto phenol and cotton blue and the slide was observed under the microscope. The standard manuals namely, manual of soil fungi (Ellis 1971), *Dematiaceous Hyphomycetes* (Subramanian 1971), Hyphomycetes (Ellis 1976) More *Dematiaceous Hyphomycetes* (Rippka et al. 1979) were used for identification process. Cyanobacterial samples were collected from the site of effluent collection using standard microbiological methods and the study of cyanobacterial characterization were made in the laboratory condition using solid agar medium, BG11 (Chan et al. 1979). The colonies that are developed in a solid medium were taken out and transferred to the liquid medium. The achievement for unialgal growth, i.e. cyanobacteria was made by repeated streaking in BG11 liquid medium. Finally, the cyanobacteria were identified with the help of keys given by Desikachary (1959).

12.9 Results and Discussion

The intensified dark brown colour indicated the increased turbidity in the processed water. The high content of organic and inorganic nutrients in the effluents strongly support the over production of the algal biomass and the lead to the algal blooms. These blooms, on other hand, eventually reduce the oxygen content in the water systems and make them as hostile environment for other organisms. Many types of the toxic materials usually found in the textile wastages, the chlorides, sulphite, higher amount of dissolved solids and the sulphides. The sulphides are comparatively lower than the other compounds. Their higher concentration may lead to their soil-persistency and leaching between the nearby water bodies. Hence, those compounds render severe damages in gills, heart, skin, etc., to the consumed animals.

The degradation of the effluents are done by different level of physiological processes and various organisms such as *Escherichia coli, Enterobacter aerogens, Klebsiella pneumoniae, Bacillus subtilis, Proteus vulgaris, Pseudomonas aeruginosa, P. fluorescens, Staphylococcus faecium*etc), fungi (*A. niger, Verticillium* sp, *Saccharomyces* sp, *Helminthosporium, Penicilliumsp, Trichoderma virideetc*) and cyanobacteria (*Oscillatoria, Phormidium, Lyngbya, Nostoc Anabaena, Gleocapsa, Plectonema, etc.).*

Among them, *Oscillatoria tenuis* had significant role due to their fast- growing, photosynthetic nature. They have the ability to degrade a number of effluent dyes and preferably used for bioremediation of textile industry effluent. Their altered physiology in those effluent waters show modified behavioural changes in swimming, surfacing and breathing activities. Several studies found significant changes in their opercular movements and oxygen consumption in normal, treated and untreated textile effluent on fishes.

12.9.1 Swimming Activity

The observation on the swimming behaviour revealed no abnormalities compared to the controls at lower concentrations. Meanwhile, their swimming behaviour was strongly affected with the raw (non- diluted) effluent wastes. They showed many abnormal movements such as fast and twisting movements, increased surfacing frequency, more gulping, frequency of vertical swimming, heavier mucus exudation, increased non- coordinated movements and loss of balance. The escaping behaviour from the medium was highly increased with the higher concentration.

12.9.2 Opercular Beats

The opercular beating frequency was increased with the concentration of the effluent wastes. But, its frequency was found to be dose- dependent with the concentration.

12.9.3 Rate of Oxygen Consumption

The consumption of the oxygen was a direct parameter for evaluating the energy need of the organisms. The oxygen consumption rate was higher in cyanobacterial treated effluents than the raw effluents. Meanwhile, the study also showed a gradual decrease oxygen consumption with the increased concentration of the raw materials, i.e. dose—dependent oxygen decrease.

12.9.4 Haematological Parameters

The haematology evaluation on the organisms revealed a strong decrease of the haematological population such as RBC count number, haemoglobin density and elevated level of the white blood cells (WBC).

12.9.5 Biochemical Studies

The cyanobacterial processed effluents showed increased amount of protein, glycogen, amino acids and lipids than the raw effluent treated organisms. The fishes in raw effluents showed a deeply decreased biochemical constituents than the control groups.

12.9.6 Enzymes Studies

The cyanobacterial treated effluents showed increased enzymes level such as SDH, LDH, ACP, ALP, GOT and GPT than the raw effluent treated groups. Those enzyme level was strongly reduced in raw effluent treated groups than the control group.

12.10 Conclusion

The impact of textile effluents on biological treatment recommends that it has an inhibitory effect on many chemical components. In general, the textile effluents are xenobiotic compounds accumulated in water bodies through the elution process using various surfactants and detergents. The major toxic ingredients present in textile effluent are high dissolved solids, COD and BOD. Hence, dilution and biological treatment of textile effluent is very much essential before it discharged to the ecosystem. Finally, this study concluded that the bioremediation and treatment of effluents by microbial community helps to neutralize the pollutants and minimize their effect in the aquatic environments.

12.11 Recommendations

The present technical achievements on the extraction and downstream techniques in algal biotechnology require further refined approaches for achieving better feasibility and sustainability. The bioactive or ethanol production from the microalgae is proportionally related with their biomass concentrations. Compared to the heterotrophic bacterial concentration, the micro algae showed ten to hundred folds biomass reduction and lower concentration on its fermented by- products. Though, the technological advancements produced modernized bioreactors for bacterial fermentation, such kind of photo bioreactors are not fully available for the micro algal production. These photo bioreactors are so expensive than their bacterial counterparts due to utilization of artificial lights. The downstream products, on other hand, consume nearly, 40-50% of total cost with untenable biomass production. The novel technique, cascade extraction is one of the better alternatives for the cost- effective approach in algal biotechnology. The extraction with the mild liquid-based solvent systems further reduces the drying dependency in downstream processes. The industrial algal wastes are distributed as the nutritive products for different agriculture cum aquaculture industries and further require a detailed analysis on their nutritive valuable components. Several studies revealed that the need of awareness creation about the algal and their associated products as valuable sources for human protein requirement and presently, used in as value added products in preparation of snakes, savouries and pastes for ensuring their anti- oxidant properties. But, the algal biomasses from the industrial wastes mostly disposed as contaminants due to the unavoidable problems in their extraction. The textile effluent contains various chemical compounds and the mixtures of suspended solids, organic materials and the higher pH is highly toxic in nature. The entry of toxic effluent to the aquatic animals through the food chain may lead to many of significant disorders viz., sporadic fever, renal damage, cramps hypertension, etc., Textile effluent changing the physico-chemical characteristic of aquatic medium in which the turbidity of water is increased by the dark colour of textile effluent. On the other hand, the effluent itself contains different types of indigenous microbes could be efficiently utilize for the treatment of various effluents. Cyanobacteria are potentially present in the textile effluent and are used for the bioremediation of textile effluent by growth enhancing strategy. *Oscillatoria tenuis* popular organisms that are used for the treatment of textile effluent because of its less retention time.

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Chapter 13
A Sustainable Solution for the Rehabilitation of Surface Water Quality Degradation

Nuruol Syuhadaa Mohd

Abstract Indifferent to point source pollution that was usually discharged into surface water from a known site, such as pipe effluent, diffuse pollution happens when contaminant goes into surface water by means of surface runoff, soil infiltration or rainfall, causing in the depreciation of surface water quality. The most common example of diffuse pollution is the leaching of pesticides and fertilizer from agricultural activities. In this context, ecological engineering practices, namely constructed wetlands and vegetated ditches, may play a paramount role in providing the sustainable solution for this issue. Though constructed wetlands have been widely used for many years, vegetated ditches have started been practiced only recently. Therefore, this review is done with the aim to illustrate the practice of vegetated ditch in treating diffuse pollution that leads into the degradation of surface water quality. This paper will highlight the application of vegetated ditch in treating diffuse pollution, the effectiveness of the system as well as the mechanisms of contaminant removal. Furthermore, this review will critically evaluate the challenges faced by vegetated ditch implementation as well as the recommendations needed for the enhancement of the system.

Keywords Vegetated ditch · Diffuse pollution · Ecological engineering · Nature-based solution

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13.1 Introduction

13.1.1 Best Management Practice (BMP) to Mitigate Diffuse Pollution

Indifferent to point source pollution that was usually discharged into surface water from a known site, such as pipe effluent, diffuse pollution happens when contaminant goes into surface water by means of surface runoff, soil infiltration or rainfall, causing in the depreciation of surface water quality. Among all sources, agricultural activities, through its heavy usage of fertilizers and pesticides, have become the predominant contributing source of diffuse pollution through surface runoff and erosion (USEPA, 2011). Due to that, elevated attention has been placed on establishing and executing novel and inventive best management practices (BMPs) to mitigate surface water contamination caused by runoff consisting of pesticides, fertilizers, nutrients, sediments and bacteria. With regard to that, three types of strategic approach are proposed in order to attenuate diffuse pollution especially for agricultural areas of the rural regions. The strategies encompass three phases: (a) pollutant control at source (e.g., minimum fertilizer usage, biological pest control, no-tillage farming, crop rotation); (b) pollution detention in the runoff (e.g., stiff grass edges, cover crops, buffer zones, vegetated filter strips); (c) rehabilitation of the contaminated waterway (e.g., vegetated ditch, retention ponds, constructed wetlands, floating wetland, submerged hydrophyte restoration, subsurface filtration) (Faust et al., 2018; Kumwimba et al., 2018; Mohd et al., 2020; Wu et al., 2017). Of these, the rehabilitation of the polluted water pathway technologies provides the last defense against surface water contamination through physical, biological and engineering methods. Additionally, as drainage ditches have become an essential component of irrigation and drainage system, and also that the ditches tend to be the dominant pathways of the polluted water before receiving water bodies, it has become critical and economical that the existing drainage system can be improved into a system that can treat and reduce the contaminant (Needelman et al., 2007). Many studies have indicated that by planting the drainage with vegetation, it may provide more efficient removal of nutrients in comparison with unvegetated ditches. Xiaona et al. (2020) made the comparison of the performances between unvegetated ditch with three VD vegetated with *Lolium perenne*, *Elytrigia repens* and *Bromus inermis*. The results demonstrated that nitrogen removal rates of the three vegetated ditches (83.3%, 90.4%, 91.1%) were considerably higher than in unvegetated ditch (58.0%). The observation was also in agreement with findings from Castaldelli et al., 2018, Kumwimba et al., 2017b, Soana et al., 2017 and Zhang et al., 2016.

13.1.2 Vegetated Ditch

Vegetated ditch (VD) system is a natural or constructed ditch system planted with one or more types of vegetation which provide unique ecosystem that can induce multiple processes of contaminant removals. VD is often integrated as part of an ecological ditch (ED) system at which ED is a more complex ecosystem of vegetation adopting numerous types of natural and engineered processes than regular VD. These two systems differ from constructed wetlands (CW) in a way that VD and ED are purposely layered with sediment and soil, whereas CW is usually layered with gravel and other substrates. VD holds a promising potential for nutrients, fertilizers and pesticides removal due to its retaining and transformation processes. A study by Castaldelli et al. (2015) suggested that 1 hectare of VD may eliminate approximately 150 to 560 kg N per year, and an average waterway density of 0.05 km/ha of agricultural area has the ability to buffer 5–17% of N from an agricultural area. In VD system, the vegetation can efficiently reduce flow velocity, increase pollution retention, increase hydraulic retention time, decrease sediment resuspension, aerate soil, serve as an attachment area for microbial biofilms and eventually provide optimum environmental condition for contaminant reduction in ditches (Faust et al., 2018).While the substrate that layered the bottom of the ditch may enhance the precipitation of contaminant, promote the absorption and impedance of pollutants, therefore, making the ditch function as nutrient retention system (Wu et al., 2013). In overall, VD encompasses multiple processes and mechanisms in contaminant removals such as sedimentation, filtration, adsorption, transformation, precipitation, evaporation, plant uptake and microbial activities (Kumwimba et al., 2018). However, the removal efficiencies remain strictly dependent on the characteristics of the ditch (i.e., length, slope, size), vegetation (i.e., density, uptake capabilities, roughness coefficient), ditch bed (i.e., soil media type) and other hydrological variabilities (i.e., flow variation, drag coefficient) that exist in the ditch system (Zhao et al., 2017).

VD has the other supplementary advantages of small land requirements, comparable pollutant removal rate, ability to treat diffuse pollution source with fluctuating flow, load and concentration, minimal infrastructure, low construction and maintenance operation costs, coexistence of human and nature, biodiversity conservation and rehabilitation, waterlogging prevention, soil erosion control, groundwater recharge as well as aesthetically pleasing characteristics (Boguniewicz-Zablocka & Capodaglio, 2017; Singh et al., 2015). Nevertheless, there are still shortcomings of VD that include its tendency to cause flooding, its inability to survive under high COD and low DO concentrations as well as its high vulnerability of pollutant removal efficiencies toward hydrological variables (Kumwimba et al., 2018). With respect to comparison with CW, VD holds several superior characteristics in a way that CW requires comparably larger area, faces sediment dumping problems as well as holds sizable bodies of stagnant water that may become a nesting ground for disease carriers (Tyler et al., 2012).

While CW has been widely used for several years, VD has started been used only recently. Therefore, this review is done with the aim to illustrate the practice of VD in treating diffuse pollution that leads into the degradation of surface water quality. This paper will highlight the application of VD in treating diffuse pollution, the effectiveness of the system as well as the mechanisms of contaminant removal process. Furthermore, this review will critically evaluate the challenges and limitations faced by VD implementation as well as the strategies needed for the enhancement of the system.

13.2 Case Studies of Vegetated Ditch

13.2.1 Nitrogen Removal

Generally, nitrogen consists of many forms according to numerous types of oxidation states. In water, nitrogen components that are of concern are ammonium (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N) and ammonia (NH_3-N). In the reviewed VD, the highest removal efficiency was observed for NO_3-N ranged from 18.5–94.0% (Castaldelli et al., 2018; Cheng et al., 2018; Iseyemi et al., 2016; Kumwimba et al., 2020; Lizotte & Locke, 2018; Moore & Locke, 2020; Soana et al., 2019; Soana et al., 2017; Speir et al., 2017; Vymazal & Březinová, 2018; Wang et al., 2019). The removals of TN were also high albeit more variable, ranged from 24.0–91.1% (Cai et al., 2017; Cui et al., 2020; Kumwimba et al., 2020; Kumwimba et al., 2017a; Kumwimba et al., 2017b; Li et al., 2016; Lizotte & Locke, 2018; Min & Shi, 2018; Vymazal & Březinová, 2018; Wang et al., 2020; Wang et al., 2019; Wang et al., 2017; Xiaona et al., 2020). Meanwhile, the removals of NH_4-N were 19.6–86.8% (Cheng et al., 2018; Kumwimba et al., 2020; Lizotte & Locke, 2018; Moore & Locke, 2020; Ren et al., 2016; Wang et al., 2019; Zhang et al., 2020; Zhang et al.,2016). Nitrogen removal may include numerous routes such as biological pathways (i.e., ammonification, nitrification, denitrification, N_2 fixation, biomass assimilation, plant uptake), physicochemical pathways (i.e., volatilization, adsorption, organic N burial) and other pathways (i.e., anammox, cannon processes) (Vymazal, 2007). Nonetheless, the removal of nitrogen in the reviewed studies was primarily mediated through nitrification–denitrification, plant uptake and sediment adsorption (Castaldelli et al., 2015; Castaldelli et al., 2018; Cui et al., 2020; Kumwimba et al., 2017b; Kumwimba et al., 2020; Soana et al., 2017; Soana et al., 2019; Vymazal & Březinová, 2018; Wang et al., 2019;Wang et al., 2020; Xiaona et al., 2020; Zhang et al., 2015; Zhang et al., 2016). Zhang et al. (2020) reported that in their ditch vegetated with *Myriophyllum aquaticum*, nitrogen was dominantly removed through nitrification–denitrification (38.9–54.6%), followed by plant uptake (12.4–21.5%) and sediment adsorption (0.0–8.1%). Meanwhile Vymazal & Březinová (2018) reported that out of 1,070 kg/ha.year of TN removed, 804 kg N/ha/year was removed through denitrification process while 26.3% of the remaining nitrogen was eliminated through plant uptake.

Nitrification is a two-stage process with the initial stage accomplished by ammonia oxidizing bacteria (e.g., Nitrosomonas sp.) to oxidize ammonium (NH_4^+) to nitrite

(NO_2^-) under aerobic condition. The second stage is accomplished by nitrite oxidizing bacteria (e.g., Nitrobacter sp.) to oxidize nitrite (NO_2^-) to nitrate (NO_3^-) under facultative condition, whereas denitrification is the transformation of nitrate (NO_3^-) to nitrogen gas (N_2) in anoxic condition by archae and facultative heterotrophic bacteria (e.g., Achromobacter sp.). Cui et al. (2020) reported the abundance of Acidobacteria (3.7 – 9.0%) in their VD vegetated with *Vallisneria natans*. Acidobacteria were postulated to contain nitrate and nitrite reduction genetic code that was capable of decomposing essential cellulose and chitin under depressed nutrient condition which possess crucial roles in nitrogen reduction by means of denitrification. The other bacteria that were found in abundance were nitrifier Nitrospira (3.6–6.8%) and denitrifier Alphaproteobacteria (3.6–5.7%), thereby further emphasizing the dominant nitrification–denitrification processes in their VD system. Castaldelli et al. (2018) investigated the denitrification process occurred in their VD through the evaluation of NO_3-N consumption and N_2 production. The experiments were done by employing laboratory experiments to simulate real conditions of VD planted with *P. australis* and fed with NO_3-rich water. Throughout the experiment, they observed a consistent decline of NO_3-N NO_3-N (62.0–90.0%) as well as an increase of N_2 production, thus indicating the occurrences of microbial-mediated denitrification process. Additionally, the measured N_2 has always exceeded predicted N_2 contributed by gas equilibrated by the atmosphere, hence further emphasized that the excess N_2 was ascribed to the N_2 produced during denitrification process. In comparison with unvegetated ditch (18–33 mmol N/m^2.day), VD appeared to be relatively effective in transforming NO_3-N to N_2(27–233 mmol N/m^2.day) as rooted vegetation stimulates denitrification directly through the execution of organic carbon in the roots as a source of energy for NO_3-N depletion. While secondarily, the plants provide numerous interfaces (i.e., on the biofilms, in the rhizosphere) that facilitate the interactions of microbial colonies accountable for denitrification process. Apart from that, they also highlighted hydrological condition (i.e., water velocity) as one of the factors influencing nitrogen removal in VD system. They found that nitrogen removal rate was elevated when the water velocity was raised from 0 to 6 cm/s, as the increased water velocity possibly enhance the removal of NO_3-N via diffusive boundary layer, thus facilitating NO_3-N dissipation from the VD.

In plant uptake, two types of nitrogen are commonly involved in the process, namely NH_3-N and NO_3-N, with NH_3-N being the most preferred. Both of them will directly be taken up by roots, followed by its accumulation in vegetations' parts and consequently assimilated into amino acids that will support biomass growth and development (Ting et al., 2018).Vymazal & Březinová (2018), Wang et al. (2020) and Zhang et al. (2015) in their studies demonstrated plant uptake as a fundamental mechanism underlying the nitrogen removal in their VD with TN removal efficiencies ranged from 35.7–64.3%.

Additionally, the presence of vegetation may also indirectly impede the water velocity, thus allowing nitrogen to be adsorbed by the sediment (Kumwimba et al., 2017b; Xiaona et al., 2020). Xiaona et al. (2020) in their study using ^{15}N nitrogen isotope tracing technique observed that plants in the VD not only intercept the nitrogen from the water, but also keep the nitrogen in the sediment from being washed away, hence facilitate the subsequent plant uptake process. They found that the plants were able to absorb almost all nitrogen remaining in the ditch after 60 days of growth. The nitrogen interception rates of all three types of VD vegetated with *Lolium perenne*, *Elytrigia repens* and *Bromus inermis* were 83.3%, 90.4% and 91.1% and higher than unvegetated ditch at 58.0%.

13.2.2 Phosphorus Removal

Phosphorus in wastewater commonly exists as phosphate (PO_4-P) in organic (i.e., orthophosphate) and inorganic forms (i.e., polyphosphate). Excessive phosphorus may cause eutrophication and lead to the blooming algae. In contrast to nitrogen removal, phosphorus removal rates appeared to be lower and more varied. PO_4-P removal ranged from 39.0 to 98.0%, whereas TP removal ranged from 24.0 to 90.0% (Cai et al., 2017; Collins et al., 2016; Iseyemi et al., 2016; Kumwimba et al., 2017a; Kumwimba et al., 2017b; Kumwimba et al., 2020; Lizotte & Locke, 2018; Moore & Locke, 2020; Ren et al., 2016; Vymazal & Březinová, 2018; Wang et al., 2019; Wang et al., 2020; Zhang et al., 2016). Phosphorus removal may occur through biological (i.e., microbial assimilation, plant uptake), chemical (i.e., chemical precipitation, evaporation as phosphine PH_3) and physical (i.e., sorption, soil accretion, sedimentation, fragmentation and leaching, mineralization and burial) processes (Vymazal, 2007).

In the reviewed studies, most of the P removal were dominated by plant uptake (Cui et al. 2020; Vymazal & Březinová, 2018; Wang et al., 2020). Cui et al. (2020) compared TP removal rates of three VD systems at three different HLRs: one ditch layered with zeolite, another ditch vegetated with *Vallisneria natans* and another one ditch layered with zeolite and vegetated with *Vallisneria natans*. They found no significant difference between vegetated ditch and vegetated and zeolite-layered ditch, hence suggested that the presence of zeolite did not have much effect to phosphorus reduction, therefore suggested plant uptake as a principal mechanism. It was probably because the amount of used zeolite was only accounted for a small part of the total ditch sediment that leads to a minimal phosphorus reduction through adsorption. Moreover, they also observed the presence of phosphate accumulating organisms (PAOs), which belong to Proteobacteria and betaproteobacteria in all their ditches, therefore suggesting the potential of microbial assimilation as the principal mechanism of P removal. As for the adsorption process, plants, substrates and sediment were observed to be the responsible adsorbents (Kumwimba et al., 2017b; Kumwimba et al., 2020; Wang et al., 2019; Wang et al., 2020). Wang et al. (2020) conducted onsite experiments investigating the ability of ecological ditch in treating nutrient from a simulated rice-growing season runoff. Their three types of ditches, namely Eh (concrete ditch planted with vegetation in the hole at the wall), Es (natural soil ditch) and Ec (concrete ditch), were able to achieve TP removals of 52.6%, 47.9% and 32.6%, respectively. They suggested that adsorption by the vegetation on the wall in Eh system was the primary phosphorus removal pathway. Moreover, the study found that TP was negatively correlated with sediment P, hence postulated that phosphorus sorption on ditch sediments could be regarded as a substantial mechanism as well.

13.2.3 Pesticides Removal

Agricultural runoff usually contains pesticides, namely herbicides, insecticides and fungicides, with herbicides considered to hold the biggest portion of global pesticide utilization. The discharge of pesticides into surface water generally happens through runoff, spray drift, leaching and subsurface underlying drainage. The elimination of pesticides from the environment may be driven by adsorption, microbial degradation, plant uptake, filtration and sedimentation (Stillway et al., 2019). Of all mechanisms, the reviewed studies have shown that, in VD, pesticides were primarily removed through adsorption (Bundschuh et al., 2016; Moeder et al., 2017; Moore & Locke, 2020; Otto et al., 2016; Phillips et al., 2017). Some parameters that will affect adsorption rates are organic matter content, clay composition, temperature, retention time and pH, while the pesticides' physicochemical properties will affect its fractioning ability and its succeeding withdrawal from the water bodies (Stillway et al., 2019). For instance, longer retention time will allow pesticide-adhered particles to settle and subsequently being adsorbed to sediment and vegetation, while at the same time will allow dissolve pesticides to stay in the water for hydrolysis, adsorption and degradation processes. Whereas indirectly, thick vegetation functions as a buffer during peak flow, impede water velocity and prolong residence time in the ditch that ultimately improve the performance of the VD system.

Moore & Locke (2020) established experimental VD comprised of silt loam and sand planted with *Myriophyllum aquaticum*, *Polygonum amphibium* and *Typha latifolia* to remediate two types of herbicides, which were propanil, clomazone and one type of insecticide that was cyfluthrin. After 60 h, they observed significant diminishing of the compound, hence suggested that by holding runoff in VD, it may substantially decrease the transport of agricultural contaminants to downstream aquatic ecosystems. Moeder et al. (2017) evaluated the diminishing of different types of pesticides, insecticides and fungicide originated from agricultural runoff in their 3.6 km natural VD system located in Sinaloa, Mexico. The pollutants were three types of herbicides (atrazine, metolachlor, bentazone), eight types of insecticides (chlorpyrifos, carbofurane, dimethoate, thiacloprid, p.p'-DDE, p.p'-DDT, λ-Cyhalothrin, endosulfan) and one type of fungicide (metalaxyl). They demonstrated that their VD systems successfully assimilated the pesticides as they observed that the concentrations of all pesticide reduce to the safe levels only within the duration of one month. Additionally, they proposed plant uptake, sediment adsorption and biotransformation as the possible removal mechanisms. Among all, biotransformation was accounted as the most substantial as it was able to eliminate pesticides with half-life of 15 and 36 days. Bundschuh et al. (2016) compared the removal efficiency of vegetated detention ponds (DP) and VD for ten types of fungicides, namely azoxystrobin, boscalid, cyprodinil, dimethomorph, myclobutanil, penconazol, pyrimethanil, tebuconazol, triadimenol and trifloxystrobin. Both systems exhibited fungicides removal of 56.0% and 38.0% for VD and DP, respectively, therefore highlighting the superior performances of VD in comparison with wetland-like DP. The reductions were most likely attributed to numerous mechanisms occurred within the vegetated systems including sediment and macrophyte adsorption, as well as abiotic (i.e., photolysis, hydrolysis) and biotic (microbial activity within the biofilms formed on the macrophytes and sediments) degradation. Additionally, it was revealed that vegetation density and configuration of the system were the principal influencing factors in fungicides removal. Other less affecting factors are fungicides' solubility in water, influent concentration, precipitation and hydraulic loading rate. The findings were in agreement in Otto et al. (2016) at which they also found that the coverage of emergent plants and the HRT that can be translated into the ditch length were of great importance. In their study with 500-m-long natural VD in Po Valley, Italy, they analyzed the removals of three types of herbicides, which were mesotrione, terbuthylazine and S-metolachlor. The removals were 99.0%, 97.0% and 91.0%, respectively. The superior removal of mesotrione was primarily because mesotrione was much more soluble, rapidly transformed into metabolites and quickly transferred to the outlet. Phillips et al. (2017) compared the capabilities of four different ditch bed installations, namely native grasses, compost filters, granulated activated carbon (GAC) filters and bare ditch bed as controls. Experiments on the constructed ditches were conducted with artificial runoff containing chlorpyrifos, a type of insecticide. Among all, ditch installed with GAC filters and ditch planted with native grass demonstrated the highest removal of chlorpyrifos, which were 99.0% and 90.0%, respectively.

The fact that all reviewed studies suggested adsorption as the predominant mechanism, and the pesticides were found in water bodies and ditch sediment, therefore emphasizing the importance of investigating adsorption characteristics in order to optimize the reduction efficiencies. Otto et al.(2016) through their fugacity model used for predicting herbicide removal behavior, suggested specific physical–chemical parameters and soil–sediment–plant compartment to be included as input for the model. K_{OC} sorption coefficient and herbicides' half-life were also determined to be crucial. Conclusively, they proposed 250 m as a distance required for the herbicides to achieve 50% removal efficiency, and the accumulation was considered minimal for herbicides with 40 days or less half-life. As a rule of thumb, for herbicides with K_{OC} of 110–400 L/kg, a VD system of 100 m length and 1 m width may achieve 99% of removal efficiency of herbicides coming from a 1 mm runoff from an area of 5 ha.

13.2.4 Organic Matter Removal

Organic matters are carbon-based compounds composed of elements coming from the remains of organisms such as plants and animals as well as their waste products in the environment. A reduction of organic matters is indicated by BOD and COD. In

VD, BOD and COD associated with settleable solids are removed through sedimentation and substrate filtration while BOD and COD in colloidal and soluble forms are removed through biodegradation activity of microorganisms as well as physical and chemical interaction within the root zone. It was observed that aerobic or anaerobic decomposition occur when dissolved organic substances come in contact with the microorganism that is found to attach themselves on submerged vegetation roots, stems, soil or substrate media through diffusion processes (Idris et al., 2014). Additionally, other than providing support medium for microbial degradation to occur, vegetation assists in conveying the oxygen to the rhizosphere deeper into an otherwise anaerobic zone, hence stimulating the breakdown of organic compounds. The rhizosphere also stimulates the biodegradation process by becoming as a carbon source through the release of root exudates (Vymazal, 2009). Furthermore, the presence of iron-associated microorganisms (i.e., Acidiferrobacter) also assist the degradation by consuming organic substance as an electron donor, thereby facilitate oxidation–reduction reaction in the system (Witthayaphirom et al., 2020). Collectively, all these facts suggested that BOD and COD removals are principally depended on microbial activities and chemical reactions surrounding the plants' root system rather than direct uptake by the plant itself (Pincam et al., 2020).

In the reviewed VD, BOD removal ranged from 46.5–48.6% and COD removal ranged from 40.6–50.6% (Vymazal & Březinová, 2018; Wang et al., 2019). Vymazal & Březinová (2018) investigated the removal of various types of pollutants through their natural VD treating agricultural runoff. Though agricultural runoff usually does not contain elevated concentrations of organic matter, the system was still capable of removing BOD and COD by 46.5–48.6% and 40.6–48.8%, respectively. The respective remove loads were 1,060–1,240 kg BOD/ha.year and 6,745–7,264 kg COD/ha.year. Moreover, they also observed strong temperature dependency of BOD and COD load removals as the removal exponentially increased as the water temperature increased. Other than BOD and COD, the organic matters content may also be represented by total organic carbon (TOC). Wang et al. (2020) through their converted ecological ditches exhibited greater TOC removal of 20.3–24.1% in comparison with concrete ditch at 12.9%. They hypothesized that diverse ecosystem that exists within the vegetated ditch has enriched the microbial community, which, in turn, enhances the biodegradation of organic matters, and ultimately, facilitating the reduction of TOC content.

13.2.5 Solids Removal

The accumulation of organic and inorganic solids is termed as total solids (TS). In solid fractions, total solids (TS) are the summation of total suspended solids (TSS) and total dissolved solids (TDS). TSS is defined as solid particles that suspend in water column as colloid and comprising mostly of organic matter. However, TDS is defined as solid that dissolves in water column, consisting of inorganic salts (i.e., calcium, iron) and some small amount of organic matter. High TSS in water, apart from increasing the turbidity, its presence may often signify higher concentrations of microorganisms, nutrients and heavy metals in the water, resulting in deterioration of water quality. While high TDS is usually correlated with water hardness and aesthetic characteristics. In the studied VD, TSS removal ranged from 69.0–86.0% (Lizotte & Locke, 2018; Vymazal & Březinová, 2018), meanwhile TDS removal ranged from 26.5–35.8% (Kumwimba et al., 2017b).

Vymazal & Březinová (2018) in their study observed the attenuation of various types of pollutants in a natural VD in south-central Bohemia, The Czech Republic. The influent that flows into the VD was originated from an overspill of a fishpond at which the water came from the irrigation drainage of the neighboring agricultural fields. In their VD, they observed a remarkable 76.0–86.0% reduction of TSS in their VD planted with *Phragmites australis*, *Typha latifolia* and *Glyceria maxima.* The removed TSS load amounted to 18,289–22,585 kg TSS/ha.year and found to be very much similar with the loads removed by CWs treating agricultural irrigation effluent. The superior TSS removal was likely due to the effect of the VD that acts as vegetation filter or grassed water channel that impede sediment-enriched runoff. The vegetation provides friction that dampen the velocity of the water flow and consequently increase the sedimentation of solids and sediments. The similar mechanisms were also responsible for the 69.0% reduction of TSS exhibited by VD system of Lizotte & Locke (2018). The system comprised of two VDs draining an agricultural area practicing soil tillage and cultivation of row crop as BMPs. The VDs were vegetated with unknown grass species (Graminae), rice cutgrass (*Leerisa oryzoides*), common cattail (*Typha latifolia*), dicot species including ragweed (*Ambrosia* sp.), smartweed (*Polygonum* sp.) and alligator weed (*Alternananthera philoxeroides*). Apart from a remarkable TSS removal, the study also demonstrated very high correlation ($r^{2\,=}$ 0.7669) between TN loads and TSS loads at which TSS accounted for more than 76% of TN variation, showing that TSS function as a carrier and transporter for TN. This was in comparison with weaker association ($r^2 = 0.3743$) of PO_4-P with TSS that signifies more soluble components of PO_4-P. These results postulated that the removal of TSS could occur simultaneously with significant TN reduction and considerable PO_4-P reduction within the systems. The authors further anticipated that a TSS reduction of more than 95% could potentially be achieved if the currently practiced conventional tillage is changed to no-tillage practices. As for TDS, Kumwimba et al. (2017b) demonstrated a notable diminishing rates of 26.5–35.8% in their VDs in comparison with unvegetated VD, thereby indicated that the removal can be ascribed to the presence of vegetation that induces several physical and biological processes such as sedimentation.

13.2.6 Pathogen Removal

Wastewater usually contains numerous groups of pathogenic microorganisms, namely bacteria, viruses, protozoa and helminths. These pathogens are capable of causing severe gastrointestinal illness and other diseases that will become lethal if timely medical assistance is not provided. Pathogenic microorganisms' removal in VD is accomplished through a combination of biological (i.e., predation, antibiosis, antibiotic or biocide secretion, biolytic processes, biofilm interaction, retention in biofilm, natural die-off, inactivation due to unfavorable water condition), chemical (i.e., oxidation, UV radiation, exposure to root exudates) and physical (i.e., adsorption, filtration, sedimentation) processes (Donde & Xiao, 2017; Shingare et al., 2019). However, the presence of vegetation will indirectly affect the pathogen removal by providing attachment, filtration and retention sites for the microbes as well as supplying oxygen into the root system, hence creating an unfavorable aerobic condition for pathogens that are usually anaerobes or facultative type of microbes (Shingare et al., 2019).

Xue et al. (2018) in their study constructed a 300 m ecological ditch through the Linshan township located at the hilly area of central Sichuan Basin in China. The ED consisted of a primary settler, followed by artificial wetlands and polished with VD and is used to treat domestic wastewater that primarily came from the septic tanks. Additionally, there was also one poultry farm and scattered small-scale pig farms spread within the area. The ED have shown significant reduction efficiency of Total Coliform (TC) at 97.7% and 99.5% for *E. coli.* They postulated that the ED system removed the considerable numbers of sediment-laden fecal bacteria through interception and sedimentation. This was supported by significant correlation of TC and *E. coli* with electrical conductivity and turbidity, thus implying that sediment and colloids were the primary carrier for pathogens.

13.2.7 Heavy Metals Removal

Heavy metals, being known as a predominant pollutant in industrial wastewater, many of them, are actually micronutrients that are essential for plant growth. Fe, Cu, Mn, Mo, Ni and Zn are the examples of elements that are substantial for higher plants. Several other elements, including As, Cd and Pb, may possibly have an essential role at very low concentrations. While necessary for plant survival, excessive concentrations will lead to toxicity to the internal plant enzymatic mechanisms, and too little of them will lead to stress in some plants, chlorosis and reduction in crop yields. In overall, heavy metals were predominantly removed through rhizofiltration, at which the metals were extracted from the water through adsorption on the roots' membrane. The metals will then either be stored within the root itself or translocated to the other parts of the vegetation and undertake tissue localization (Prasetya et al., 2020). Some of the plants may also be capable of producing secondary metabolites that act as metal chelating that can store metals in their root system (Tuheteru et al., 2016). In addition to assimilating metals directly into their tissues, plants may also enhance heavy metals accumulation and transformation through three indirect mechanisms: firstly, through physical effects of roots such as filtration, flow reduction, sedimentation and resuspension reduction (Vymazal, 2011). Secondly, the root system may act as a base for microorganism colonies, as the root releases oxygen that facilitates a conducive aerobic condition for microorganisms to live in as well as to do microbial degradation (Vymazal, 2011). Thirdly, the oxidative condition may also promote oxidizing environment suitable for precipitation to occur. Other than rhizofiltration, heavy metals may also be removed by adsorption on the substrate material (Prasetya et al., 2020; Thathong et al., 2019). Though adsorbed heavy metals, usually the one that were physically adsorbed, were highly likely to leach back into the water once it reached its maximum adsorption capacity.

Kumwimba et al. (2017a) in their study constructed a VD system comprised of pre-settlement tank, followed by CW before flowing into VD and received domestic sewage from residential areas in Jieliu in the hilly Sichuan Basin, China. The VD was 300 m long and 2.2 m wide, and the ditch bed was layered at the top with 0.15 m of sediments and 0.18 m of gravel at the bottom and has been in operation for more than 10 years. The VD was vegetated with nine ditch plants species, namely *Cyperus alternifolius, Colocasia gigantea, Phragmites australis, Iris pseudacorus, Red Canna indica, Thalia dealbata, Acorus calamus, Acorus gramineus* and *Hydrocotyle vulgaris*. The primary objective of the study was to explore the capability of these plants to extract heavy metals (i.e., Al, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn) from the water through plant uptake. The relative orders of the removals were Zn > Pb > Cd > Cu > Cr > Fe > As > Mn > Ni > Al. It was observed that the accumulation of heavy metals was greater in sediments rather than in the water due to its high affinity toward particulate matter that encourages more adsorption and co-precipitation (Sundaray et al., 2011). Therefore, the subsequent accumulation of heavy metals in the plants was mostly adsorbed from the sediments. In terms of the most effective plant, no specific plant can be concluded as the most effective as the study revealed that different vegetation showed different tolerance toward different types of heavy metals. Nonetheless, the average concentration of metals in the nine vegetation types ranged from 0.0146 to 199 mg/m^2 in the sequence of Al > Fe > Mn > Zn > Cr > Pb > Cu > Ni > As > Cd. The metals accumulation was affected by seasonal variation as the metals concentrations demonstrated the maximum levels in August than May due to higher plant biomass in summer season. Nevertheless, despite of low biomass observed in spring season in May, Al, Fe and Mn remained highly accumulated, hence suggested high uptake and translocation rate of these elements from sediment to plant. In overall, heavy metals concentrations were greater in roots followed by leaves and stems. However, if the plants were to be considered as hyperaccumulator, at which the plants are capable of withstanding very high concentration of heavy metals (i.e., > 10,000 mg/kg of Zn or Mn; > 1,000 mg/kg of Pb, Ni or Cu ; > 100 mg/kg of Cd), none of the studied species have exceeded the metal hyperaccumulator threshold concentrations (Prasad et al., 2006).

13.2.8 Contaminants of Emerging Concern (CECs) Removal

Contaminants of emerging concern (CECs), commonly present in pharmaceutical and personal care products (PPCPs), have attracted attention in recent years mainly due to their capability in causing severe human health issues. As PPCPs dissolved readily in water and will not evaporate easily under normal conditions, as well as was abundantly produced for daily usage, coupled with the fact that it can be active even at trace concentration, therefore, the existence of these compounds in the environment needs to be crucially investigated.

Moeder et al. (2017) studied the removal of pharmaceuticals (ketoprofen, ibuprofen, diclofenac, naproxen, propranolol and carbamazepine), household chemicals and food additives (caffeine and acesulfame) from domestic wastewater using their natural VD. Along the ditch, they observed the diminishing of diclofenac by 90.0%, ibuprofen by 96.0%, naproxen by 90.0% and acesulfame by 91.0%. They hypothesized that the dominant mechanism was through plant uptake, and it was supported by the analysis on the vegetation *Typha domingensis* that assimilates ten of the studied pollutants. Meanwhile, sorption onto the sediments was considered as secondary mechanism contributing to the accumulation of pollutants within the ditch. In overall, the ability of VD to remove organic anthropogenic pollutants (i.e., pharmaceuticals, sweetener) appeared to be another beneficial advantage besides its main purposes to irrigate agricultural areas, accumulate sediments, as well as providing living grounds for organisms.

13.3 Challenges Faced by the VD and Recommendations for the Enhancement of VD Systems

13.3.1 Contaminant Removal Efficiencies

13.3.1.1 Challenges

VD has been proved to be able to achieve remarkable treatment of agricultural runoff, especially in terms of nutrient and pesticide, together with the promising removal of heavy metals, and some emerging contaminants like pharmaceutical and personal care products (PPCPs). Nevertheless, nitrogen reduction was highly reliance on water temperature, and effective nitrogen dissipation at low temperatures remains a challenge. At low temperature or during winter, the ditch vegetation will wilt and rot, hence releasing nutrients back into the water and further contaminating the water. Therefore, instead of serving as nutrient sink, the VD will now serve as nutrient source. Furthermore, the microbial denitrification process, which is the dominant nitrogen removal pathway, together with other supporting microbial processes, will also be hindered by low temperatures. de Klein (2008) revealed that the impact of low temperature was not only limited to denitrification process alone, but further involves other nitrogen removal pathways. Numerous studies have demonstrated the inhibition of both nitrifying and denitrifying microorganisms as the temperature goes down to below 10 °C, particularly when it is reduced to 6 °C, and is almost stopped as the temperature decrease to 4 °C (Cookson et al., 2002).

Despite the remarkable diminishing of pollutants observed along the ditch, in situations where VD was to be used to treat domestic wastewater that contains pathogen (i.e., coliform), the system was only capable for one or two log reduction, which in many cases was not enough to satisfy the discharge requirements (i.e., 1000 CFU/100 mL fecal coliform, (WHO, 2006)). This is critical in order to minimize the threat of pathogen spreading if the water is to be reused for crop irrigation and aquaculture farming.

Nonetheless, a crucial question regarding nature-based treatment system like VD is how the performance can be sustainably maintained over time. VD systems are designed to let the contaminants being adsorbed at the surface of vegetation root and sediment. As the time advances, natural processes will degrade the adsorbed contaminants, though some of them will sink in the system if routine mowing and dredging are not practiced. However, if the pollutant reduction rate and routine removal frequency are slower than the pollutant accumulation rate, it may increase the level of toxicity within the VD system. Ultimately, the efficiency of these systems in impeding agricultural runoff may diminish, and the waterbody within the VD will gradually become toxic, therefore, restricting the ecosystem services offered within these VD.

13.3.1.2 Recommendations

Many researchers believed that successful VD system are more likely to happen in warm areas. However, there were number of studies that recommended the use of cold-hardy wetland plants as a good alternative for VD systems in low-temperature season. Kumwimba et al. (2020) in their study found that of seven studied vegetation, *Acorus gramineus, Myriophyllum aquaticum* and *Iris sibirica* were the most tolerant species during winter. However, Zhang et al. (2020) suggested *Myriophyllum aquaticum* as a cold-resistant vegetation for effective nitrate reduction in VD. In general, the selection of plant should not only be restricted to the ones that can survive in cold environments, but to also have rapid growth rate, high pollutant assimilation, heavy plant biomass, easy to be harvested and high ability to survive under high pollutant loads (Kumwimba et al., 2018).

Other than the type of vegetation, the performance of VD to reduce contaminants could also be improved by using appropriate substrates (e.g., expanded clay, perlite, sand, peat, charcoal) as the ditch bed. The presence of these substrates, especially a porous media, will assist in the establishment of microbial community structure and provide additional surfaces for the pollutant attachment. Li et al. (2016) observed that volcanic rocks and brick scrappings that they used in their VD possess high surface area and porosity, at which they believed were the factors contributing to the nitrogen removal within their system. However Collins et al. (2016) made a comparison between VD layered with organic sediment and mineral sediment, at which the results demonstrated higher phosphorus uptake in a VD layered with organic sediment, thereby suggesting organic sediment possesses higher potential surfaces that allow more sorption of the phosphorus.

Additionally, as Wang et al. (2019) have emphasized that VD might not be a favorable option for removing pathogens from domestic sewage treatment, thus, the system needs to be succeeded with tertiary disinfection treatment processes such as chlorination, UV disinfection or ozone disinfection. Apart from that, the nature of varying hydraulic rate of domestic sewage may also be controlled by incorporating a method that can consistently handle the flow rate variation within the VD system.

If VD is to be compared to CW, clearly, CW has substantial restrictions, for example, comparably larger area requirement, high retention capability, sediment dumping problems, and these sizable bodies of stagnant water may become a nesting ground for disease carriers (Tyler et al., 2012). Meanwhile VD, posing the characteristics of both flowing watercourse and linear wetland, requires relatively less area while at the same time possesses similar enriched multiple ecosystem services, and yet, still can achieve comparable pollutant removal performances. Vymazal & Březinová (2018) demonstrated that the removal of nutrients, suspended solids and organic matters was comparable with the removals reported from CW treating agricultural drainage. Similarly, Lizotte & Locke (2018) also suggested that the performance of VD was comparable with their vegetated sedimentation pond in removing nutrients. And, if correctly managed, VD has a huge potential toward the abatement of diffuse pollution of nutrients that will eventually reach rivers and ocean.

13.3.2 Operational and Maintenance Issues

13.3.2.1 Challenges

While theoretically the use of vegetation within agricultural ditches appeared to be beneficial, many farmers perceived that the presence of vegetation will obstruct the water flow and restrict the main purpose of the ditches. Unlike CW that may also serve as retention pond during storm event, vegetation in VD acts like a soft structural complexity that attenuates flow velocity and significantly hinders or sometimes completely blocks the flow of runoff, thereby contributing to the unintended flood in the area. Owing to that, the vegetation was regularly being removed during routine management practices for the purpose of preserving the hydraulic performance. As a result, the drainage ditches will have little and insufficient vegetation, hence lead to shorter hydraulic residence time (HRT) and consequently function ineffectively in attenuating diffuse pollution in agricultural area. Apart from the presence of vegetation, clogging caused by sediment accumulation may as well cause a shorten of HRT. As the bed of the VD becomes thicker due to the settlement of sediment, it will reduce the depth of the ditch, shorten the flow HRT and eventually impede the operation of VD systems.

Other than HRT, many investigations have exhibited that pollutant removal efficiencies are highly influenced by hydraulic loading rates (HLR) as well (Li et al., 2016; Soana et al., 2017; Castaldelli et al., 2018). Due to that, for VD with highly variable HLR, either with or without plants, limited nutrient reduction ability was often observed (Davis et al., 2015).

13.3.2.2 Recommendations

As increasing the HRT and contaminant removal efficiency of VD has become an arising challenge, Baker et al. (2015; 2016) through his modified ditch have demonstrated that by implementing weirs in their ditch, it will help prolong hydraulic retention time (HRT), decreasing incoming flow velocities, allowing enhanced sediment and nutrient retention, creating more saturated state of soil, providing more areas with anaerobic condition conducive for denitrification, altering soil carbon and moisture and eventually enhancing the nutrient removal capability. Other than that, as HRT is highly reliance on the length, width and depth of the VD, installing a larger and deeper ditch might as well help in enhancing the performance of the VD. Another recommended alternative is through implementing a two-stage ditch, at which floodplains or benches are added prior to the VD system. By having these, pipes entering the VD will first drain into the floodplain, hence slowing the water velocities and reducing erosion potentials. Studies done by Davis et al. (2015) have demonstrated that their two-stage ditch system was able to promote longer HRT for more effective plant, water and soil interactions, thereby facilitate enhanced removal of contaminants, increase denitrification rates as well as decrease sediment load.

As for clogging issues, it is necessary to routinely dredge out sediment that was gathered at the bed of VD system. Wang et al. (2019) recommended the settled sediment in the ditch to be routinely managed, dredged and renewed once every three months. These measures are crucial to ensure the sustainable operation of the VD system. In cases at which the VD was lined with other materials (i.e., zeolite) for the purpose of enhancing the nutrient adsorption, the materials need to be routinely backwashed, plowed and changed (Cui et al., 2020; Kumwimba et al., 2017b). This was crucial because as the operation goes on, the capability of the materials to remove pollutants will decrease due to the diminishing of adsorption efficiency and clogging caused by biofilm growth. However, in some cases, ditch dredging can be potentially harmful to the VD as it may alter the growth of plant biota in the ditch that was responsible for pollutant removal. Additionally, the dredging may modify the properties of ditch bed, thus altering the ditch hydrology, and gradually increase flow velocity that will ultimately lead to reduced HRT (Kumwimba et al., 2018).

Another maintenance routine that was crucial for the well-being of a VD was the harvesting of the VD vegetation. With reference to numerous previous studies, annual and multiple harvesting of vegetation is proved to be effective in improving the water quality of VD ecosystems as it can remove the nutrients accumulated in the plant tissues (Kadlec & Wallace, 2009). Regular harvesting of above-ground biomass may encourage new plant shoots, thereby increase plant uptake and nutrient storing capacity and subsequently improve the quality of water bodies within the VD (Kuehn & Suberkropp, 1998). If the plants are not routinely pruned and harvested, the nutrient assimilated by the vegetation will remain inside the system before it is eventually being released back into the water once the plant rots (Kröger, 2007). Nonetheless, indifferent with these findings, Iseyemi et al. (2016) observed no significance difference in nutrient removal efficiency between harvested VD and unharvested VD. While Soana et al. (2019) observed that harvesting and pruning exercise will only cause limited N removal and more importantly, the practice will negatively impact the denitrification process of the VD. Thus, they suggested a more traditional management practice that includes the delaying of pruning and harvesting to the end of winter, right prior to the beginning of the next planting season. Xiaona et al. (2020) recommended that the VD to be planted with perennial species, namely, *E. repens*, *L. perenne* and *B.inermis*. These perennial plants were demonstrated to be very convenient as there is no need for replanting, thereby the operational costs will only be accounted for labor and vegetation seeds during the early years. In the subsequent years, only routine harvesting is needed, and other maintenance exercise like fertilization is no longer necessary. Additionally, other than scheduled and routine harvesting, plant recycling and frequent removals of competitive species may as well be practiced (Kumwimba et al., 2018).

As for cases of VD with high HLR, it becomes very critical for the VD to be operated under low HLR, which implies long HRT, as longer time will amplify the interactions between contaminated water, vegetation root system and microorganisms, thereby increasing the removal of the contaminants. For that reason, Zhao et al. (2017) recommended VD with smaller flow rate as it will contribute to increased ditch roughness coefficients, decreased hydraulic surface loading, longer retention time, lesser plant resistance and increased plants drag coefficient that indicate more favorable hydraulic characteristics.

13.4 Conclusion

Conclusively, nature-based water quality treatment system, such as VD, has been shown to be able to serve as a sustainable solution in mitigating diffuse pollution occurring in agricultural areas. Apart from its acknowledged ability to remove the most common contaminants of agricultural runoff, which are nutrient and pesticides, VD system has also been demonstrated to be able to remove organic matters, pathogen, heavy metals and contaminant of emerging concerns (CECs). Nevertheless, moving forward, there are still challenges and limitations that need to be addressed through various strategic moves, namely (1) efficient VD maintenance routine (e.g., regular harvesting, occasional ditch dredging), (2) selection of ideal vegetation, (3) selection of suitable sediment composition, (4) emphasize attention on hydrological variables (i.e., HLR, HRT) and (5) installation of supporting structures on VD system (i.e., weirs, two-stage ditch, deeper ditch). All these taken together may substantially lead to a more effective operation of VD system (Table 13.1).

Table 13.1 Research studies involving vegetated ditch within the last 5 years (2016–2020)

Type of VD	Place	Source of diffuse pollution	Plants	Substrate	Dimension HRT	Removal Efficiency	Mechanism	Reference
VD (constructed)	China	Simulated agricultural runoff	*Vallisnerianatans*	Zeolite, soil	L: 30 m W: 0.4–1.05 m D: 1.3 m HRT: NA	Nitrogen: TN: 24.0– 45.0%, 46.0–60.0%, 52.0–62.0% Phosphorus: TP: 24.0 – 64.0%, 45.0 – 69.0%, 52.0 – 70.0%	N: Nitrification–denitrification P: Plant uptake, microbial assimilation	Cui et al. (2020)
VD (constructed)	China	Rural domestic sewage	*Canna indica*, *Acorus calamus*, *Myriophyllum aquaticum*, *Cyperus alternifolius*, *Acorus gramineus*, *Iris sibirica*, *Oenanthe javanica*,	Gravel, clay, silt	L: 200 m W: 1.4–1.6 m D: 0.30–0.50 m HRT: 0.15 day	Nitrogen: TN: 44.0%, NH_4-N: 46.0%, NO_3-N: 43.0% Phosphorus: TP: 52.0%, PO_4-P: 46.0%	N: Nitrification–denitrification P: Sediment adsorption	Kumwimba et al. (2020)

(continued)

Table 13.1 (continued)

Type of VD	Place	Source of diffuse pollution	Plants	Substrate	Dimension HRT	Removal Efficiency	Mechanism	Reference
VD (constructed)	US	Simulated agricultural runoff	*Myriophyllum aquaticum, Polygonum amphibium, Typha latifolia*	Sand, silt loam	L: NA W: NA D: NA HRT: NA	Nitrogen: NH_4-N: Not in %, NO_3-N: Not in % Phosphorus: PO_4-P: Not in % Pesticide: Propanil: Not in %, Clomazone: Not in %, Cyfluthrin: Not in %	N: NA P: NA Pesticide: NA	Moore & Locke (2020)
VD (constructed)	China	Simulated agricultural runoff	*Vallisneria natans*	Soil	L: 30 m W: 0.4–0.93 m D: 1.05 m HRT: NA	Organic matter: TOC: 20.3–24.1% Nitrogen: TN: 35.7–42.8% Phosphorus: TP: 47.9–52.6%	TOC: Microbial assimilation N: Plant uptake, nitrification–denitrification P: Plant uptake, adsorption	Wang et al. (2020)
VD (constructed)	China	Simulated agricultural runoff	*Lolium perenne, Bromus inermis, Elytrigia repens*	Sand, silt, clay	L: 3 m W: 0.5 m D: 0.6 m HRT: NA	Nitrogen: TN: 83.3–91.1%	N: Plant interception, sediment adsorption	Xiaona et al. (2020)

(continued)

Table 13.1 (continued)

Type of VD	Place	Source of diffuse pollution	Plants	Substrate	Dimension HRT	Removal Efficiency	Mechanism	Reference
VD (constructed)	China	Rural domestic sewage + Aquaculture + Agricultural drainage	*Myriophyllum aquaticum*	Soil	L: 15 m W: 0.5 m D: 0.15, 0.30, 0.45 m HRT: NA	Nitrogen: NH_4-N: 75.8–86.8%	N: Nitrification–denitrification, plant uptake, adsorption	Zhang et al. (2020)
VD (natural)	Italy	Nitrate-rich groundwater	*Typhoides arundinacea*, *Elodea canadensis*	Soil	L: 330 & 380 m W: 3.2 & 2.8 m D: 0.05 – 0.5 m HRT: NA	Nitrogen: NO_3-N: Not in %	N: Denitrification	Soana et al. (2019) Soana et al. (2017)
VD (constructed)	China	Rural domestic sewage	*Thalia dealbata*, *Iris pseudacorus*, *Canna indica*, *Phyllostachys heteroclada oliver*, *Acorus tatarinowii*, *Rumex patientia*, *Calla palustris*	Soil	L: 150 m W: 1.0 - 1.5 m D: 0.1 m HRT: NA	Organic matter: COD: 50.6% Nitrogen: TN: 30.8%, NH_4-N: 19.5%, NO_3-N: 18.5% Phosphorus: TP: 33.5%, PO_4-P: 39.0%	OM: NA N: Nitrification–denitrification P: Adsorption	Wang et al. (2019)

(continued)

Table 13.1 (continued)

Type of VD	Place	Source of diffuse pollution	Plants	Substrate	Dimension HRT	Removal Efficiency	Mechanism	Reference
VD (constructed)	Italy	Agricultural drainage	*Phragmites australis,*	Soil	L: NA W: NA D: NA HRT: NA	Nitrogen: NO_3-N: 61.0–90.0%	N: Nitrification–denitrification	Castaldelli et al. (2018)
VD (constructed)	China	Agricultural drainage	*Lolium perenne*	Soil	L: 50 m	Nitrogen: TN: 23.0–62.0%	N: NA	Min & Shi (2018)
VD (natural)	China	Rural domestic sewage	*NA*	NA	L: 300 m W: 2.2 m D: 0.25–0.40 m HRT: NA	Coliform: TC: 97.7%, EC: 99.5%	Coliform: Interception, deposition	Xue et al. (2018)
VD (constructed)	China	Agricultural runoff	*Calamagrostis angustifolia*	Soil, biochar	L: NA W: NA D: NA HRT: NA	Nitrogen: NO_3-N: Not in %, NH_4-N: Not in %	N: Nitrification–denitrification	Cheng et al. (2018)
VD (natural)	US	Agricultural runoff	*Typha latifolia, Graminae, Leerisa oryzoides, Ambrosia sp., Polygonum sp., Alternananthera philoxeroides*	Soil	L: 250–1000 m; 250 m W: 5–15 m; 2–7.5 m D: 1.5 m; 0.6 m HRT: NA	Solid: TSS: 69.0% Nitrogen: TN: 85.0–91.0%, NO_3-N: 76.0–89.0%, NH_4-N: 85.0% Phosphorus: TP: 84.0–90.0%, PO_4-P: 73.0%	N: NA P: NA TSS: Plant interception	Lizotte & Locke (2018)

(continued)

Table 13.1 (continued)

Type of VD	Place	Source of diffuse pollution	Plants	Substrate	Dimension HRT	Removal Efficiency	Mechanism	Reference
VD (natural)	Czech Republic	Aquacultural effluent	*Phragmites australis*, *Typha latifolia*, *Glyceria maxima*	Soil	L: 200 m W: NA D: 0.05–0.15 m HRT: NA	Organic matter: BOD: 46.5–48.6%, COD: 40.6–48.8% Solid: TSS: 76.0–86.0% Nitrogen: TN: 38.3–52.6%, NO_3-N: 41.4-62.2% Phosphorus: TP: 51.3–52.6%	N: Nitrification–denitrification, plant uptake P: Plant uptake OM: NA TSS: Filtration, sedimentation	Vymazal & Březinová (2018)
VD (constructed)	China	Agricultural drainage	*Sagittaria sagittifolia*, *Zizanialatifolia*, *Fimbristylis miliacea*, *Nelumbo nucifera*	Soil	L: 170 m HRT: 3–5 days	Nitrogen: TN: 9.3%, Phosphorus: TP: 14.0%	N: NA P: NA	Cai et al., (2017)

(continued)

Table 13.1 (continued)

Type of VD	Place	Source of diffuse pollution	Plants	Substrate	Dimension HRT	Removal Efficiency	Mechanism	Reference
VD (constructed)	China	Rural domestic sewage	*Cyperus alternifolius*, *Colocasia gigantea*, *Phragmites australis*, *Iris pseudacorus*, *Red Canna indica*, *Thalia dealbata*, *Acorus calamus*, *Acorus gramineus*, *Hydrocotylevvulgaris*	Gravel, sediment	L: 300 m W: 2.2 m D: 0.25–0.40 m HRT: 12 h	Nitrogen: TN: 49.0% Phosphorus: TP: 33.0% Heavy Metal: Ni: 13.0%, Cu: 53.0%, Cr: 51.0%, Zn: 83.0% Cd: 68.0%, Pb: 72.0%, As: 37.0%, Fe: 48.0%, Al: 11.0%, Mn: 15.0%, Na: 24.0%, Mg: 32.0%, Ca: 89.0%, K: 41.0%	N: NA P: NA HM: Plant uptake	Kumwimba et al. (2017a)

(continued)

Table 13.1 (continued)

Type of VD	Place	Source of diffuse pollution	Plants	Substrate	Dimension HRT	Removal Efficiency	Mechanism	Reference
VD (constructed)	China	Rural domestic sewage	*Canna indica, Acorus calamus, Acorusgramineus, Cyperus alternifolius, Iris sibirica, Myriophyllum verticillatum, Alternanthera philoxeroides Phyla nodiflora, Oenanthe javanica, Polygonum hydropiper, Eichhornia crassipes, Origanum vulgare*	Soil, gravel, sediment	L: 300 m W: 2.5 m D: 0.25–0.50 m HRT: NA	Solid: TDS: 26.5–35.8% Nitrogen: TN: 31.2–64.3% Phosphorus: TP: 27.5–58.0%	N: Plant uptake, substrate adsorption P: Substrate adsorption	Kumwimba et al. (2017b)

(continued)

Table 13.1 (continued)

Type of VD	Place	Source of diffuse pollution	Plants	Substrate	Dimension HRT	Removal Efficiency	Mechanism	Reference
VD (natural)	Mexico	Rural domestic sewage + Agricultural runoff	*Typha domingensis*, *Amaranthus palmeri*, *Urochloa mutica*	Soil	L: 3.6 km W: 4.5 m D: 2.0 m HRT: NA	Dicoflenac: 90.0% Ibuprofen: 98.0% Pharmaceutical: decreased Food-related compounds: decreased Herbicides: decreased Fungicides: decreased Fuel (PAH): decreased	Pesticides: Plant uptake	Moeder et al. (2017)
VD (constructed)	US	Agricultural runoff	*Native grass*	Soil	L: NA W: NA D: NA HRT: NA	Chlorpyrifos: 90.0%	Chlorpyrifos: NA	Phillips et al. (2017)
VD (constructed)	US	Agricultural runoff	*Leersia oryzoides*	Soil	L: NA W: NA D: NA HRT: NA	Nitrogen: NO_3-N: 30.0–40.0%	N: Nitrification–denitrification	Speir et al. (2017)

(continued)

Table 13.1 (continued)

Type of VD	Place	Source of diffuse pollution	Plants	Substrate	Dimension HRT	Removal Efficiency	Mechanism	Reference
VD (constructed)	China	Agricultural drainage	*Zizania aquatica, Bermudagrass*	Hollow hexagonalbricks, Zeolite	L: 30 m W: NA D: NA HRT: NA	Nitrogen: TN: 24.7–30.4%	N: NA	Wang et al. (2017)
VD (natural)	Germany	Agricultural runoff	*Lemna minor, Typhaangustifolia, Sparganiumerectum, Phragmites australis, Iris pseudacorus, Carex elata, Glyceria sp.*	Loamy sand	L: 22 – 176 m W: NA D: 0.1 – 0.25 m HRT: 1 – 11 h	Fungicide (azoxystrobin, boscalid, cyprodinil, dimethomorph, myclobutanil, penconazol, pyrimethanil, tebuconazol, triadimenol, trifloxystrobin): 53.0%	Fungicide: Adsorption, microbial assimilation	Bundschuh et al. (2016)
VD (constructed)	USA	Agricultural drainage	*Pontederia cordata, Eichhornia crassipes, Lemnaminor*	Organic sediment Mineral sediment	L: NA W: NA D: NA HRT: 0.11 – 0.46 days	Phosphorus: SRP: 13.0–55.0%	P: NA	Collins et al. (2016)

(continued)

Table 13.1 (continued)

Type of VD	Place	Source of diffuse pollution	Plants	Substrate	Dimension HRT	Removal Efficiency	Mechanism	Reference
VD (constructed)	USA	Agricultural runoff	*Typha latifolia*	Soil	L: 58.7 m W: 1.89 m D: NA HRT: 4 h	Nitrogen: NO_3-N: 79.0–94.0% Phosphorus: PO_4-P: 95.0–98.0%	N: NA P: NA	Iseyemi et al. (2016)
VD (constructed)	China	Agricultural drainage	*Iris pseudacorus, Lythrumsalicaria*	Soil, volcanic rocks, brick fragments	L: 6 m W: NA D: NA HRT: 3 days	Nitrogen: TN: 33.1%	N: NA	Li et al. (2016)
VD (natural)	Italy	Simulated - Agricultural	*Phragmites australis,* *Iris sp.,* *Scirpus sp.,* *Typha sp.*	Soil	L: 500 m W: 1 - 2 m D: 1.8 m HRT: NA	Herbicide: Mesotrione: 99.0%, S-metolachlor: 91.0%, Terbuthylazine: 97.0%	Herbicides: Adsorption	Otto et al. (2016)
VD (constructed)	China	Rural domestic sewage	*Lolium perenne*	Hydroponic	L: 15 m W: NA D: NA HRT: 6 days	Nitrogen: NH_4-N: 82.8%, Phosphorus: TP: 27.7%	N: NA P: NA	Ren et al. (2016)
VD (constructed)	China	Agricultural runoff	*Pontederia cordata, Myriophyllum elatinoides*	Soil	L: 16 m W: 2 m D: 0.55 m HRT: 30 days	Nitrogen: NH_4-N: 50.8–71.4%	N: Nitrification–denitrification, plant uptake	Zhang et al. (2016)

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Chapter 14
Recovery from Natural Disasters and Environmental Destruction in East Japan

Makoto Tanifuji

Abstract Japan is susceptible to several natural disasters, including earthquakes and typhoons. Thus, the government, local governments, businesses, other organisations, and individuals are faced with the challenge of responding quickly to restore the systems. However, depending on the scale of the disaster, recovery can be expensive and arduous. The Great East Japan Earthquake in March 2011 and the COVID-19 pandemic are significant disasters. It is now difficult to establish a natural, economic, and social environment before disasters. In particular, social rather than physical and financial damage is more complex to measure. Often, it is not possible to restore the situation to the pre-disaster conditions. Presuming that people cannot secure a safe environment, they will need to live in a new area, even if it is only temporary. Even if safety can be ensured, the inability to belong to a traditional community can significantly impact people of all ages. Therefore, it is essential to maintain the same pre-disaster living environment, build convenience, strengthen disaster prevention, and priorities the environment. Moreover, community development in which the people are directly engaged, is required.

Keywords Natural disaster · The Great East Japan Earthquake · Reconstruction · Social capital

14.1 Introduction

In 2011, the Great East Japan Earthquake (GEJE) devastated the Tohoku region of Japan. Many buildings in the affected region were damaged, while the tsunamis triggered by the earthquake killed thousands. As a result, people's knowledge about natural disasters and how to prevent them has increased significantly. Additionally, efforts were made to strengthen the region's infrastructure, despite frequent and intense aftershocks. However, was it essential to rebuild infrastructure as soon as possible?

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In the coastal areas of Iwate Prefecture, a new seawall, nearly double the height of the previous structure, has been built. Subsequently, the beautiful coastal scenery has been completely altered. Thus, one of the regions' main tourist resources that could have revitalised the region has disappeared entirely. The construction of seawalls has also affected the fishing industry. Additionally, investment in this complex project has affected the local economy.

Regarding nuclear power plants in Tohoku, there were concerns about radiation damage to agriculture and fisheries. Thus, the radiation levels and manufacturing products from the region were carefully examined to ensure safety. However, harmful rumours regarding the safety of the area and its products prevail. Therefore, Japanese people's mind-sets have not returned to their pre-earthquake state. To recover the living environment to its pre-disaster condition, as well as to strengthen disaster prevention while prioritising environmental improvement, we must create a close-knit community.

In contrast to the GEJE, the pandemic caused by the coronavirus disease 2019 (COVID-19) did not destroy the physical environment. However, this 'invisible' disaster radically changed our way of life. People have been forced into isolation, and it remains unclear how long this health crisis will last. Local governments have imposed travel restrictions and strict social distancing measures to prevent surges in infections. The resulting downturn in the economy has reduced employment opportunities and forced people to relocate. Telecommuting has become more common, presenting a new way of working in rural areas.

Infrastructure development is one of the key factors in regional development. In addition, human resources are crucial for this purpose. In the post-pandemic era, wherein human relationships and networks will have changed immensely, how should regions utilise human resources and discover new values? In this paper, we review the impact of the GEJE and the COVID-19 pandemic to redefine the concept of regional resources to better respond to similar crises in the future. We will describe how East Japan is improving in terms of convenience and safety, considering the impact of the GEJE. Additionally, we will also discuss how we should adjust to life with natural disasters.

14.2 Characteristics of the East Japan Area

The Tohoku region is located in the north-eastern part of Honshu, the largest island in Japan. It consists of six prefectures: Aomori, Iwate, Miyagi, Akita, Yamagata, and Fukushima. The Tohoku region comprises a vast area that accounts for approximately 20% of the total land area of Japan.

The region is also blessed with fertile land and rich fishing grounds. It is agricultural industry is one of the largest in Japan, producing about 30% of the nation's rice, with rice destined for animal feed accounting for half of the country's production. The production of soya beans and buckwheat accounts for approximately 20% of the national share. The Tohoku region is also known to be one of Japan's leading granary areas. Itis is also widely known for livestock farming, with many breeds of dairy and beef cattle raised in various regions. The total volume of apples and cherries produced in the Tohoku region accounts for 80% of the national total. The area harvested for leaf tobacco, a regional specialty, accounts for 29% of the national total, while hops, a raw material for beer, and account for 98% of the national total.

The Tohoku region is also blessed with abundant forest resources and a thriving forestry industry with a forest coverage of approximately 70%. Among all the prefectures, Iwate is second only to Hokkaido in terms of forest area. It is one of the top producers of unique forest products, such as shiitake mushrooms, charcoal, wood vinegar, and lacquer.

The Sanriku coast on the Pacific side of the Tohoku region is fuelled by many rivers that originate in the Ou Mountains. The rivers that flow into the bay carry nutrients from the forests in the upper reaches, nurturing fish and shellfish. Consequently, Tohoku's fishery industry is thriving. On the Pacific side of Sanriku and Joban, which are excellent fishing grounds with large catches, the nutrient-rich and cold Oyashio Current collides with the warm Kuroshio Current flowing from the south, forming a tidal channel that attracts a large number of fish because of the large amount of plankton. In 2009, the Pacific coast accounted for 20% of Japan's total sea fishery catch of 4.15 million tonnes. The coastal area ranging from Aomori Prefecture to Miyagi Prefecture is intricate. Many fishing ports have been built in deep bays, where the waves are calm, and the water is deep. The ria in the Tohokuand Sanriku regions is an ideal location for aquaculture. In 2009, the sea surface aquaculture industry accounted for 27% of Japan's total catch of 1.2 million tonnes.

14.3 The Impact of the Great East Japan Earthquake

Japan has experienced many major natural disasters and is expected to experience more in the future. Since the Japanese archipelago is located at the intersection of four tectonic plates, it has experienced many tsunamis caused by earthquakes. In addition, much of the country is covered with mountain ranges from which short and steep rivers flow. As a result of the heavy rains, the water level in rivers rises, and flooding is likely to occur. Moreover, in mountainous areas, sediment flows out, and mudslides occur.

In recent years, due to global warming, the Japanese archipelago has been struck by abnormally high temperatures, typhoons, snowfall, and earthquakes every year. Therefore, this chapter looks back at the GEJE and how it has increased people's awareness of natural disasters and disaster mitigation and prevention. The GEJE has been widely reported in various media, and relevant data are still being updated (e.g. Disaster Management 2017).

14.3.1 Assessing the Scope of the Damage

The GEJE occurred at 14:46 on 11 March 2011. The magnitude of the earthquake was 9.0 M_w. It had a maximum seismic intensity of seven in Kurihara City, Miyagi Prefecture. A seismic intensity of 6.0 M_w was also observed in the rest of Miyagi, Fukushima, Ibaraki, and Tochigi prefectures. In addition to the four prefectures above, an intensity of $_>$6.0 M_w was also observed in Iwate, Gunma, Saitama, and Chiba prefectures. Tremors with an intensity between 6 and 1 on the Japanese scale have been reported from Hokkaido to Kyushu. The epicentre was located approximately 130 km east-southeast of the Oshika Peninsula, Miyagi Prefecture, off the Pacific Ocean, and Sanriku coast of Miyagi Prefecture, with an epicentre depth of 24 km.

Tsunami warnings were issued in several stages. At 14:49, a tsunami warning was issued for Iwate, Miyagi, and Fukushima prefectures; at 15:14, a warning was issued for the Pacific coast of Aomori, Ibaraki, and Chiba prefectures; at 15:30, for the Izu Islands (the islands of Tokyo) and the eastern and western Pacific coast of Hokkaido; at 16:08, for the Japan Sea coast of Aomori, Uchibo, and Ogasawara islands of Chiba, Sagami Bay, and Miura Peninsula (Kanagawa), Shizuoka, Wakayama, and Tokushima prefectures; and at 22:53 for Kochi. Subsequently, all tsunami warnings were cancelled at 17:58 on 13 March.

According to observations at major tide stations, the maximum tsunami heights were as follows: 8.0 m at Ofunato, Iwate Prefecture, at 15:18 on 11 March; 8.5 m at Kamaishi, Iwate Prefecture, at 15:21; 8.5 m at Miyako, Iwate Prefecture, at 15:26; 8.6 m at Ayukawa, Ishinomaki and Miyagi Prefecture, at the same time; and over 9.3 m at Soma, Fukushima Prefecture, at 15:51 on 11 March (Fire Disaster and Management Agency [FDMA] 2021).

According to the damage report by the FDMA (2021), there were 19,747 dead, 2556 missing, and 6242 injured (including seriously injured, slightly injured, and injured [injury extent unknown] individuals). The search for missing data is ongoing. As for the damage to dwellings, 122,005 houses were destroyed, 283,156 were partially destroyed, and 749,732 were partially damaged. Non-residential damage included 14,527 public buildings, 92,890 other buildings, and 330 fires. A comparison of the situation of the three affected areas revealed that Miyagi Prefecture suffered the most damage.

According to the Japan Meteorological Agency (JMA) (2021), there were three aftershocks with a maximum intensity of 6.0, three with a maximum intensity of just under 6.0, 17 with a maximum intensity of 5.0, 58 with a maximum intensity of 5.0, and 348 with a maximum intensity of 4.0 (as of 1 March 2021). However, in April 2021, ten years after the earthquake, the government announced that it would change the wording used in press releases about large earthquakes occurring in the areas affected by aftershocks of the GEJE. They reported that the number of aftershocks in the earthquake zone approached the pre-GEJE average and that it was becoming more challenging to determine which earthquakes were the aftershocks. In addition to paying attention to the aftershocks, the Agency also asked the audience to pay attention to other possible aftershocks.

Historically, several earthquakes and tsunamis have affected the Tohoku region (Ito 2018; JMA 2021) (Table 14.1).

Table 14.1 Major earthquakes and tsunamis that have affected the Tohoku region

Date	Name/Affected area	Overview
13 July 869	Jokan Earthquake	–
December1611	Keicho Earthquake	M 8.1, 1800 dead
15 June 1896	Meji Sanriku Earthquake	M 8.5, 21,959 dead, more than 10,000 houses flooded, fully or partially destroyed
3 March 1933	Showa Sanriku Earthquake	M 8.1, 3064 dead or missing, 4034 houses lost, 1817 houses destroyed, 4018 houses flooded
23 May 1960	Great Chilean Earthquake	M 8.5, 142 dead or unknown, more than 1500 destroyed houses, more than 2000 partially destroyed houses
30 April 1962	Northern Miyagi Prefecture	M 6.5, 3 dead, 340 fully destroyed houses and 1114 partly destroyed houses
16 June 1964	Niigata	M 7.5, 26 dead, 1960 fully destroyed houses and 6640 partially destroyed houses
16 May 1968	Off the coast of Tokachi, Hokkaido	M 7.9, 52 dead, 330 injured, 673 fully destroyed houses, and 3004 partially destroyed houses
12 June 1978	Off the coast of Miyagi Prefecture	M 7.4, 28 dead, 1325 injured, 1183 fully destroyed houses, and 5574 partially destroyed houses
26 May 1983	Central Sea of Japan	M 7.7, 104 dead, 163 injured, 934 fully destroyed houses, and 2115 partially destroyed houses
28 December 1994	Far off the coast of Sanriku	M 7.6, 3 dead, 788 injured, 501 fully or partially destroyed houses
26 May 2003	Off the coast of Miyagi Prefecture	M 7.1, 174 injured, 23 fully or partially destroyed houses
26 July 2003	Northern Miyagi Prefecture serial earthquakes	M 5.3–6.2, 675 injured, 5085 fully or partially destroyed houses
16 August 2005	Off the coast of Miyagi Prefecture	M 7.2, 89 injured, one house fully destroyed, and 849 partially damaged houses
14 June 2008	Iwate Miyagi Nairiku Earthquake	M 7.2, 17 dead and 426 injured

14.3.2 Effects of the Earthquake on the Physical Environment

According to the Geospatial Information Authority of Japan (2021), the GEJE caused horizontal crustal deformation of over 5 m around the Oshika Peninsula (2021). In contrast, the cumulative crustal movement over the five years preceding the GEJE was approximately 6 m.

Earthquakes with a magnitude of 5.0 occurred off the Pacific coast of the Tohoku region in 2020 and 2021. People in Japan are wary of the occurrence of earthquakes of this magnitude. Although it appears that Japanese people have become accustomed to the earthquakes of this magnitude and frequency, the fact that these earthquakes are aftershocks of the GEJE is astonishing.

14.3.3 Effects of the Earthquake on the Economic Environment

The GEJE has had a significant impact on the Japanese economy because of the scale of its damage and secondary effects (such as power outages) compared with past large-scale disasters. The damage caused by the tsunami to nuclear power plants and other facilities significantly reduced the power supply capacity in eastern Japan. These power constraints made it impossible for households and businesses to meet their electricity needs, which gradually led to a decline in economic activity. In addition, the Fukushima Daiichi nuclear disaster resulting from the GEJE led to the widespread shutdown of nuclear power operations across the country. In addition, the promotion of renewable energy sources, which are environment-friendly and aimed at deoxygenation, has led to a reliance on the operation of thermal power plants to secure a stable electricity supply.

Disruptions in the supply chain also have a significant impact. Several factories located in the affected areas were shut down. The supply of certain components and materials was disrupted, forcing factories across Japan (and others overseas) to suspend operations. Consequently, these supply chain disruptions have led to a nationwide decline in production activities.

14.3.4 Effects of the Earthquake on the Social Environment

In the aftermath of the GEJE, extensive efforts have been made to transmit these lessons to future generations and archive various memories, assuming that tsunamis and earthquakes of the same scale will occur in the future. The inhabitants of areas affected by natural disasters have set up stone monuments to send messages to future generations, such as 'Do not build houses below this point. A tsunami is coming'. Since individuals can now transmit their experiences through various media, a tremendous amount of information has been gathered. However, properly uncategorised data are not easily accessible.

On 1 September1923, an earthquake of similar magnitude to the GEJE (around 7.9 on the Richter scale) caused extensive damage to the Kanagawa and Tokyo prefectures. At that time, Japan had many wooden houses; thus, most of the casualties were caused by collapsing buildings and fires. As a result, 1 September was designated as Disaster Prevention Day. Many media outlets continue to create yearly reports to memorialise the disaster and the ensuing recovery efforts during March.

Universities in and outside the Tohoku area are researching disaster prevention and recovery, sharing their findings with residents and businesses (e.g. the Research Centre for Regional Disaster Management, Iwate University, Iwate and the International Research Institute of Disaster Science, Tohoku University, Miyagi). The Great East Japan Earthquake and Nuclear Memorial Museum (Fukushima) serves as a place of remembrance for the damage caused by the GEJE and the lessons learned. These facilities are collectively known as the '3.11 Tradition Road'. They are actively working to keep the memory of the disaster alive. Furthermore, they are passing on this knowledge to future generations by networking these facilities across four prefectures from Aomori to Fukushima and disseminating knowledge regarding disaster prevention in Japan and abroad.

While it is essential to pass on knowledge of the disaster to future generations, we must not forget the people who continue to live in the area. According to Miyaji and Yamauchi (2021), there are several options regarding the plan of action to deal with post-disaster remains, such as immediate demolition, preservation as post-disaster remains, and withholding the decision for a specific period. It is necessary to know that the multi-layered nature of the stakeholders involved will force them to unify, which will cause conflict and division.

After the GEJE, a great deal of attention has been paid to mental health. When dealing with the disaster as a subject of study in educational institutions, such as elementary and junior high schools, great care must be taken so that memories of the disaster are not processed as trauma.

14.3.5 Disaster Prevention and Infrastructure Strengthening

In Japan, earthquakes of magnitude 9.0, occurring in the Nankai Trough, earthquakes directly under the Tokyo metropolitan area, and the eruption of the Mt. Fuji might ensue soon. The damage has been estimated, and countermeasures are being studied. The Tohoku coast, which experienced the GEJE, was no exception.

Immediately after the earthquake, the Tohoku Regional Development Bureau issued a basic concept of tsunami disaster prevention measures based on the GEJE, which stated that disaster-affected areas were highly vulnerable to tsunamis, storm surges, and tidal waves. As of 2021, 621 coastal-dike restoration and rehabilitation projects in the six prefectures affected by the disaster have been created, of which 78% (485) have been completed thus far. The total length of the coastline in the three affected prefectures is 1700 m; however, only approximately 400 m is required for coastal embankment facilities. Some local governments have decided to lower the height of the levees or change their location to mitigate the impact of relatively frequent tsunamis, considering the safety of the town, the combination of hardware and software, environmental protection, and urban planning in these municipalities (e.g. Otsuchi Town, Iwate). In some areas, large seawalls have been mockingly dubbed 'the Great Wall of China' by the population as a result of their height and length. Thus, a new environment has been formed in which people living in coastal areas are separated from the sea by human-made structures. New calculations regarding tsunami height simply that seawalls are not completely effective against tsunamis. Conversely, their purpose is to slow down the speed of the tsunami or buy time for evacuation even if the tsunami has surged over the seawall. However, there have been reports of people sometimes miscalculating their evacuation actions because seawalls preclude them from noticing changes in sea levels.

However, some municipalities (e.g. Onagwa, Miyagi Prefecture) have refused to build seawalls. For the past ten years, Onagawa has been working to build a town without seawalls, a choice that has allowed the inhabitants of the area to maintain their proximity to the sea and their way of life. As the town's main industry is fishing, the inhabitants refused to be separated from the sea; therefore, during reconstruction, the town's houses were moved to higher ground. All roads were designed as tsunami evacuation routes in the fishing port and commercial district. In towns adjacent to the sea, the way infrastructure is designed depends on the relationship between the inhabitants and the sea.

The first phase of the Reconstruction Agency's activities in the reconstruction area (part of the 'reconstruction and creation period') will end in March 2021. Further, the Reconstruction Agency has designated the period from 2021 to 2031 as the second phase of the 'reconstruction and creation period' and has indicated that it will steadily promote efforts to support its remaining projects, such as psychological care for victims.

14.4 The Impact of COVID-19

The COVID-19 pandemic has both similarities and differences with the natural disasters described thus far. In Japan, the Basic Act on Disaster Management defines a disaster as follows: 'the term 'disaster' means damage resulting from a storm, tornado, heavy rainfall, heavy snowfall, flood, slope failure, mudflow, high tide, earthquake, tsunami, eruption, landslide or other abnormal natural phenomena, a large fire or explosion or other causes, as determined by the Cabinet Order in the extent of damage they cause' (Article 2, Item 1). Additionally, the Cabinet Order specifies in the first article of the Disaster Countermeasures Law Enforcement Order: [disasters include] 'the massive release of radioactive materials or sinking of a ship, and any events resulting in many victims or any other large-scale accidents'. This definition includes not only natural disasters but also anthropogenic disasters. There are several other ways to classify disasters. However, in terms of the relationship between individuals and society, the following common points can be identified.

First, disaster victims should be considered. If individuals cannot live in a secure area because of a disaster, they may be temporarily sheltered in evacuation centres or moved to temporary housing. In Japan, people with pets are not allowed to stay in evacuation centres. In the event of infectious diseases, infected individuals are quarantined to mitigate viral transmission. If an isolation area (such as a hospital or an isolation hotel) cannot be secured, patients are treated at home, which places their family members at risk of infection. Moreover, the rate at which the number of victims increases varies between different disasters. In the case of earthquakes, the survival rate drops significantly if people are not rescued within 48–72 h of the disaster, and emergency operations are said to be a race against time. In cases of infection, the number of infected people varies depending on the infectivity of the pathogen. However, infected people may also be asymptomatic, making it difficult to correctly measure the number of cases.

The second factor is the disaster area. While natural disasters are often localised, infections spread through the movement of people, which can increase the likelihood of a pandemic. In the COVID-19 pandemic, the speed at which the infection spread was very high because of the accessibility of high speed and international travel. Thus, travel restrictions were imposed in the early stages of the pandemic. In some countries, strict lockdown measures, including quarantine, have been implemented. In Japan, the government asked people not to travel and avoid going outside their homes, except when necessary. In April and May 2020, the government declared a state of emergency, and many citizens responded to this request. However, some citizens did not follow these requests. Additionally, some companies denied their employees the possibility of telecommuting.

It is hard to say how the concept of freedom is perceived in Japanese society. However, there seems to be a tendency to think of these control measures as an infringement on individual freedoms. Moreover, some government officials have encouraged people to act according to their judgments rather than specific guidelines. It is not uncommon for the media to report on people who are in a situation where they have to decide whether or not to become infected at their own risk and who suffer from the double anxiety of threatening their survival due to infection and infecting others. For example, according to Hiraishi et al. (2021), from the perspective of immanent justice reasoning, the proportion of people who think they deserve it is more robust than in other countries.

Third, we must consider the effects of disasters on mental health. Within the context of COVID-19, some people experience uncertainty. It could be regarding the causes and treatment of diseases, the duration of social distancing, and anxiety over not going to work or school because of social isolation. Staying at home and not exercising is also said to increase the likelihood of depression, giving rise to the term 'corona depression'. Difficulty communicating online with colleagues and classmates also increases feelings of isolation. Of course, several individuals also experience anxiety over losing their job because of the economic recession caused by the pandemic, making it difficult for some people to secure an income and make ends meet. During the COVID-19 pandemic, the prevalence of suicide has increased due to unemployment and increased emotional burden. Moreover, it is easy to imagine the prevalence of secondary sources of anxiety besides the ones described above. Therefore, the effects of COVID-19 on mental health must be reduced or eliminated.

To safely interact with people face-to-face, vaccination is essential. However, Japan lags behind other developed countries because of various factors. First, there is an issue with securing vaccines. Even if vaccines are developed domestically, the approval process is time-consuming. Therefore, it is necessary to adopt vaccines developed by foreign pharmaceutical companies. Moreover, it has been difficult for local governments (in charge of vaccination) to secure appropriate vaccination sites and medical personnel. Although the number of people over the age of 65 is relatively small in some cities, vaccination appointments have been distributed to older adults in different age groups because of the large number of people over 65 years of age. This is a problem unique to Japan, which has one of the world's most agedsocieties. If vaccination rates reach a certain level, many economic activities can return to the pre-pandemic levels.

However, the COVID-19 vaccination programme has not progressed, as expected. Additionally, some people exhibit side effects as a result of vaccination. Due to culture-specific factors, this has slowed the progress of vaccination in Japan, which is more concerned with preventing the death of even one person rather than achieving herd immunity.

Finally, the medical systems in Japan must be analysed. In Japan, the number of infected people is small compared to that in other countries. However, COVID-19 hospitalisations have put additional pressure on medical institutions, causing the medical system to collapse. Thus, to cope with similar future crises, Japan's medical system must be overhauled; however, there is no indication that the government will take immediate action.

14.5 Rias and Industrial Reconstruction

The Sanriku coast extends over 600 km from Sameikado, Hachinohe City, in south eastern Aomori Prefecture, and through the coast of Iwate Prefecture to Mangokuura Ishinomaki City, in eastern Miyagi Prefecture. The northern part of the coastline, bordered by Miyako City in Iwate Prefecture, has developed coastal terraces, while the southern part is ria.

According to Miura and Yonechi (2015), the conventional perception of rias has transformed over time. Although many researchers have discussed the strong correlation between the topography of rias and tsunami disasters, they argue that this correlation has not been mentioned in the media or research reports. This is because of the expansion of tsunami-affected areas during the GEJE. However, it is recognised that rias, because of their topography, amplify the height of tsunamis.

The Meiji Sanriku Earthquake Tsunami, which occurred on 15 June 1896, had an intensity of 2–3 on the Japanese scale; however, some parts of the city were hit by a 10-m-high tsunami that killed approximately 22,000 people. Moreover, the Showa Sanriku Earthquake of 3 March 1933 had an intensity of about 5 on the Japanese scale; however, a 7-m-high tsunami hit parts of Kesennuma. Further, the Great Chilean Earthquake of 23 May 1960 caused a tsunami 24 h later in Japan.

Jodogahama (Miyako City, Iwate Prefecture) is located in the centre of the Sanriku Reconstruction National Park and Sanriku Geopark. It is rich in scenic beauty, with a forest of sharp, white rhyolite rocks, beautiful contrast between the green of the pine trees, the white of the rock surface, and the blue of the sea. It draws parallels with paradise (Pure Land or *Jodo*) in the Buddhist religion, as described by a Buddhist priest in the Edo period (Miyako City 2021).

According to the Ministry of Agriculture, Forestry, and Fisheries (2021), in the ten years since 2011, the areas affected by the GEJE have been restoring fishing port facilities, fishing boats, aquaculture facilities, and fishing grounds. The average landings in significant fish markets in Iwate (Kuji, Miyako, Kamaishi, andOfunato), Miyagi (Kesennuma, Onagawa, Ishinomaki, andShiogama), and Fukushima (Onahama) prefectures were 76% of the total value of landings and 69% of the total volume of landings (compared with the year before the disaster). Since fishing is a leading industry in coastal areas, appropriate measures will be ensured.

14.6 Accelerated Convenience and Safety Improvement in East Japan

Even before the earthquake, the coastal areas of Tohoku had been suffering from an ageing and declining population, poor access to transportation, and other problems exacerbated by the disaster.

High-quality arterial roads form the backbone of Japan's road system. They are constructed as automobile-only roads necessary to support the active exchange between regions and ensure high speed automobile traffic. These arterial roads connect core cities to central regional cities. In addition, regional highways are being developed to strengthen the regional structure by promoting mutual exchange between regional agglomerations and linking them with transportation hubs.

For example, Sendai City in Miyagi Prefecture is the core city of the Tohoku region. Its network to neighbouring Akita, Iwate, Yamagata, and Fukushima prefectures has been strengthened in recent years, providing ease of access between industrial and logistical hubs in the event of natural disasters.

Since the GEJE, major natural disasters have occurred infrequently throughout Japan. Each time, a blockage occurs in the transportation network. However, various transportation systems such as Shinkansen, railroads, buses, and subways have compensated for these interruptions, ensuring a quick recovery.

Japan, as an island nation, is one of the most earthquake-prone regions because of its location on top of multiple tectonic plates. Earthquakes of varying intensities occur daily. After the GEJE, efforts have been made to examine Japan's history to analyse the cycle of significant earthquakes in each region. Since tsunamis can occur along with earthquakes in coastal areas and large rivers, an emergency bulletin describes the magnitude of the earthquake and whether a tsunami is issued by the government. The Ministry of Internal Affairs and Communications (MIC) (2011) has been working on infrastructure strengthening and cooperation with telecommunication providers to secure communications in the event of large-scale disasters.

14.7 Visible and Invisible Damage Caused by Natural Disasters

The collapse of buildings and social infrastructure caused by earthquakes, tsunamis, and other disasters is a traumatic event. News reports on disasters can have similar effects on viewers. However, rebuilding collapsed or damaged buildings and social infrastructure makes it easier to elucidate recovery. This is because it allows people to visually understand the rebuilding process by receiving data on the duration of rebuilding, its progress, its budget, and other numerical values. However, when evaluating measures related to disaster reconstruction, the appropriateness of the original objectives and indicators may be questioned.

First, is the goal of reconstruction to go back to the way things were before the disaster? Or is it to build a new social environment altogether? This point of view has not yet been sufficiently discussed. For example, in the event of the total collapse of infrastructure due to a tsunami, the city and environment will be rebuilt from the ground up. However, history teaches us that earthquakes and tsunamis, which occur every few decades, will damage the area once more in the future. However, this does not deter us from building in vulnerable areas. In some cities, urban functions may be relocated to higher ground. In some cases, this is done without consulting the citizens. Although there are differences in the direction between the regional government and the people, the newly designed infrastructure may guarantee more safety than before. However, this does not guarantee that people's mental health will improve. It is important to remember that people's emotional care and community building are difficult to measure numerically and will take time to rebuild.

14.8 What Has Been Gained and Lost After the Great East Japan Earthquake

According to traditional Japanese culture, people are supposed to live in harmony with nature and respect it. Therefore, various disaster prevention efforts have been made to minimise damage from similar disasters in the future while simultaneously avoiding damage to the natural environment. For instance, flood and seismic hazard maps are updated regularly; these maps reflect areas most likely to be affected by tsunamis flowing back into rivers as well as potential landslide disaster areas during localised heavy rains. In particular, in April 2020, the Cabinet Office reviewed a model of a massive earthquake along the Japan Trench and the Kuril Islands Trench, which presented a tsunami of just less than 30 m. Moreover, the city of Miyako in the Iwate Prefecture conducted a simulation of flooding by the largest class of tsunami and held study sessions for citizens.

However, normality bias can prevent us from making correct decisions. For instance, Japanese citizens are frequently alerted by tsunami and earthquake warnings. However, the expected damage does not always occur, which could lead to the development of a false sense of security. Additionally, as we can see from the tragedy at Okawa Elementary School in Ishinomaki City, Miyagi Prefecture, the ability to act based on intuition and quick-thinking can be the deciding factor between life and death.

In emergencies, there is often a surge in misinformation. As crises put people in a situation that they have never experienced before, it is easy for them to rely on false information. In Japanese culture, individuals can be greatly affected by the opinions of those around them. Resultant of peer pressure, they may be inclined to exclude those who are different from them. However, it is necessary to find a way to survive without being influenced by such misinformation and biases.

People and families who have lost their jobs or homes because of the GEJE relocated to urban areas. However, rural areas were already facing various problems, such as a declining population, a shortage of labour due to their ageing population, and the exodus of young people to cities, all of which have been aggravated by the GEJE. Therefore, local communities must work cohesively to prevent the outflow of the next generation of leaders. However, there have been no significant efforts in this regard; thus, the rural population has continued to decline.

14.9 Forming Environment Surrounding People in a Region

As mentioned earlier, people are moving to urban areas because of unemployment. In addition to the gradual decline in the number of people using the oversupplied infrastructure, the shrinking population due to the declining birth rate is keeping people out of the countryside. Local governments have made several efforts to encourage people to settle in rural areas and disaster-affected areas, including regional revitalisation in education. To rebuild the affected areas, special budgets have been set up by the government, and many projects have been planned and implemented. However, there is nothing more uncertain than predicting the future without recognising that the present is changing. Therefore, questioning the status quo would be beneficial.

If we formulate policies and build communities without a long-term plan, we will end up in a city without children and youth. It is only active when people live in a city. How should people build relationships and create a society to achieve this? This world has never been attained before, and it is impossible to imagine it with the existing values. However, the recovery from the disaster will make it easy to understand.

14.10 Conclusion

This study examines the transformation of resources in the Tohoku region as a result of the GEJE. The region's social infrastructure has been strengthened, while some industries have been restored to their pre-earthquake conditions, and many economic support measures have been implemented. However, even though the recovery efforts seem to be going well, there seems to be no stopping the population outflow from rural to urban areas. Establishing and preserving a social infrastructure in areas where the population is decreasing will not lead to the maintenance and development of the disaster area. Therefore, it is necessary to consider nature as an integral part of society and continue to build communities to mitigate the effects of disasters.

In sum, the Great East Japan Earthquake is not a thing of the past, as the country continues to recover from this disaster even ten years later. In addition to the contributions made by the government, non-profit and non-governmental organisations, private corporations, universities, newspapers, and even individuals continue to collect data and publish books and articles on this subject through various media. However, most of the reports written in English comprise outdated information, while most of the data that is still being collected and analysed are available only in Japanese. Thus, we would like more people to have access to new information. Over time, the data recorded in detail will provide insights that may prove useful in disaster recovery and prevention in the future.

14.11 Recommendations

Areas, where natural disasters occur, are unlikely to be completely restored to their pre-disaster state. However, suppose we can ensure a safe living environment for the people who live there. In that case, it may not be possible to restore the pre-disaster environment completely, but coexistence between the region and its people may be feasible.

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Chapter 15
Biodiesel and Its Environmental Impact and Sustainability

Manickam Mathiyazhagan, Giridharan Bupesh, and K. Meenakshi Sundaram

Abstract Ever increasing the demand of petroleum diesel, environmental degradation, fuel-hike and depleting petroleum stashes encourage the study of alternate fuel to diesel engines. Several low-cost and accessible bio-resources and agro-industrial waste are available for alternate liquid fuel production including the biodiesel. Biodiesel production from plant-based materials became more and more attractive in the recent years, due to the increasing economic concerns and environmental awareness about the use of conventional diesel fuel. Many researches have ascertained better emissions in biodiesel because of its higher proportionality of O_2 content, cetane rating and lubricity. Besides, domestic production of biodiesel from edible oils leads the food oil crisis. Hence present research emphasis waste cooking oil for biodiesel production to minimize the environmental pollution and cost.

Keywords Alternate fuel · Biodiesel engine · Low pollution · Transesterification · Waste oil

15.1 Introduction

Biodiesel is a mono alkyl ester resulting from the catalytic or non-catalytic transesterification of plant or animal fats and glycerin as the by product. The ever-increasing cost of fossil fuel makes hardship in the day-to-day life of the people (Drexler 2005). Modernization, urbanization and industrialization of current world demanding higher usage of diesel result in the decrease of fossil fuel age and increasing the greenhouse emissions (Fernandes 2020), Alternatively, biodiesel is similar to petroleum diesel

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(PD) in its physio-chemical aspects. Awareness about global warming and other environmental degradation urges us for reducing fossil fuels. Awareness about the global warming and other environmental degradation urges us for reducing the fossil fuels (Nanda et al. 2015). Demand of environment-friendly, biodegradable fuel for the diesel engines is the need of the hour. Biodiesel is clean-burning, renewable substitute for PD in nature, and it could be domestically produced (Zahan and Kano 2018). Biodiesel increases the energy security of the countries. On its usage, the resultant air quality is better than fossil fuels and impacts lesser on the environment. Biodiesel reserves the capabilities such as for higher flash, better fire point and easy for its transportation. Biodiesel has better lubricity and higher oxygen content (Noor et al. 2018). Biodiesel provides local employment to educated and uneducated youths. Biodiesel provides additional income to farmers. Biodiesel reduces the import PD, and it saves the economy of the nation (Mothupi 2015).

At present, most of the biodiesels were tried from vegetable oils which is costly than the petroleum price. Moreover, diversion of vegetable oil to fuel also leads to food oil crises (D'Odorico et al. 2018). Similarly, vegetation of plants is requiring man power, water, fertilizer and land for its cultivation. Waste oil or used cooking oils are overcoming all those problems. Meanwhile, conversion of the waste oil in to biodiesel is a cost-effective technique and produces lesser environmental pollution compared to its counterpart. In addition, it also reduced the proportion of polluted oils in the soils (Kannah et al. 2020).

The present study focused to develop standard protocol for transesterification of waste cooking oil and its physico-chemical properties using international standard method. Further, its environmental suitability (gaseous pollutants) of biodiesel blend in 5HP kirloskar diesel engine was also done.

15.2 Materials and Methods

Waste oil or used cooking oils are collected from local restaurants of Tiruchirappalli District of Tamilnadu and are subjected to two steps, i.e., acid and alkali catalyzed transesterification to make the biodiesel.

15.2.1 Titration

It is a process of chemical analysis in which the requirement of molar ratio of catalyst and alcohol is determined with the known quantity of sample.

15.2.2 Acid Catalyzed Transesterification

In general, 10 ml of HCL or H_2SO_4 and 200 ml of ethanol or methanol is used for 1 l of oil. Acid was carefully added to 200 ml of methanol through edges of glass vessel using pipet. Present study starts with minimum quantity of waste oil, i.e., one liter of filtered waste oil was taken in 2-liter conical flask and is kept in temperature-controlled water bath below the boiling point of methanol for 30 min. Acid catalytic agent was added carefully in to the heated oil, and the container was tightly closed. It was kept in shaker for r2–3 min; again, the container was kept in water bath for 4–5 h at 55 °C. After the incubation time, the container was taken out from the water bath. Two distinct layers were separated, and the upper and lower layer contained ester and glycerin, respectively. The ester and glycerin layers were separated by using 2-liter separating funnel. The upper ester layer was saved for further study, and the glycerin was used for another industrial purposes. The main aim of this acid treatment is that to reduce the free fatty acid content below 1% since more than 1% of FFA may difficult for the separation of glycerol (Fig. 15.1).

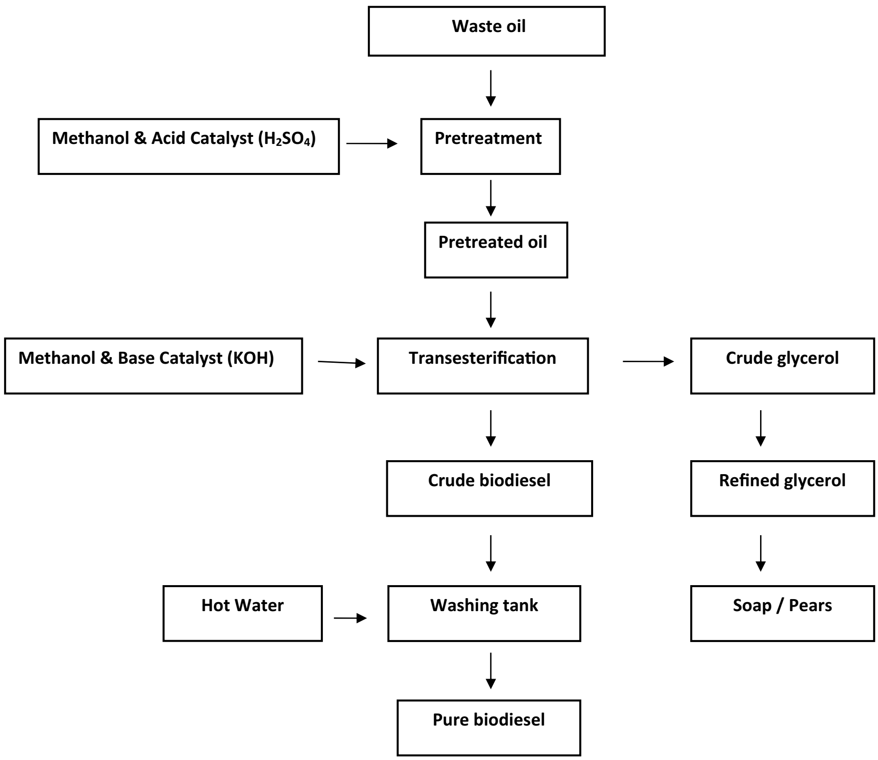

Fig. 15.1 Process flow diagram

15.2.3 Alkali Catalyzed Transesterification

In general, 7.5 g of sodium hydroxide or potassium hydroxide and 200 ml of ethanol or methanol is used for 1 l of oil sample along with the titration amount. In the present study, 200 ml of methanol and the 7.5 g of potassium hydroxide were dissolved thoroughly without any precipitation using the magnetic stirrer. One liter of acid treated ester was taken in air tight conical flask and is kept in the water bath for 30 min at 50 °C. Carefully, the base catalyst agent was mixed with the heated ester sample, and the container was tightly closed. For 2–3 min, it was gently shaked well then, and it was kept in the water bath for 4–6 h as the incubation time without any disturbance. After the completion of the incubation, the container showed two distinct layers. The sample was transferred to separation funnel in order to separate the content by bi-phasic separation. The funnel was vigorously shaken and kept vertically for a while. The glycerol layer and methyl ester layer were separated from each other. The upper layer was saved for purification process, and the lower glycerol was taken into refinery process to make soap and other cosmetics.

15.2.4 Purification of Ester

The separated upper layer (yellow colored) was taken into separating funnel. The equal amount of hot distilled water was added to the ester layer and is mixed gently and kept in stand without any disturbance. After 5 min, ester and water along with the impurities are separated. The bottom of the funnel contains water along with other impurities such as unreacted catalyst and glycerol, and the water washing process was repeated until we got clear water at the bottom of funnel. Finally, upper ester layer was saved in the container for drying purpose.

15.2.5 Drying of Ester layer

Water in ester layer favors for microbial growth, increases the acid value and viscosity of biodiesel fuel. Similarly, presence of methanol in fuel leads to reduction in the flash and fire point of fuel. On the other hand, presence of methanol in fuel can corrode the fuel hoses of engines. Hence, the removal of water and methanol from ester layer is essential. For this process, a heating mantle with stirrer was used. The ester layer was heated at 100 °C for 15–30 min for eliminating the water and alcohol content of ester layer (biodiesel). Finally, the dried biodiesel fuel was saved for further study.

15.3 Results and Discussion

15.3.1 Biodiesel Quantification

The values of glycerol, methyl esters and biodiesel were calculated, and the experiment derived 890 ml of biodiesel from 1 l of waste oil after purification. The values are represented in Table 15.1.

15.3.2 Physico and Chemical Characterization of Biodiesel

The important fuel properties of biodiesel from the waste oil were checked using International ASTM and standard European methods. The physical properties of waste oil-derived biodiesel were tested in authorized laboratories, namely Sargam Laboratory Pvt. Ltd., Manapakkam, Chennai—89, and Omega laboratory and Research Centre (Industrial Testing and Analytical Lab.), Namakkal, Tamilnadu, India. The main aim of this study is to analyze the fuel suitability of derived biodiesel compared to with the PD as per the international standard values. The important parameters of pure biodiesel were analyzed, and the values are presented in Table. 15.2 for comparative study.

15.4 Emission Study

The waste of biodiesel was taken for the preparation of various biodiesel blends at different concentration (10, 20, 30, 40 and 50%) using conventional PD. Because direct use of pure biodiesel in diesel engines requires slight modification for long running and better emission than the PD. The engine efficiency analysis was checked using a common PD engine (5 HP Kirloskar) located in the Department of Automobile and Mechanical Engineering, Anna University of Technology, Tiruchirappalli, Tamilnadu, India (Fig. 15.2).

Figure 15.2 shows experimental kiroloskar engine setup including smoke meter and digas analyzer used to measure the important pollutants at different engine loads in different concentrations of waste oil biodiesel fuels. The speciation of DIGAS analyzer and the smoke meter is mentioned in Tables 15.3 and 15.4.

15.4.1 Smoke Density (SD) of WBD Blends

The variation of smoke density of waste oil-derived biodiesel blends at various engine loads is presented in Fig. 15.3. SD of WBD blends were lower at lower blend level,

Table. 15.1 Quantification of biodiesel

Source	Initial volume of oil (ml)	Acid (H_2SO_4) volume (ml)	Methanol (ml)	Glycerol (ml/lit)	Esterified oil (ml/lit)	Acid treated ester layer (ml)	KOH(g)	Methanol (ml)	Alkali treated ester layer (ml/lit)	Glycerol (ml/lit)	Biodiesel (ml/l)
Waste oil	1000	10	200	130	1070	1000	7.5	200	985	215	890

Table. 15.2 Properties of biodiesel

Properties	Methods	WBD	PD	International standard value
Density @ 15 °C kg/m^3	D 1298	886	838	890
Kinematic Viscosity @ 40 °C (mm^2/s)	D 445	6.9	2.0-4.5	6.0
Calorific value (MJ/kg)	D 240	37.20	44.21	–
Specific gravity @20 °C	D 1298	0.846	0.816	0.862
Cloud point (0 °C)	D 97	13	7	−1
Flash point (0 °C)	D 92	152	53	130–173
Fire point (0 °C)	D 92	161	59	–
Acid value (mg KOH/g)	D 664	0.41	0.22	0.50 max
Iodine value	EN 14111	118	108	120 max
Water content and sediment (%)	D 2709	0.33	0.02	0.05
Sulfur content (mg/kg)	D 129	0.46	–	10 max
Phosphorus	D 4951	4	3	10.0 max
Cetane number	D 613	52	40–55	51.0 min
Methanol content (%)	EN 14110	0.31	0.30	0.20 max
Copper corrosion (3h@50 °C)	D 130	1	1	1 max
Oxidative stability@ 110 °C	D 2274	4 h	2 h	6 min
Mono-glyceride (%)	EN 14105	0.8	0.9	0.80 max
Di-glyceride (%)	EN 14105	0.3	0.3	0.20 max
Free glycerol (%)	D 6584	0.04	0.04	0.020 max
Total glycerol (%)	EN 14105	0.35	1.60	0.250 max
Na & K (mg/kg)	EN 14538	8	4	5 max

WBD Waste oil biodiesel, *PD* Petroleum diesel

i.e., up to 30% blend. Lower smoke at lower blend levels was achieved due to efficient combustion of WBD fuels. This may be due to the presence of more oxygen content of WBD fuel. But further increase of WBD fuel with PD increases the SD of WBD blends due to the presence of higher viscosity and subsequent poor combustion. Similarly, the smoke density of all the fuels increases with increase in engine load.

15.4.2 Exhaust Gas Temperature (EGT) of WBD blends

The variation of exhaust gas temperature of waste oil-derived biodiesel blends at different engine loads is presented in Fig. 15.4. The exhaust gas temperature of WBD blends increases with increase in the concentration of WBD with PD. This was achieved by the better combustion of WBD fuel than PD. Presence of higher

Fig. 15.2 Experimental engine **a** AVL smoke meter, **b** AVL DIGAS analyzer

Table 15.3 Specification of AVL DIGAS analyzer

Make	AVL
Type	AVL DIGAS 444
Power supply	11–22 voltage ≈ 25 W
Warm up time	≈7 min
Connector gas in	≈ 180 I/h, max. Overpressure 450 hPa
Response time	$T_{95} \leq 15$ s
Operating temperature	5–45 °C
Storage temperature	0–50 °C
Operating temperature	5–45 °C
Storage temperature	0–50 °C
Relative humidity	≤95% non-condensing
Inclination	0–90º<
Dimension (w × d × h)	270 × 320 × 85 mm^3
Weight	4.5 kg net weight without accessories
Interfaces	RS 232 C, pick up, oil temperature probe

Table. 15.4 Specification of AVL smoke meter

Make	AVL 437°C
Light source	Halogen bulb 12 V/5 W
Color temperature	3000–150 °C
Detector	Selenium photocell
Measuring range	0–99.99 opacity in %
Max smoke temp @entrance	250 °C

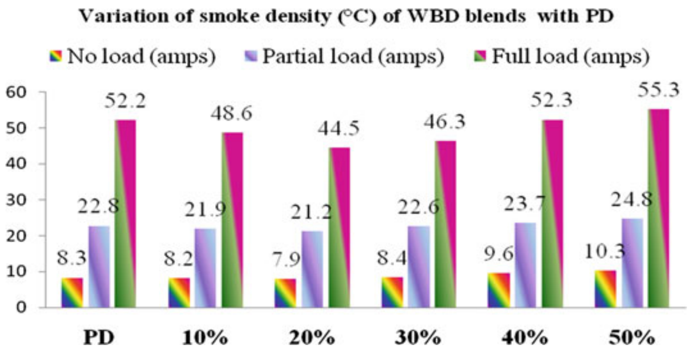

Fig. 15.3 Variation of smoke density (SD) of waste oil-derived biodiesel blends with PD at different engine loads

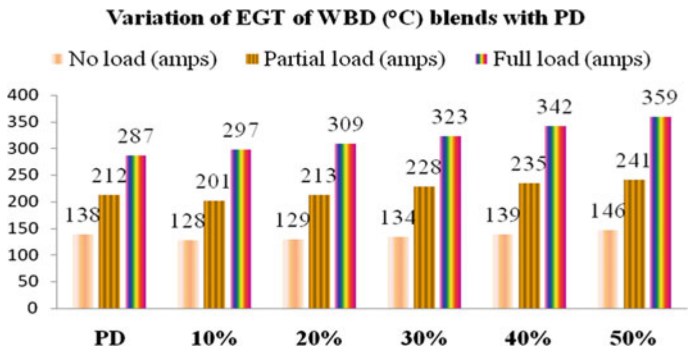

Fig. 15.4 Variation of exhaust gas temperature (EGT) of waste oil-derived biodiesel blends with PD at different engine loads

oxygen content of WBD fuel was the main factor for better combustion of WBD fuel. In addition to this, presence of high pressure and flame temperature may be the reason for formation EGT. The EGT of all the fuels was increased with increase in engine load.

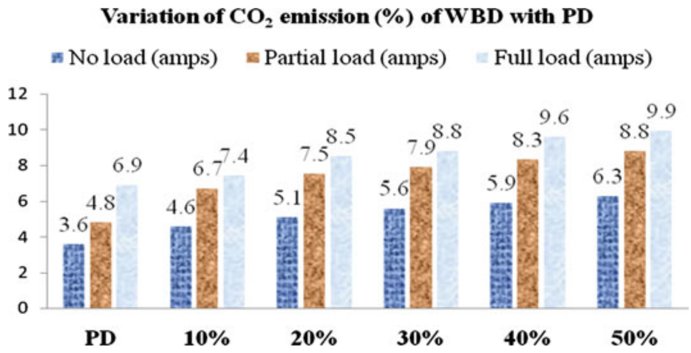

Fig. 15.5 Variation of carbon dioxide emission (CO_2) of waste oil-derived biodiesel blends with PD at different engine loads

15.4.3 Carbon Dioxide (CO_2) Emission of WBD Blends

The variation of carbon dioxide emission of waste oil-derived biodiesel blends at various engine loads is presented in Fig. 15.5. Carbon dioxide emission of WBD blends increases with increasing the concentration of WBD with PD. This higher CO_2 emission of WBD fuel showed the presence of more oxygen in WBD fuel than PD. However, the CO_2 emission from WBD fuels is not considered as pollutant because it can be consumed by plants at the time of photosynthesis. Therefore, CO_2 emission of biodiesel fuel is neutral (Lang et al. 2001; Antolin et al. 2002; Vicente et al. 2004; Candal et al. 2017).

15.4.4 Carbon Monoxide (CO) Emission of WBD Blends

Variation of carbon monoxide of waste oil-derived biodiesel blends at different engine loads is presented in Fig. 15.6. Carbon monoxide mainly formed due to incomplete combustion fuel. The CO emission of WBD blends was lower than PD because the blends are efficiently burnt inside combustion chamber leading reduction to CO emission. This was achieved due to the presence of more O_2 content in WBD blends.

15.4.5 Hydrocarbon (HC) Emission of WBD Blends

The variation of hydrocarbon emission of waste oil-derived biodiesel blends at different engine loads is presented in Fig. 15.7. Hydrocarbon emission of WBD blends was lower than PD due to better combustion of WBD fuel. This was achieved

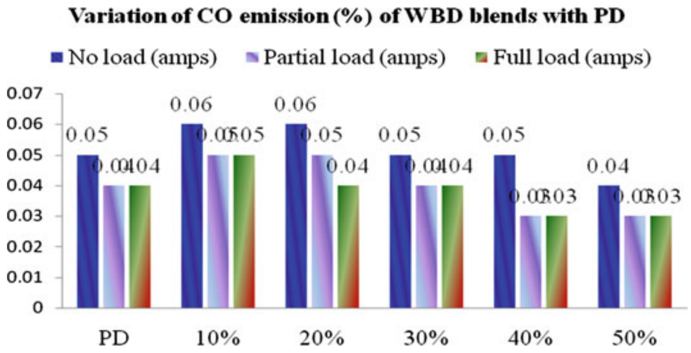

Fig. 15.6 Variation of carbon monoxide (CO) of waste oil-derived biodiesel blends with PD at different engine loads

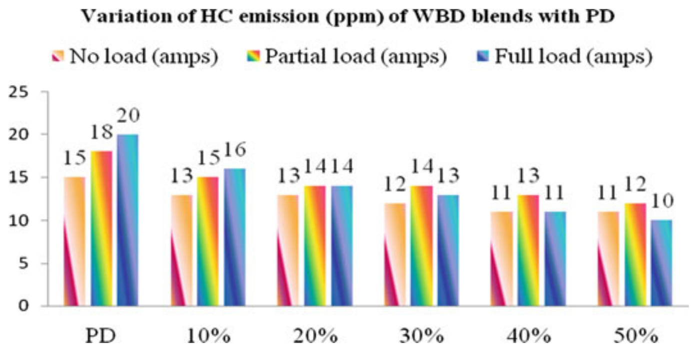

Fig. 15.7 Variation of hydrocarbon emission (HC) of waste oil-derived biodiesel blends with PD at different engine loads

due to the presence of more oxygen content of WBD fuel leading to complete combustion resulting in the formation of lower HC emission in WBD. In addition to this, presence of higher cetane number of WBD fuel also reduces the ignition delay period leading to better combustion and thus lowers the HC production in WBD blends.

15.4.6 Nitrogen Oxide (NOx) Emission of WBD Blends

The variation of nitrogen oxide emission of waste oil-derived biodiesel blends at different engine loads is presented in Fig. 15.8. The NOx emission of WBD blends increased with increase in the concentration of WBD with PD. This was achieved due to the availability of more oxygen (Dorado et al. 2003; Senda et al. 2004; Usta 2005; Labeckas and Slavinskas 2006; Canakci et al. 2006; Kumar et al. 2020; Wang et al. 2021) and high flame temperature of WBD fuel. Similarly, the NOx emission

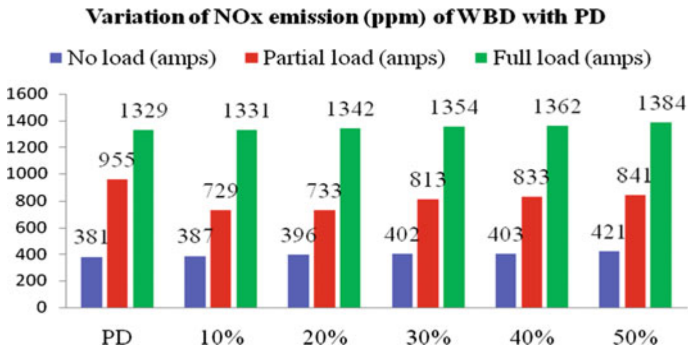

Fig. 15.8 Variation of nitrogen oxide emission (NO_x) of waste oil-derived biodiesel blends with PD at different engine loads

of all the fuels increases with increase in engine load due to the combustion of more fuel with higher temperature (Geng et al. 2017). On the other hand, the vegetable oil-based fuel contains small amount of nitrogen which will facilitate the formation of NOx in WBD blends.

15.5 Conclusion

In this study, the waste oil collected from local restaurants is successfully converted into biodiesel using two-step catalyzed transesterification with the minimum equipment's. In addition, to find out fuel quality of biodiesel, the important physico-chemical characters were analyzed using international standard methods. It is found that the results of pure biodiesel were higher than PD but within the recommended limit of international standards. However, when we use the biodiesel in the form of biodiesel blends, then the biodiesel values are very closer to PD especially density, viscosity, calorific value, flash and fire point, etc.

On the other hand, to analyze the environmental suitability of biodiesel, the pure form of biodiesel was converted into different blends. The blends are used in common diesel engine to measure the important gaseous pollutants along with the smoke density and exhaust gas temperature. Smoke density of waste oil-derived biodiesel blends is lower up to 30% than PD. It may be due to the better combustion of biodiesel. The exhaust gas temperature of biodiesel blends gradually increases with the increase of biodiesel blends due to the presence of high pressure and flame temperature.

The important pollutants such as carbon dioxide concentration are increasing when we increase the concentration of biodiesel percentage. This is evident that presence of higher oxygen content leads the complete combustion. However, CO_2 is not considered as pollutant because released CO_2 is utilized by the plants by the process of photosynthesis. Incomplete combustion is the main reason for the production of carbon monoxide. But biodiesel blends are showing lower emission than the PD confirms the complete combustion of biodiesel. The higher oxygen level showed a decreased hydrocarbon emission and cetane number. This resulted in better combustion and reduced ignition delay. Similarly, emissions of nitrogen oxides are increased with the increase of biodiesel concentration and the engine load.

15.6 Recommendation

Biodiesel is considered to be a domestic, renewable, environmentally low polluted sustainable energy source. Biodiesel reduces the oil dependence of developing countries like India. Hence, the detailed investigation of present study recommends the usage of 20% biodiesel blend from used cooking oil as the alternative fuel to diesel engines without modifications.

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Chapter 16
A Case Study on Practices and Acute Toxicity Symptoms Associated with Pesticide Use Among the Farmers of Mid Brahmaputra Valley of Assam

Anamika Nath and Pratibha Deka

Abstract In this study, an attempt was made to assess the knowledge, attitude, practices regarding pesticide handling and acute toxicity symptoms of pesticide use among the farmers of mid Brahmaputra Valley of Assam. The study included a sample size of 90 farmers taken from 6 villages of Sonitpur district of Assam, India. The farmers include both full-time and part-time agriculturists. Data collection was done through a questionnaire survey. Of the total samples, 82.2% used chemical pesticides and majority acknowledged them as harmful. Despite awareness of the health risk by the handling of pesticides, 75.68% reported not using any personal protective measures. 13.51% stated that they did not have separate work clothing, neither they washed them separately. Of the pesticides used, 52% belong to WHO class II (moderately hazardous), 8% belong to class III (slightly hazardous), and 4% belong to class Ib (highly hazardous). We had found that 59.46% of the farmers complained of Acute Pesticide Poisoning (APP), 24.32% sometimes complained of APP whereas 16.22% never complained of APP. The main self-reported toxicity symptoms include headache, nausea, burning of eyes, vomiting, shortening of breath, vision disturbance, and excessive sweating. The study revealed that lack of adequate knowledge and risky behavior during handling; storage and disposal of pesticides were a common scenario among the farmers. The use of pesticides in modern times cannot be stopped but certainly can be checked with proper training and Government initiatives.

Keywords Agriculture · Chemical pesticides · Knowledge of farmers · Safety measures · Acute Pesticide Poisoning

16.1 Introduction

Present-day farming is highly dependent on pesticides. It played a major role in increasing agricultural production. Pesticides are used in agriculture to manage

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pests and diseases, as well as to assure healthy crops and food security, affecting an estimated 1.8 billion people throughout the world (Mubushar et al. 2019). As a subtropical country, India; a different range of temperatures as well as humidity profile is present all through the year, thus a wide range of pests need to be tackled (Bhanti et al. 2004). Ideally, a pesticide should not harm the non-target species. But, as the expression goes, “if a little is good, a lot more is better,” the overuse of these substances has caused problems in humans and other life forms (Aktar et al. 2009).

The basis of the Indian economy is agriculture, with various agro-ecological zones. To meet the food security of the rising population along with heavy pest attacks, pesticides are considered an essential constituent. It plays a key role in increasing agricultural efficiency and output since the Green Revolution. As a result, without a second thought and inadequate knowledge, farmers started using chemical pesticides beyond heaps and bounds and fell into the malicious cycle. It includes unnecessary outbreaks of pests leading to additional use of pesticides, in turn causing heavy damages to crops creating pesticide resistance and secondary pests. Furthermore, use of wrong (heavy) doses than required causes contamination of the farm product, leading to a greater risk for the consumers (Bhanti et al. 2004; Yuantari et al. 2015). Worldwide 1500 types of chemicals are used as pesticides (Bolognesi and Merlo 2011). In India, there are 269 registered pesticides with 736 total formulations according to the Department of Agriculture and Farmers Welfare, Govt. of India. The pest industry of India holds the first place in Asia and 12th in the world (Devi et al. 2017).

Human exposure to pesticides is harmful in innumerable ways based on the type and the extent of exposure. While all individuals can have some sort of vulnerability toward pesticides but farmers especially those who are managing the pesticides directly face more risk of exposure (Hashemi et al. 2012). Adding to a lower literacy rate in rural masses, it provokes inappropriate and non-judicious use of pesticides. Along with it, improper handling, no use of proper protective equipment, unsafe storage, and disposal leads to ill effects in farmers (Yassin et al. 2002; Hurtig et al. 2003; Atreya 2008; Jallow et al. 2017). Lower literacy rate hampered the ability of the farmers to understand the potential threat and hazard warnings written on the pesticide packets and follow recommended safety labels and application procedures (Jallow et al. 2017). The World Health Organisation (WHO) and The United States Environment Program (UNEP) had estimated that approximately 20,000 workers die annually due to pesticide poisoning, the majority in developing countries (Dasgupta and Meisner 2005). Common signs of exposure are headache, nausea, vomiting, dizziness, and loss of consciousness. Long term chronic health conditions such as cancer, reproductive, immunological, endocrine, and congenital developmental disorders were reported by researchers (Sanborn et al. 2007; Calvert et al. 2008; Kesavachandran et al. 2009). On a brighter side, education can play a very important role in avoiding the potential threats associated with pesticide poisoning (Blanco-Munoz and Lacasana 2011; Mohanty et al. 2013). Research should be done to understand the ways to control pesticide reduction, cause of poor utilization of personal protective equipment (PPE), and effective training methods are highly appreciated (MacFarlane et al. 2013).

Keeping these in the backdrop, this study was conducted in the mid- Brahmaputra Valley of Assam with the objectives to determine the farmers' knowledge regarding pesticides and their attitudes; to assess the Acute Pesticide Poisoning (APP) among the farmers during pesticide handling; and to evaluate the personal protective measures used by the farmers to reduce occupational pesticide exposure.

16.2 Experimental Design

16.2.1 Study Site

Six villages of Tezpur in Sonitpur district of Assam, India were selected for this study (Fig. 16.1a, b). The total geographical area of Sonitpur is 2, 71,729 ha of which total cultivable land is 1, 12,281 ha. The district of Sonitpur consists of 12% big farmers, 37% small farmers as well as 36% marginal farmers (Agriculture Department 2018). The villages included are Amolapam, Napam, Borguri, Punioni, Beseria, and Rudrapad. Villages were chosen based on simple random sampling. From each village, 15 farmers were taken, adding to a total of 90 samples consisting of both full-time agricultural workers whose livelihood depends on farming only along with part-time agriculturists.

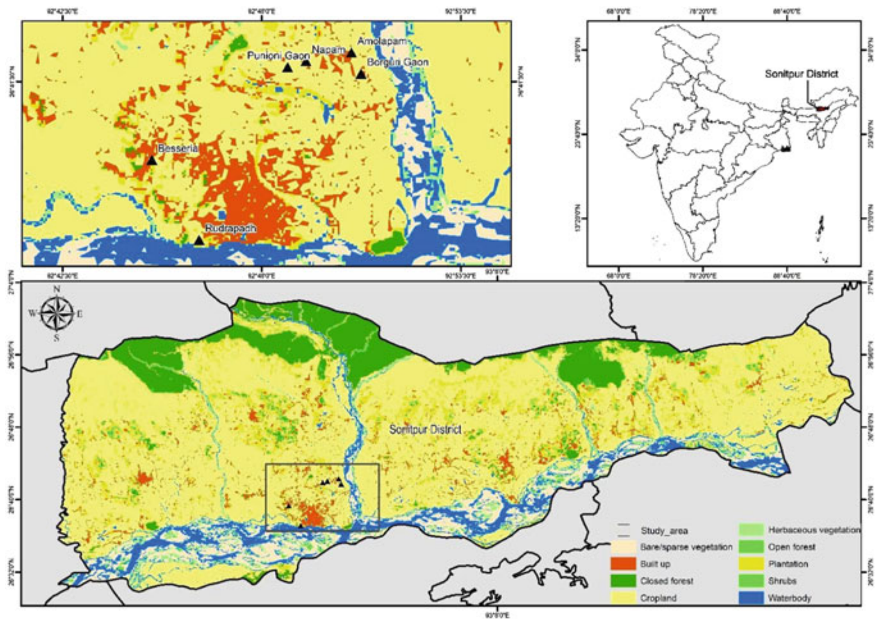

Fig. 16.1 Map of Sonitpur district, Assam, India showing the six surveyed villages

16.2.2 Questionnaire Survey

A questionnaire survey was carried out, and data were collected through face-to-face interviews. The questionnaire was prepared in English and translated to Assamese, the vernacular language of the region, and answers were recorded in the questionnaire at the same time by the interviewer. Each interview took approximately 20–30 min. Both open and closed ended questions were asked. Questions were prepared by studying various research articles, journals related to similar work. Information obtained from agricultural experts was also included in formulating the questionnaire. A pre-test survey was carried out to see the clarity of the language and effectiveness of the survey questions. Modifications were done based on this test to finalize the questionnaire. The questions include socio-demographic characteristics like age, gender, religion, educational level, and training received; farmers' perceptions and attitudes regarding pesticides storage, disposal, and its usage; use of protective measures and other measures taken during pesticide spraying; toxicity symptoms among the farmers; names of the products, active ingredients and so forth. Face-to-face interviews with pesticide retailers were conducted and most commonly used pesticides were listed. The mentioned pesticides were classified according to the WHO toxicity classification.

16.2.3 Statistical Analysis

The collected information is encoded and entered in Microsoft excel. Data were analyzed and interpreted.

16.3 Results and Discussion

16.3.1 Age and Education

Seventy four (74) farmers out of 90 farmers used chemical pesticides. All the farmers, involved in spraying pesticides work in open fields. The majority of the participants were male (84.4%). The highest percentage (50%) belongs to the age group of 45 and above followed by 37.78% in the age group of 31–45 years. The smallest percentage of 12.22% belongs to the age group 15–30 years, with an average age of 46.28 years.

Regarding education level, many respondents (using chemical pesticides) were either illiterate or under matriculation level, accounting for 34.44% and 31.11%, respectively. This data is similar to Suryawanshi and Patil (2016); Mubushar et al. (2019), and Jallow et al. (2017). Literate farmers have a better understanding of the health and environment than illiterate ones (e.g., Sa'ed et al. 2010; Mohanty et al. 2013; Mattah et al. 2015; Yuantari et al. 2015). This lines up with our collected

Table 16.1 Farmer's education level and use of protective measures

Education level of farmers	Farmers using protective measures	Pesticide using farmers ($n = 74$)	% of people using protective measures
College level	5	6	83.33
Higher secondary	1	2	50.00
Matriculation	4	7	57.14
Under matriculation	5	28	17.85
No education	3	31	9.67
Total	18	74	24.32

data where 83.33% of farmers having higher education levels use safety measures as shown in Table 16.1. The use of protectives measures was low in the case of illiterate and under matriculation level farmers. Of total pesticide using farmers, 24% used protective measures.

16.3.2 Sources of Information on Pesticide Use, Knowledge, Practices, and Training

Multiple responses of the participants were taken to get information regarding the usage of pesticides (Table 16.2). Our data revealed that sources of information on pesticides were mostly from fellow experienced farmers (42%). Rehman et al. (2013) also stated that selecting pesticides and information regarding pesticide usage are shared among fellow farmers. A significant percentage (31%) of farmers use their long years of experienced hands in farming and their estimation regarding pesticide use. Again, 78% of farmers depend on sellers/ distributors to gather knowledge about the standard ratio of mixing pesticides. Many educated farmers were also dependent on sellers/distributors and long farming experiences rather than reading labels and following instructions. Bhanti et al. (2004) mentioned that more than 90% of the farmers depend on pesticide sellers for extending their knowledge on what and which pesticides to be used in their farms. Rather than written labels, the majority of farmers depend on the instructions given by pesticide dealers or distributors (Jallow et al. 2017; Bhanti et al. 2004; Chitra et al. 2006). This is a big concern and indicates the general importance of pesticide labels (Jallow et al. 2017). Distributors can downplay the environment and the health implications of pesticides for higher profits (Alam and Wolff 2016). A worrying 20% use rough estimation for pesticide spraying in their fields. Respondents sometimes take expert advice from Krishi Vigyan Kendra and read labels, but the digits are not very satisfying; and constitute only 14% and 15%, respectively. More often, Govt. agencies focus mainly on large farmers than the small ones. The small farmers find it unimportant to visit the Govt. agencies for any further help (Banerjee et al. 2013). Only 25 farmers (33.78%) out of pesticide using 74 farmers received formal training on pesticide use from Krishi Vigyan Kendra (KVK),

Table 16.2 Respondent's perception and practices regarding pesticide

Question	Variable	*N*	%
Where pesticide bottles/packets are thrown?[a, b]			
	Pit	27	36
	Burn	27	36
	Drain	14	19
	Kabariwala	5	7
	River	2	3
	Bushes	6	8
Source of pesticide information[a, b]			
	Krishi Vigyan Kendra	12	16
	Nurseries	1	1
	Experienced farmers	31	42
	Long years of experience	23	31
	Distributor	11	15
	Panchayat	5	7
How the standard ratio of mixing pesticide known?[a, b]			
	Distributor	58	78
	KVK	10	14
	Rough estimation	15	20
	Labels	11	15
	Long years of experience	1	1
Received Formal Training from?[a, c]			
	Krishi Vigyan Kendra	24	96
	NERIWALM	1	4
	Assam Agriculture University	4	16
	Agriculture department	2	8
	Panchayat	1	1
	Organic farming training	1	1
Reason behind not using personal protective equipment[a, d]			
	Heat	37	66
	Discomfort	35	63
	Costly	3	5

[a] Multiple responses allowed
[b] Percentage (%) of farmers who used chemical pesticides ($n = 74$)
[c] Percentage of farmers who had formal training regarding the use of pesticides ($n = 25$)
[d] Percentage of farmers with no protective measures during pesticide use ($n = 56$)

Agriculture Department of Assam, Assam Agriculture University, NERIWALM, Panchayat, and Organic Farming Experts whereas 66.22% ($n = 49$) did not receive any formal training. This data is in line with Suryawanshi and Patil (2016).

16.3.3 Storage of Pesticide and Its Safe Disposal

71.62% of pesticide users stored pesticides at veranda or farm (outside), whereas 28.38% stored in their houses (inside). A similar finding was reported by Suryawanshi and Patil (2016). The present study found that disposal of pesticide packets/bottles/containers was not done properly. This is similar with the studies conducted by Mohanty et al. (2013) and Shrestha et al. (2010). A high number of farmers burned (36%) the pesticide's packets/bottles/containers and buried (36%) in pits. Sa'ed et al. (2010) had also reported that pesticide packets/bottles/containers were not disposed of properly and the majority burned them. Moreover, Singh and Gupta (2009) and Ibitayo (2006) mentioned that most of the farmers reused the empty containers to store drinking water. The unsafe disposal of the pesticide packets poses a greater risk to the common people. This takes place by contamination of soil, surface, and groundwater and also threats to the non-target organisms.

16.3.4 Classification of the Pesticides Used

In this study, 25 types of pesticides were reported by the farmers. These pesticides are classified according to WHO Classification (WHO 2019). 52% belong to WHO toxicity class II (moderately hazardous), 8% belong to class III (slightly hazardous), and 4% belong to class Ib (Highly hazardous) which include Monocrotophos. Monocrotophos is acutely toxic to birds and humans and is also banned in the USA. Organophosphates, carbamates, pyrethroids, and pyrethrins were the most common pesticides applied by the farmers. Through field surveys and informal discussions, it could be concluded that farmers were less aware of banned pesticides. In Table 16.3, commonly used pesticides by the farmers in the present study and their classification are given . A comparative account of pesticide uses in the world, India, and present study is given in Fig. 16.2.

A comparative study of the different classes of pesticides used by farmers across India and the world is shown in Table 16.4. It is found that Ia category pesticides were not used by the farmers in the present study. To gain additional insight, informal discussions were held to know about farmers' knowledge on pesticides and their role in the protection of crops. Farmers stated that stronger pesticide is directly proportional to crop protection and good quality crops are not possible without pesticides. They also consider pesticides as a guarantor for a good harvest. Banned pesticides with deadly effects tend to have a lower cost in markets along with negligence in the execution of regulations against the application of hazardous pesticides (Wesseling et al. 1997; Perez et al. 2015). Cheaper rates made them available to a large group of farmers. Our findings are in line with Yadav et al. (2015).

Table 16.3 Commonly used pesticides and their classification. Here Ib indicates Highly hazardous; II indicates Moderately hazardous; III indicates Slightly hazardous; U indicates Unlikely to pose an acute hazard in normal use; and NC indicates Not classified. (Source: FRAC Code List 2018; Herbicide Classification 2016; IRAC MoA Classification Scheme 2018; WHO 2019)

Commonly used pesticides	Insecticides/fungicides/plant growth hormone/herbicides	Active ingredients	WHO classification	Classification by main groups
Bactinash—200	Bactericide	2-Bromo-2-nitropropane-1,2-diol	NC	Bactericides
Kavach	Fungicide	Chlorothalonil	U	Chloronitriles
V-3	Fungicide	Validamycin	U	Glucoppyranosyl antibiotics
Indofil m-45	Fungicide	Mancozeb	U	Dithiocarbamates and relatives
Anakon	Fungicide	Myclobutanil	II	Triazoles
Ratan	Fungicide	Carbendazim and Mancozeb	U	Benzimidazoles and Dithiocarbamates and relatives
Society	Herbicide	Propaquizafop	U	Herbicides
Cedaar	Herbicide	Glyphosate	III	Herbicides
Wilquat	Herbicide	Paraquat	II	Herbicides
Ustaad	Insecticide	Cypermethrin	II	Pyrethroids and pyrethrins
Profex	Insecticide	Profenofos and Cypermethrin	II	Organophosphates and Pyrethroids and Pyrethrins
Tatafen	Insecticide	Fenvalerate	II	Pyrethroids and Pyrethrins
Chlorpyrifos	Insecticide	Chlorpyrifos	II	Organophosphates
Larvin	Insecticide	Thiodicarb	II	Carbamates
Rogor	Insecticide	Dimethoate	II	Organophosphates
Monocrown	Insecticide	Monocrotophos	Ib	Organophosphates
Celcron	Insecticide	Profenofos	II	Organophosphates
Actara	Insecticide	Thiomethoxam	NC	Neonicotinoids

(continued)

Table 16.3 (continued)

Commonly used pesticides	Insecticides/fungicides/plant growth hormone/herbicides	Active ingredients	WHO classification	Classification by main groups
Cypercid-10	Insecticide	Cypermethrin	II	Pyrethroids and Pyrethrins
Antenna	Insecticide	Acetamiprid	NC	Neonicotinoids
Tricel	Insecticide	Chlorpyrifos	II	Organophosphates
Rogo-30	Insecticide	Dimethoate	II	Organophosphates
Jadu	Insecticide	Trizophos and Deltamethrin	II	Organophosphates and Pyrethroids and Pyrethrins
Kripon	Plant growth Hormone	Ethephon	III	Plant growth Hormones
Vipul	Plant growth hormone	Triacontanol	NC	Plant growth Hormones

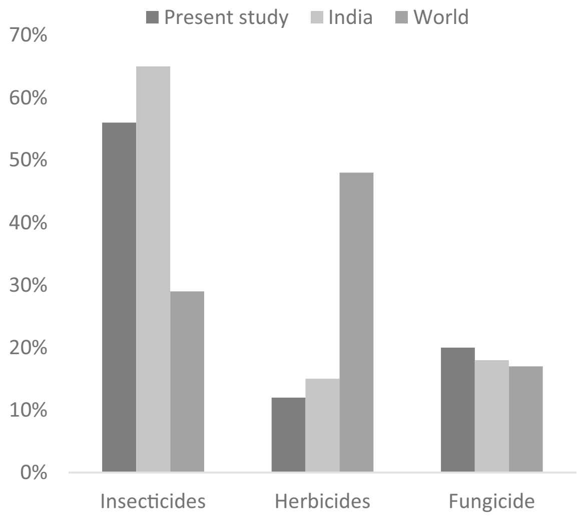

Fig. 16.2 Comparative study of different pesticides use in the world, India and present study. (Source: Abhilash and Singh 2009)

16.3.5 Personal Protective Equipment (PPE), Work Clothing, and Acute Pesticide Poisoning (APP) Symptoms

It is necessary to take proper measures while working in hazardous conditions. It is therefore important to use PPE while handling pesticides. Both safety and work productivity is ensured while using protective measures (Health and Safety Executive 2005; Weigel 2012). Findings of the present study showed 24.32% use protective measures like goggles, masks, gloves whereas 75.68% did not use any protective measures. Similar results were reported by Sekiyama et al. (2007), Damalas et al. (2006), Hashemi et al. (2012) in Iran, Mohanty et al. (2013), and Dey et al. (2013). Table 16.5 shows the percentage of farmers using protective measures and different types of protective measures used by them.

Proper work clothing was used by 64.86% of farmers. Figure 16.3 shows the percentage of farmers with or without work clothing and if they wash their clothes separately after each spray.

Clothing used during the handling of pesticides must be considered contaminated until washed properly (Whitford et al. 2002). It becomes harder to remove pesticide residues with the longer storage time. Proper cleaning of work clothing is equally important to prevent contamination and secondary exposure to farmers and their families (Damalas et al. 2006). The reasons given by 56 farmers without the use of PPE were heat (66%), discomfort (63%), and the high expense of work clothing and PPE (5%) (Table 16.2). India being a subtropical country, heat and humidity also play a prime reason for not using any protective measures. Performing work in hot and humid environmental conditions is more stressful than a comfortable environment. For farmers carrying out heavy labor in hot weather accompanied by unfit clothing hinder free body movement increasing further discomfort (Damalas et al. 2006).

Table 16.4 Comparative study of most used classes of pesticides (in terms of toxicity) in India and abroad. Ia: Extremely hazardous; Ib indicates Highly hazardous; II indicates Moderately hazardous; III indicates Slightly hazardous; U indicates Unlikely to pose an acute hazard in normal use

Name	Location	Most used classes of pesticides (According to descending order)	Commonly used group
Present Study	Sonitpur, Assam, India	Class II Class U Class III Class Ib	Pyrethroids and pyrethrins, Organophosphates, Carbamates, Chloronitriles, Glucoppyranosylantibiotics, Dithiocarbamates and relatives
Hazarika (2011)	Sorbhug Area of Lower Assam, India	Class II Class Ib	Organochlorine, Organophosphate, Carbamate, Synthetic Pyrethrums,
Banerjee et al. (2014)	Burdwan, West Bengal, India	Class II Class Ia Class Ib	Pyrethroids and Pyrethrins, methyl parathion, Neonicotinoids, Organophosphates,
Chitra et al. (2006)	South India	Class II Class Ib Class U Class Ia and Class III	Organophosphate, Carbamate, Pyrethroid, Organochlorine, Triazine, Combination Pesticide
Mattah et al. (2015)	Catchment of Ashaiman of Ghana, Republic of Ghana	Class II Class III Class U	Organophosphates, Pyrethroids Pyrethrins, Azadirachtin
Jallow et al. (2017)	Kuwait	Class II Class III Class Ib Class U	Organophosphate, Pyrethroid, Carbamate, Neonicotinoid, Avermectin, Fenpyroximate, Cyromazine, Bifenazate, , Amitraz, Benzoylurea, Nereistoxin, Pyriproxyfen, Chlorfenapyr, Buprofezin, Phenylpyrazole
Pobhirun and Pinitsoontorn (2019)	Thailand	Class II Class III	Neonicotinoids, Organophosphates, Pyrethroids, Bipyridyl, Avermectin, Triazines

Table 16.5 Protective measures used and its types

Use of protective measure ($n = 74$)		Type of protective measures	
Yes	24.32%	Gloves	61.11%
		Mask	66.66%
		Goggles	61.11%
		Boots	0%
No	75.68%		

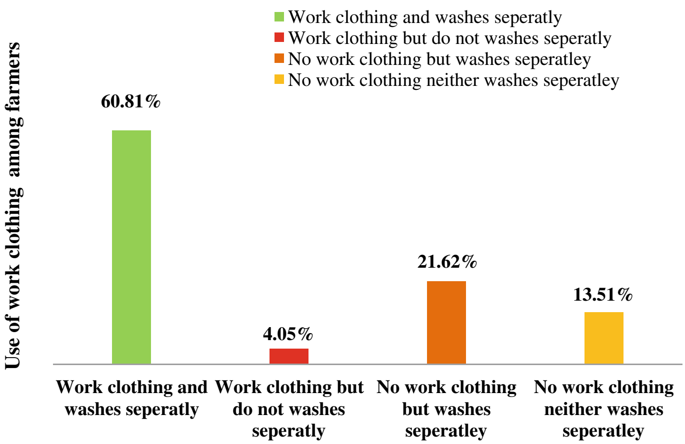

Fig. 16.3 Use of work clothing among the farmers

Jones et al. (2009) had stated that farmers are mostly focused on the higher returns of economic value than their health and safety. They also consider using protective measures to be impractical and expensive. Similar findings were reported by Sam et al. (2008); Sivayoganathan et al. (1995); and Damalas et al. (2006). However, in our study, it was found that some farmers know the importance of protective measures but their negligent behavior has become habitual. Banerjee et al. (2013) mentioned the unconcerned attitude of the farmers and stated that they often open pesticide containers with their mouths and some even taste the same before applying.

The findings of the present study showed self-reported toxicity symptoms like headache, nausea, burning of eyes and hands, shortening of breath, excessive sweating, vision disturbance, and vomiting (Table 16.6). These symptoms were also reported by other researchers from India and abroad (e.g., Chitra et al. 2006, Kumari and Reddy 2013, Suryawanshi and Patil 2016, Jallow et al. 2017, Afshari et al. 2018). Acute Pesticide Poisoning (APP) was reported by a majority of farmers (63.51%) followed by those who sometimes complained of APP (24.32%). 12.16% never

Table 16.6 Symptoms related to pesticide use reported by pesticide using farmers

Symptoms	Count (*n*)	Percentage (%)
1. Headache	52	70.3
2.. Burning of eyes and hands	62	83.8
3. Nausea	44	59.5
4. Vomiting	19	25.7
5. Shortening of breath	14	18.9
6. Vision disturbance	12	16.2
7 Excessive sweating	18	24.3

complained of APP symptoms. In the present study, pesticide spraying is exclusively done by the males but females also complained about APP. Owing to exposure to these chemicals in the fields during pesticide spraying and washing of clothes contaminated with pesticide residues at home might be the reason (Damalas et al. 2006).

16.4 Conclusion

This study indicated that there is an inadequate level of knowledge among farmers which influenced their practices. Personal experiences are more important than abstract knowledge, and thus it is important to bridge the gap between knowledge and practices by making more relevant and interactive models for training for the farmers. Additionally, a continuous program should be designed to change their habit of negligence while spraying/using pesticides. Enforcement mechanisms of current pesticide laws by regulatory authorities need to be strengthened through regular observation and monitoring. Safety agreement at the distributor and farm level is necessary. It is also important to restrict the use and sale of banned and highly hazardous pesticides. Enforcement mechanisms of current pesticide laws, safety agreement at the distributor and farm level, along with strict restrictions on the use of banned and highly hazardous pesticides, are important for the safeguard of human health and the environment.

16.5 Recommendation

As reported in this study, only one-third of the pesticide using farmer population received formal training. This is a matter of serious concern as improper and inadequate knowledge poses potential threats to farmers and their families. Farmers must learn the hazardous health implications associated with pesticides use and handling. The priority should be on designing concrete educational and health-related training programs to lessen pesticide-related risks and protect them. The training authorities should ensure that the farmers are provided with PPE during the training session. Farmers should be taught the use of PPE's, identification and interpretation of color labels on pesticide bottles (Goeb and Lupi 2021), and proper storage and disposal techniques of pesticides packets and bottles. Additionally, the role of policymakers is also crucial. After training sessions, proper monitoring and follow-ups should be organized to evaluate the success rate of the training programs.

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Chapter 17
Laccase Enzyme in Nanoparticle for Pesticide Degradation: A Special Emphasis on Chlorpyrifos Degradation

Anamika Das, Saloni Sachdeva, Vijay Jaswal, and K. N. Yogalakshmi

Abstract Synthetic chemicals were used as pesticides for killing numerous pests. There are various classes in which insecticides are one of the types which are responsible for causing dangerous effect on human beings. Due to their efficacy, these insecticides gained popularity, and easy access has made them popular among farmers. Chlorpyrifos is a type of insecticide having broad spectrum effect which makes it a favourable candidate against numerous pests. When it is being used, it remains in the environment for several years, contaminating the quality of soil and the groundwater. The chlorpyrifos pesticide is used rigorously in farming practices. Chlorpyrifos inhibits acetylcholine esterase enzyme causing convulsion, paralysis and ultimately death. Deleterious effect of the chlorpyrifos pesticide has led researchers to ponder about its efficient and eco-friendly degradation/removal process. Biological method of degradation involves microbes where enzymes play a crucial role in degradation of chlorpyrifos. Laccase is an enzyme having broad substrate specificity and explored for chlorpyrifos degradation in its free and immobilized form. And it has been observed that enzyme immobilized onto a suitable support shows more efficiency than the free enzymes. Moreover, the immobilized enzyme can be reused multiple times. So far, numerous carriers or supports have been reported. However, role of nanoparticles in immobilization is in infancy. Large surface area, eco-friendly nature and inexpensive characteristics may enhance the degradation efficiency by retaining the enzymes intact and enhancing the reusability. This chapter will focus on laccase enzyme, their sources of generation, characteristics and application. Further, the chapter would highlight the application of nanoparticle in pesticide degradation and its role as a carrier for enzyme immobilization. Lastly, the chapter would discuss about the mechanism of action of laccase immobilized nanoparticle in pesticide degradation.

Keywords Pesticide · Chlorpyrifos · Laccase · Degradation · Immobilization · Nanoparticles

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17.1 Introduction

Pesticides are constituents that are utilized to stop or control the proliferation of organisms that are harmful for other biological systems. There are many types of pesticides, but insecticides and rodenticides are acutely dangerous to human health. With introduction of green revolution in India, the consumption of synthetic pesticides tremendously increased from 154 MT to 210,600 MT within the span of 60 years (http://indiaforsafefood.in/farminginindia). Characteristic features including low cost, increased productivity, simplicity in application and widespread availability have made these pesticides popular among farmers. Over the passage of time, these chemical compositions have become inescapable element in current agricultural practices. On a global front, the consumption of pesticides in India is relatively on a lower side that is 0.6 kg/ha when compared to 7 kg/ha in USA and 13 kg/ha in China (OUTLOOK 2014). However, in coming years, industries have procrastinated high growth potential of pesticides in India (CSE 2005). Among the 29 states of India, certain states, namely Uttar Pradesh, Punjab, Maharashtra, Haryana and Rajasthan have been recorded with consumption of 9563 MT, 5810 MT, 4639 MT, 4070 MT and 3527 MT pesticides, respectively. The consumption of monocrotophos has been recorded to be the highest with 10,700 MT followed by acephate, endosulfan and chlorpyrifos with 6400 MT, 5600MT and 5000 MT, respectively (INDIASTAT 2015).

There are a number of ways to classify the pesticides which provides an idea on the chemical nature of the pesticides, their mode of entry and the target organism (Zacharia 2011). The chlorinated hydrocarbons were used extensively during the Second World War (Gupta 2012). Till 1960s, the organochlorine pesticides (OCPs) have been used in agriculture and mosquito control after which their usage has been banned. Characteristic features of OCP include long residual effect and broad-specificity. Also, they are responsible for detrimental effect on physiology of insects by opening sodium channels within nerve cells (Vijverberg et al. 1982). They are persistent in nature which makes it very difficult for the breakdown of the pesticide. DDT, dieldrin, chlordane, mirex, kepone, toxaphene, lindane, methoxychlor, endosulfan and benzene hexachloride are some of the popularly used OCPs. Extended usage of OCPs in huge amount coupled with its characteristics had a serious effect on the environment and health of animals and human beings. Reports have been published to support the fact; OCPs get accumulated in mammals causing severe damage. Preliminary studies conducted by Kalra and Chawla 1981 and Kalra et al. 1994 in Punjab, India, reported accumulation of DDT residues of above 0.05 mg/kg in bovine milk and 0.510 mg/L in breast milk in addition to 0.195 mg/L of BHC residue in breast milk. The OCPs target the central nervous system (CNS), causing convulsions in brain and other signs of neurologic toxicity such as tremor, myoclonic jerking, ataxia, hyperreflexia and paresthesias. These were the main reasons for the ban of OCPs as pesticides. The ban on OCPs leads to the production of new synthetic pesticides.

17.2 Chlorpyrifos

Chlorpyrifos [O,O-diethylO-(3,5,6-trichloro-2-pyridinyl-phosphorothioate] is extensively used against a wide range of insects. Broad-spectrum nature of chlorpyrifos makes it a favourable candidate for wide usage as insecticide, leading to contamination of water and terrestrial ecosystems in abundant array (Wang et al. 2007). It is used against insect pests of major crops which are economically important. It is applied to almost all vegetables and rice crops. Worldwide, chlorpyrifos was the foremost active ingredient to be used in agricultural practices.

17.2.1 Detrimental Effects of Chlorpyrifos

Chlorpyrifos are widely known to cause severe harmful effects. Commonly recognized ill effects of chlorpyrifos include fatality in extreme cases, birth defects, headache, nausea, muscle twitching, convulsions and disorders in the male reproductive system. However, the severity of the effects depended on several factors (Sai et al. 2014). Several reports have been published indicating the presence of chlorpyrifos pesticide in soil which ultimately leaches into the groundwater. With contamination of soil and water resources, these chemicals hold a potential to cause ecological imbalance in the area. A part per million concentrations of chlorpyrifos is able to kill fish population. Numerous beneficial insects such as parasitic wasps, bees and ladybird beetles experience negative impacts due to chlorpyrifos toxicity.

In order to understand harmful influence of organophosphate pesticides on humans, certain factors are taken into consideration such as physicochemical properties associated with pesticides, route and extent of exposure, and rate at which the pesticide retaliate metabolic pathways. In addition to this, health status of the human at risk also holds a significant position in evaluating the severity (Karalliedde et al. 2003). There are reports of abnormal cell division, delayed emergence of seedlings and fruit deformities in the plant (Cox 1995).

17.2.2 Degradation of Chlorpyrifos

Considering the harmful effects of chlorpyrifos pesticide on the environment and living beings, there is an alarming need for its degradation or removal from the environment. Scientists have reported various methods of pesticide degradation. Figure 17.1 illustrates a detailed mechanism of organophosphate pesticides when exposed in environment. According to Pimentel 1995, when a certain amount of pesticide is applied, only 0.1% reaches the target pest and rest of the portion goes off site. The off sites include atmosphere, soil and ground water where they reach by volatilization, leaching and run off and causing alarming situations. It is well

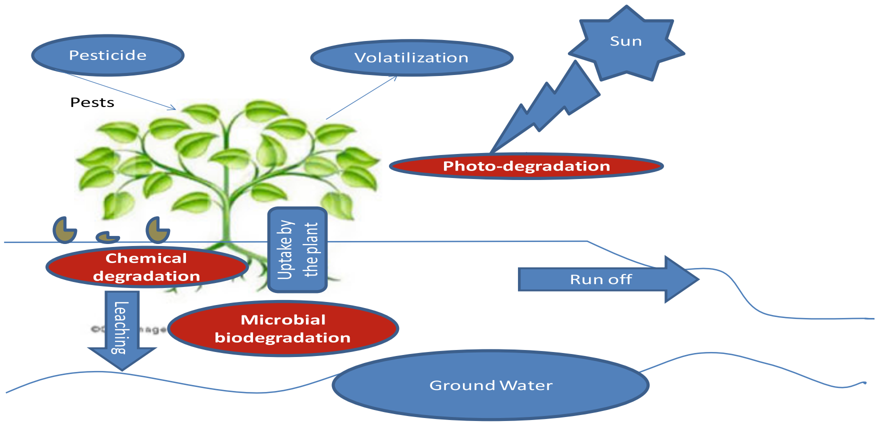

Fig. 17.1 Mechanism of pesticides within different spheres of environment. *Source* http://extension.missouri.edu/publications/DisplayPrinterFriendlyPub.aspx?P=G7520

established that these chemicals persist in the soil environment for years and, hence, degrade the soil and groundwater quality. The fate of pesticide follows three stages which include degradation, adsorption and transfer. Degradation can be done by three types of methods such as photodegradation, chemical degradation and microbial degradation. Photodegradation is caused by sunlight, chemical degradation is caused by the chemicals present in the soil and microbes (bacteria and fungi) are the ones that play a role in microbial degradation. However, no method has achieved sustained results so far, thereby increasing the thirst of new research.

Given this background, the chapter is predominantly focussed on chlorpyrifos pesticide.

17.3 Biological Degradation of Chlorpyrifos Pesticide

Biological degradation of pesticides by native environmental microorganisms is more popular due to its multiple advantages such as eco-friendly, economical, and ability to degrade a wide range of chemicals, causing less harm to the environment unlike other chemical, physical and thermal methods that produce harmful intermediate compounds and are commonly put to service (Finley et al. 2010). Also, these methods are too expensive for the clean-up as compared to biological degradation.

17.3.1 Degradation of **Chlorpyrifos Using Microorganisms**

This section of the chapter mainly focuses on microbial degradation of chlorpyrifos. Certain microorganisms possess an ability to completely metabolize organic compounds (including aromatic as well as aliphatic), and thus, decreasing their concentration in the environment (Bhagobaty et al. 2006). Table 17.1 provides a comprehensive understanding of different microbial communities and their efficacy to remove pesticides from the contaminated surroundings. On comparing different

Table 17.1 List of microorganisms involved in chlorpyrifos degradation

S. no	Name of the microorganism	Incubation period	Removal efficiency	References
1	*Phanerochaete chrysosporium*	18 days	27.5%	Bumpus et al. (1993)
2	*Trichoderma viride and Aspergillus niger*	14 days	95.7% and 72.3%	Mukherjee and Gopal (1996)
3	*Flavobacterium* sp. ATCC 27,551	24 h	100%	Mallick et al. (1999)
4	*Arthrobacter* sp.	48 h	10 mg L^{-1}	Mallick et al. (1999)
5	*Hypholoma fasciculare* and *Coriolus versicolor*	42 days	33%	Bending et al. (2002)
6	*Trichoderma* Y	7 days	88.53%	Liu et al. (2002)
7	*A. faecalis* DSP3	18 days	76.2%	Yang et al. (2005)
8	*Stenotrophomonas sp.* YC-1	24 h	100%	Yang et al. (2006)
9	*Klebsiella sp.*	4 days	92%	Ghanem et al. (2007)
10	*Serratia* sp.	7 days	100%	Xu et al. (2007)
11	*Verticillium sp.* DSP	3 days	50%	Fang et al. (2008)
12	*Stenotrophomonas sp.* DSP-4	24 h	100%	Li et al. (2008)
13	*Pseudomonas fluorescence*, *Bacillus subtilis*, *Bacillus cereus*, *Klebsiella* species, *Brucella melitensis*, *Serratia marcescens* and *Pseudomonas aeroginosa*,	20 days	75–87%	Lakshmi et al. (2008)
14	*Bacillus* and *Pseudomonas*	7 days	75%	Madhuri and Rangaswamy (2009)
15	*Cyanobacterium synechocystis sp. strain PUPCCC 64*	24 h	75%	Singh et al. (2011)
16	*Cladosporium cladosporioides Hu-01*	6 days	100%	Chen et al. (2012)

studies conducted worldwide, *Stenotrophomonas sp.* (specifically *Stenotrophomonas sp.* YC-1 and *Stenotrophomonas sp.* DSP-4) has been proved to be more effective in break down of chlorpyrifos within 24 h incubation period (Yang et al. 2006; Li et al. 2008).

In the course of bioremediation of chlorpyrifos, the parent compound breaks down into numerous metabolites depending on the environmental factors and type of microbial enzyme used. 3,5,6-trichloropyridinol (TCP) is considered to be one of the primary metabolites as reported by Thiegs, (1966) using $^{36}Cl^{-}$ labelled CP in soil samples. Similarly, Bidlack in (1979) successfully identified a secondary metabolite TMP (3,5,6-trichloro-2 methoxy pyridine) from the contaminated soil samples. Published literature so far provide an exhaustive list of metabolites (Diethylthiophosphate, 1, 2 Benzenedicarboxylic acid, oxon, 2, 4-bis (1, 1 dimethylethyl) phenol etc.) that are produced during bioremediation process. A study conducted by Singh et al. in (2004) revealed that diethylthiophosphate formed during hydrolysis process can be utilized as a source of energy and growth by *Entrobacter* strain B-14. For the very first time, Xu et al. in (2008) reported complete mineralization of chlorpyrifos by a bacterial strain *Paracoccus* sp. without the formation of primary and secondary metabolites.

17.3.2 Degradation of **Chlorpyrifos** **Using** **Enzymes**

Enzymes which are able to break phosphotriester bond are known as phopshotriesterase and they are involved in the breakdown process of OPs as a whole. Collectively, organophosphorus hydrolase (OPH), paraoxonase 1 (PON1), diisopropylfluorophosphatase (DFP), organophosphorus acid anhydrolase (OPAA) and methyl parathion hydrolase (MPH) comprise phosphotriesterase (Bigley and Raushel 2013). Although the subcategories of the enzyme phosphotriesterase share certain common features, they differ remarkably in their three-dimension structure, catalytic mechanism and protein sequence. The different types of enzymes involved in pesticide degradation are described below.

17.3.2.1 Organophosphorus *A*cid *A*nhydrolase (EC 3.*1.8.2*)

OPAA is particularly involved in degeneration of compounds containing organophosphates. Moreover, the structure of these enzymes shows decent homology with amino-peptidase P in *E. coli* and human prolidase, i.e. 30–22%, respectively (Cheng et al. 1995). Through different studies it has been established that this enzyme loses its activity in harsher conditions such as organic solvents, long storage and at high temperature.

17.3.2.2 Paraoxonase (EC 3.*1.8.1*)

PON1 was named after enzymes that possess ability to metabolize paraoxon which is basically an oxygen analogue of parathion. However, several studies have confirmed that paraoxonase can also breakdown chlorpyrifos oxons and are found in all mammalian species along with serum of reptiles, birds, fishes and insects. Serum PON1 is one of the subtypes of the three subtypes of paraoxonase reported (Li et al. 2003). Based on this understanding, different studies conducted by researchers concluded that this enzyme protects human from low doses of organophosphate pesticides.

17.3.2.3 Diisopropyl-*F*luorophosphatase (EC 3.*1.8.2*)

DFP are the enzymes that act by hydrolysing the P–F bond and is a calcium-dependent enzyme (Elias et al. 2013). This enzyme is isolated from the brain and ganglion of *Loligo vulgaris* and known as squid-type DFPase (Latifi et al. 2015). Despite its advantage in remediating organophosphates, researchers do not show enough interest because its intracellular production is slow and affects the rate of metabolism in endemic species (Yang et al. 2008).

17.3.2.4 Methyl *P*arathion *H*ydrolase (EC 3.*1.8.1*)

This enzyme generally catalyses the organophosphate, methyl parathion but explored for other organophosphates also. A study conducted in 2015 concluded that *Stenotrophomonas* sp. G1 is capable enough to degrade organophosphate pesticides (Deng et al. 2015). They reported that the species is able to degrade 63% of chlorpyrifos concentration. Degradation occurred due to the intracellular presence of MPH.

17.3.2.5 Organophosphorus *H*ydrolase (EC 8.*1.3.1*)

OPH is one of the most frequently and widely accepted enzymes with an intention to degrade organophosphate. The enzyme contains two Zn^{2+} or Co^{2+} ions per subunit as it is a metal-dependent enzyme. Catalytic activity is also exhibited by the enzyme where Zn^{2+} or Co^{2+} gets replaced by Cd^{2+}, Mn^{2+} or Ni^{2+}. Highest catalytic activity with respect to phosphotriesters is being observed by enzyme containing Co^{2+}. Unlike MPH, OPH holds potential to hydrolyse three different bonds, i.e. P–S, P–O and P–F. However, lowest specificity was observed on P–S bond because phosphotriesters are more prone to hydrolysis than the diesters. Toxicity of organophosphates gets reduced to several magnitudes when hydrolysed using OPH (Sogorb et al. 2004).

This enzyme can be extracted from various microorganisms namely *Arthrobacter* sp., *Flavobacterium* sp., and *Pseudomonas putida.* A study by Singh et al. in

(2004) investigated chlorpyrifos degradation by the novel phosphotriesterase enzyme extracted from *Enterobacter* strain B-14. In the study, they have reported that enzyme is efficient in degrading chlorpyrifos concentration of 35 mg/L when supplied without any other carbon source in 24 h of incubation.

17.3.3 Laccase as a Protagonist in Remediation

Laccases (benzenediol: oxygen oxidoreductases) were first identified in 1883 by Yoshida, from Japanese lacquer tree (*Rhus vernicifera*) exudates (Thurston 1994). These are hydrolytic enzymes that are involved in degradation of lignocellulosic biomass into its constituents. The enzyme has gained considerable interest in industrial and environment biotechnology, due to their broad substrate specificity and higher stability in the natural environment. It does not require any low molecular weight cofactor because their co-substrate O_2 is usually present in the environment (Couto and Herrera 2006). Most of the laccase enzymes are extracellular. Due to this, the purification procedures for laccase enzyme is very easy.

Source: They are widely distributed in fungi such as *Pleurotus, Pholiata, Polyporus versicolor, Podospora anserina, Aspergillus nidulans*, *Neurospora crassa,* white-rot fungi and *Pyricularia oryzae* (Gardiol et al. 1998). Whereas, bacterial species including *Bacillus subtilis, Marinomonas mediterranea, Azospirillum lipoferumand and Streptomyces griseus* have been reported to contain laccase (Givaudan et al. 1993; Endo et al. 2002). Other than micro-organisms, *Rhus succedanea, Rhus vernicifera, Prunus persica and Lactarius piperatusy* are the examples of higher plants that are the sources for laccase enzyme.

Structure: The enzyme laccase belongs to the largest subcategory of multi-copper oxidases that make use of their redox abilities acquired by copper ions to oxidize aromatic compounds, with simultaneous molecular oxygen reduction to water (Majeau et al. 2010). Laccases are polyphenol oxidases that play a vital function in regulating oxidation processes of numerous aromatic compounds, specifically those compounds with electron-donating groups, such as phenols (–OH) and anilines (–NH), using molecular oxygen as an electron acceptor. Furthermore, laccase is ubiquitous in nature. Its structure can be monomeric, dimeric and tetrameric, and each monomer consists of four atoms (Type 1, 2 and 3) of copper in its catalytic site. Type 1 copper present in laccase facilitates the enzyme to perform oxidation and concurrently imparts blue colour to the enzyme. Each copper centre in the laccase enzyme is attached to the imidazole sidechains of histidine.

Mechanism: The oxidation mechanisms carried out by laccases involves chemically active radicals of molecular oxygen that readily oxidize aromatic and non-aromatic compounds. Formation of aryloxy radical was observed when phenolic substrates were oxidized by laccase which is an active species to convert into quinine during oxidation at the second stage. Depending on the substrate and various environmental parameters, the quinone intermediates form soluble or insoluble coloured oligomers spontaneously by reacting with one another.

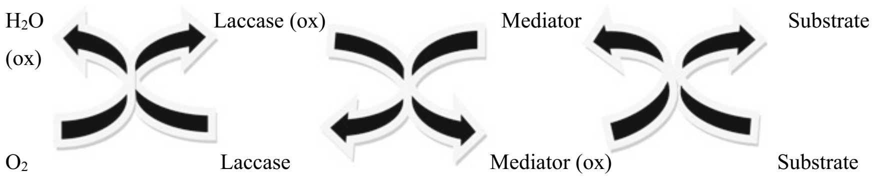

Fig. 17.2 Catalytic cycle of laccase mediator system (Baiocco et al. 2003)

Redox potential of laccase enzyme is a barrier towards its non-specificity of substrates. It ranges between 0.5 and 0.8 V. A study conducted in 2010 asserted that pH and enzyme inhibitors regulate the enzymatic activity (Stoilova et al. 2010). However, non-phenolic substrates can be metabolized using redox mediators. Like in case of pesticides, the degradation can be enhanced using redox mediators, viz. ABTS, HBT and veratryl alcohol (Kunamneni et al. 2007). The redox mediators are small molecule which oxidizes a non-substrate compound via a non-enzymatic reaction by diffusing out the catalytic pocket, when it gets oxidized by the enzyme laccase. Figure 17.2 precisely illustrates the catalytic cycle regulated by laccases (Baiocco et al. 2003). Redox meditators employed in the system are compounds that can be readily reduced to lower molecular weight. In laccase mediator system (LMS), the reaction initiates with redox mediators that possess high redox potential, by generating intermediates which subsequently oxidizes the pesticides with a greater effect. Though this mechanism has been studied before for several years, it was not fully understood.

17.3.4 Pesticide **D***egradation* **U***sing* **L***accase*

Combination of pesticides along with glyphosate degradation by laccase with different redox mediators were studied by Pizzul et al. (2009). They have found out that, different mediators affect the degradation variably. Laccase in the presence of ABTS showed 40.9% degradation of glyphosate after 24 h of incubation. Further, addition of Tween80 together with Mn^{2+} to the reaction mixture, the degradation reached 62.8%. Later, a combination of all the three mediators was used (ABTS, Mn^{2+} and Tween 80) along with laccase where 90.1% removal of glyphosate was observed. A degradation ranging from 20 to 100% was observed when 22 different pesticides were subjected to similar enzyme reaction mixture. Zhao et al. (2010) observed that dichlorodiphenyltrichloroethane (DDT), an insecticide, has been effectively degraded by laccase showing 47–52% degradation after 25 days of enzymatic treatment. Jing et al. (2011) studied degradation of dimethoate, chlorpyrifos, trichlorfon and parathion-pyridazine pesticides using laccase with different inductive agents such as ABTS, RB-bright blue and o-toluidine. Published literature so far indicates that ABTS is one of the best suited inductive agents as the rest affected the laccase production. Pesticide degradation is always influenced by pH and temperature. The best temperature for the degradation by laccase enzyme was identified as 25 °C. However, pH varied with pesticides. A distinct pH value of 8.0 and 10.0 is required for degradation of trichlorfon and chlorpyrifos, respectively. Additionally, parathion and dimethoate also require pH value of 10 for degradation.

17.3.5 Drawbacks of **Free E***nzyme*

Although enzymes show very good degradation potential, enzymes in free form suffers from certain drawbacks such as storage instability, sensitivity at high temperatures and pH which result in loss of enzyme activity, reusability and recovery problems. Enzymatic degradation has a huge potential on chlorpyrifos degradation, but the process of isolation and purification is extremely costly. Due to non-reusability of free enzyme, the cost associated with the usage of free enzyme is higher. As a result, enzymes in free form are not desirable to the industries. In order to overpower the limitations offered by free enzymes, scientists attempted for immobilizing the enzyme on to a support medium. Such support systems can help in repeated use of enzymes (Munnecke 1977).

17.4 Enzyme Immobilization

Enzyme immobilization is a technique wherein enzymes are confined to a specific region onto/within a carrier material, such that catalytic attributes do not change. The key feature associated with this method is to enhance steady operational conditions including continuous reuse of the enzymes (Brena and Batista-Viera 2006).

17.4.1 Types of Immobilization

There are two broad categories into which immobilized enzymes can be classified: irreversible and reversible methods (Gupta and Mattiasson 1992).

17.4.1.1 Irreversible *M*ethod of *E*nzyme *I*mmobilization

The irreversible method of immobilization involves adherence of biocatalysts to a solid support in such a way that the catalytic activity and structure of enzyme are not altered. It involves four types of methods by which enzymes are immobilized, viz. entrapment, micro-encapsulation, covalent coupling and cross-linking. Figure 17.3 depicts the irreversible methods of enzyme immobilization.

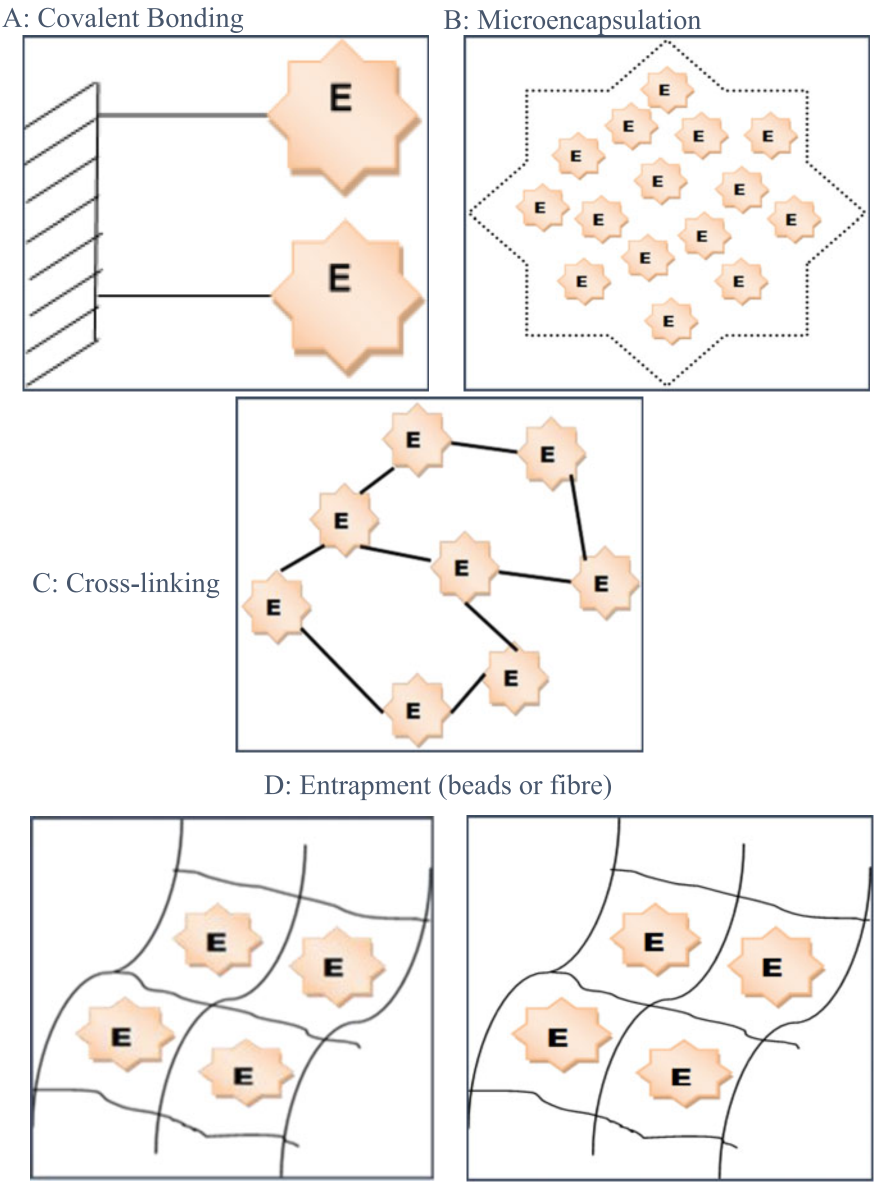

Fig. 17.3 Enzyme immobilization—irreversible methods (Brena and Batista-Viera 2006)

Covalent *B*onding

The property of enzymes to form covalent bonds with the specific carrier material is exploited in this method. Side chain (histidine, aspartic acid and arginine) and functional groups (phenolic hydroxyl, imidazole and indolyl) of the enzyme execute peculiar function of attachment to carrier material and extent of reactivity, respectively. Enzyme immobilization via covalent bonding is considered to be highly stable and thereby the most frequently used method. Once the enzymes are successfully adhered to the matrix, the synthesized matter can also be operated in solution due to the formation of stable bonds (Guisan 2006). Additionally, the process ensures there is no contamination and enzyme leakage in the reaction mixture. Contrary, a study conducted by Brena and Batista-Viera (2006) reported reduced catalytic activity during enzyme immobilization by covalent bonding and thus, reducing the chances of intended results. Support material such as mesoporous silica, chitosan etc. are extensively used in covalent bonding as it enhances half-life of the enzyme along with thermal stability (Ispas et al. 2009). Coupling reaction can also contribute to enhancement of enzyme activity when substrate analogues are used. A study conducted by Fu et al. (2011) observed that enzyme activity and stability can be enhanced by using peptide modified surfaces.

Micro-*E*ncapsulation

Micro-encapsulation is a technique that entraps and immobilize enzymes within semi-permeable and spherical membrane.

Cross-*L*inking

Unlike other immobilization techniques, cross-linking method do not necessiate support material and thus also called as carrier-free immobilization method (Honda et al. 2006). In this process of entrapping enzymes, multifunctional reagents are used that allows enzyme molecules to form three-dimensional aggregates via covalent bonding. The coupling agents used for cross-linking has almost negligible molecular weight, therefore the fabricated biocatalyst composed has 100% weight of the desired protein (Schoevaart et al. 2004). Also, the technique ensures that functional and structural attributes remain intact during the reaction. Widely accepted bi-/multifunctional reagents include glutaraldehyde, bisdiazobenzidine and hexamethylene diisocyanate. Since glutaraldehyde is water soluble, it is preferred over other reagents as it enables enzymes to form stable inter and intra-covalent bonds.

Entrapment

Entrapment is a technique that involves incarceration of enzymes by forming bonds (covalent or non-covalent) with gels or fibres. Since, the enzymes are enclosed within the carrier material with no chemical bonding between the gels or fibres it impedes the diffusion process. The enzyme is not bonded to the surface of the material in this technique of immobilization but distributed onto the lattice structure of the material used for immobilization, which allows substrate and product to pass while enzymes remain within (Klotzbach et al. 2008). A great concern for this method of immobilization includes the issue of enzyme leakage. However, this method of immobilization does not modify the native structure of enzyme (Sassolas et al. 2012). Sodium alginate is one such material used for entrapment purpose. Hybrid carriers such as alginate–gelatin–calcium bring forth effective entrapment of enzyme preventing leakage and providing an increased mechanical stability. Chitosan, carrageenan and alginate are also some of the materials used for entrapment.

17.4.1.2 Reversible Method of Enzyme Immobilization

This practice of enzyme immobilization involves swift attachment and detachment of the desired enzymes from the carrier material. The reversible method of enzyme immobilization involves five types of process. Figure 17.4 depicts the schematic view of reversible methods used in immobilization of enzymes.

Adsorption

The fundamental principle behind adsorption process involves non-covalent and weak bonding between the target enzyme and surface of the carrier material (Flickinger and Drew 1999). Aminoacylase adsorbed to a DEAE-Sephadex is the first procedure in industry which involved immobilized enzyme for continuous resolution of amino acids.

Chelation

This process is also known as metal binding. Here, without prior derivatization of activated support, the transition metal compounds such as titanium and zirconium (Kennedy and Cabral 1985) were used to activate the surface of support. Chelate formation takes place and direct coupling of enzyme occurs. Thereby, chelation or metal binding method is widely accepted method to immobilize enzymes in research, industries and especially in chromatography techniques. It involves safety issues and is reasonably expensive, so this method is not popular in industries.

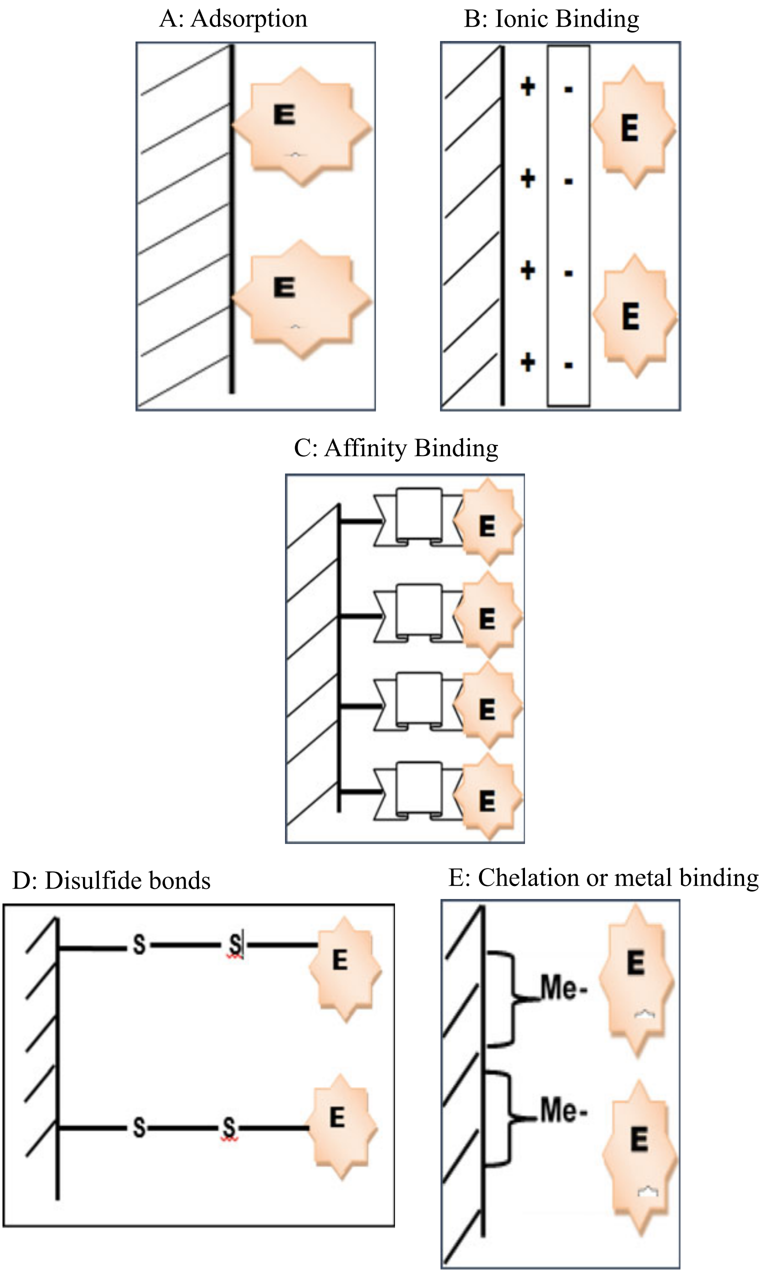

Fig. 17.4 Enzyme immobilization—reversible methods (Brena and Batista-Viera 2006)

Disulphide *B*ond

This particular method intends to form disufide (–S-S–) linkages between the enzyme and support matrix. The exposed nonessential thiol groups (SH) present in the enzyme is allowed to bond with disulphide oxides present on the surface of the support in a stable environment (Ovsejevi et al. 2013). In order to reverse the linkage between the thiol-reactive support and enzyme, surplus amount of thiol groups having low molecular weight such as dithiothreitol can be incorporated (Carlssonet al. 1998).

Ionic *B*onding

It involves the binding of enzymes to the support material by salt linkages. In chromatography, the protein–ligand interaction principles were the basis of this process of enzyme immobilization. This method is the reversible method of immobilization, and in ion exchangers, it was used for the first time (Sharp et al. 1969).

Affinity *B*inding

Biomolecules are assumed to have affinity towards certain specific substances. This property of biomolecules is exploited in affinity binding techniques, where particular enzymes is complemented against explicit region in the antigen. There are two ways by which affinity binding can be achieved between enzyme and support. One way is that, for the target enzyme, the support needs to be pre-coupled to an affinity ligand, or an entity having affinity for support should be conjugated to the enzyme (Datta et al. 2013).

17.4.2 Carriers/Supports for Immobilization

Carriers are support system required for holding the enzymes on its surface during the process of immobilization and play a crucial role in regulating performance of enzymes immobilized. Depending on the applicability, distinct category of matrix can be used. A good support system will always improve the enzyme immobilization efficiency.

An ideal carrier should possess properties such as hydrophilicity, rigidity, easy retrieval of enzyme, compatibility with biological material and economical (Buchholz and Klein 1987). Based on the chemical conformation, the carrier materials can be categorized into organic and inorganic. Table 17.2 summarizes the various properties of organic and inorganic carriers used for immobilization.

Accomplished immobilized enzyme systems are assessed by physical attributes of the matrix such as protruding actions, mean particle diameter, mechanical strength and compression behaviour (Guisan 2006). The capacity for binding of enzymes to

Table 17.2 Properties of inorganic and organic support system

S. no	Inorganic support system (ISS)	Organic support system (OSS)
1	Non-porous metal and its oxides have less binding surfaces	Natural OSS carbohydrate is cost effective and widely available
2	Defined porous materials like silica are expensive and unstable in alkaline conditions	Synthetic OSS are compatible with almost all enzymatic processes
3	Thermally stable	The gel structures are less stable
4	Highly resistant against microbial attack	Inertness against microbial attack
5	Can be possibly regenerated by single pyrolysis process	In chemical binding or adsorption of cells, OSS can bind more cells than ISS

the support material gets critically affected by the dimension of particles and pores over the entire surface area. Though, non-porous support materials are associated with very low enzyme loading capabilities but provides lesser diffusional constrains. Due to these, the porous support materials are generally preferred over them as they have high surface area, allowing more enzyme loading. Although inorganic carriers show minor degradation when subjected to different physical, chemical and biological agents, organic carriers are preferred in industries because they have more binding surfaces. In context with organic matrix, higher the hydrophilic character, higher will be the enzymatic activity (Gemeiner 1992).

17.4.2.1 Classification of *C*arriers

The materials used for the immobilization of enzymes can be divided depending on the origin of materials and also on the basis of their mode of interaction with enzymes. On the basis of their origin, they can be classified as inorganic materials and organic polymers. Organic is further divided into natural polymers and synthetic polymers. Figure 17.5 depicts the origin-based categorization of different carriers.

17.4.2.2 Role of *I*mmobilized *E*nzymes and *W*hole *C*ell in *D*egradation

Researchers have studied the role of immobilized enzyme and whole cell on degradation of pollutants, which indicates that immobilized enzymes are efficacious because of their potential of reusability. Further, their slower contact with the substrate (pesticide) facilitates degradation process (Vijayalakshmi and Usha 2012). It was reported that immobilized cells of recombinant strain of *Escherichia coli* possessed roughly twice detoxification rate when as compared with free enzymes for organophosphate coumaphos pesticide. Moreover, the study demonstrated that fabricated cells maintained their catalytic activity and mechanical stability for over four months. A fluorescent *Pseudomonas* species immobilized in sodium alginate showed 83.2% degradation of catechol when compared to free cells (82.2%) (Tewari and Malviya 2002).

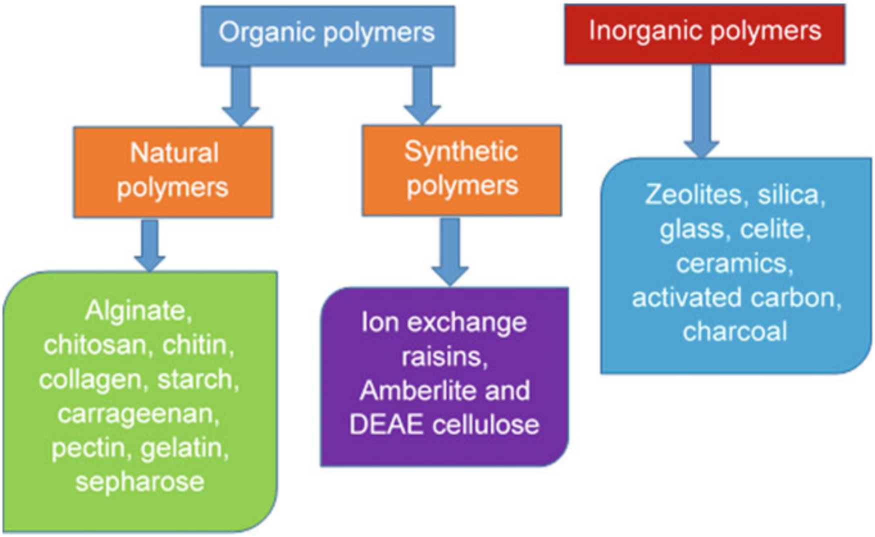

Fig. 17.5 Origin based classification of support materials

Pradeep and Subbaiah (2015) studied chlorpyrifos degradation using *Pseudomonas putida* along with Ca-alginate beads. They observed that at the end of the 50th cycle, immobilized cells showed 65% chlorpyrifos degradation. In the same study, 100% degradation was observed for chlorpyrifos concentration of 2 mg/L, while in case of 10 mg/L of pesticide concentration, 98% degradation was achieved.

A study conducted by Xie et al. in (2010) identified and immobilized the enzyme isolated from the fungus *Fusarium* and studied its efficiency to degrade chlorpyrifos. The results showed that the immobilized enzyme can withstand harsher conditions than the free extract of enzyme. The immobilized enzyme showed a loss in its activity after three repeated uses and retained an overall activity of 69.4%. Liu et al. (2016) reported that laccase immobilized on the surface of engineered cells of *Pseudomonas putida* has efficiently degraded the total chlorpyrifos concentration. In soil slurry, chlorpyrifos degradation using laccase immobilized on sodium alginate was performed by Wang et al. (2016) at 25 °C and shaking speed of 120 rpm. 70% of chlorpyrifos degradation was successfully achieved after an incubation of 48 h. Maximum rate of degradation was observed, when 100 mg/mL of chlorpyrifos was present in the reaction mixture, but it significantly reduced when concentration reached 200 mg/mL. High chlorpyrifos concentration might have inhibited the catalytic function of laccase.

Though immobilization was achieved using different types of carrier material, still the technology could not be successfully transferred to the field due to certain problems and lacunas. With the objective to fill the lacunas, researchers began to explore more efficient support systems. Nanoparticles came into framework of research due to its several advantages such as high surface area to volume ratio, small size and various other properties. Further review will focus on nanomaterials as potential carriers for enzyme immobilization.

17.4.3 Nanoparticles as an Efficient Carrier

Nanotechnology is an upcoming field with a potential for providing ample solution to combat the environmental problems at the nano-scale. The prime feature associated with nanoparticles is its greater surface area to volume ratio; thereby, they increase the space for its application in various fields like biomedicine, pharmaceuticals, cosmetics and environment. In particular to enzyme immobilization, nanoparticles as support material offers significant decrease in mass transfer resistance and diffusional limitations along with enhanced enzyme loading capability (Hwang and Gu 2013). Additionally, nanoparticles are considered to improve stability and functioning of the immobilized enzymes as they do not interfere with tertiary structure of protein. These particles can readily diffuse into and out of macromolecular matrix and overpower the limitation of diffusion associated with other micro or macro-scale particles. In comparison to free enzymes, enzymes attached onto nanoparticles follow Brownian movement in aqueous solution which increases the efficiency.

According to the several reports, the most widely used nanoparticles for enzyme immobilization are porous nanoparticles, metal nanoparticles, polymeric nanoparticles, metal oxide nanoparticles and magnetic nanoparticles. Enzymatic immobilization has been performed with enzymes like lysozyme, glucose oxidase, amino-peptidase and alcohol dehydrogenase on Au and Ag nanoparticles.

Catalytic efficiencies were remarkably high for the immobilized enzymes *Candida antarctica* lipase B derived from *S. Carlsberg* using silica nanoparticles (Cruz et al. 2009). For paraoxon sensing, the acetylcholinesterase enzyme was immobilized on iron oxide/silica. Later, the same enzyme acetylcholinesterase was tried on nickel nanoparticles which showed high detection sensitivity for organophosphate pesticide (Ganesana et al. 2011). The amino-functionalized $Fe_3O_4@SiO_2$ nanoparticles were used to construct glucose biosensor where ferrocene monocarboxylic acid is covalently bonded to nanoparticles as the building block of biosensor. When glucose is added to the medium, the steady-state current of the biosensor reached 95% within 10 s. According to Ahmad and Sardar (2015), the enzyme immobilized on TiO_2 nanoparticles showed accelerated efficacy in comparison with free enzymes. In addition to this, other significant understanding includes that the enzyme in its soluble form showed reduced stability at higher temperature than the immobilized counterpart. Numerous nanoparticles were prepared using different elements such as silver, gold, copper, silica, carbon and iron. But iron nanoparticles possess an additional advantage of easy separation and low cost to be used as a support carrier.

17.5 Enzyme-Immobilized Carriers in Organic Pollutant Degradation

An attempt was made to immobilize α-amylase enzyme on magnetic poly (2-hydroxyethyl methacrylate-N-methacryloyl-(l)-phenylalanine) nanoparticles (Uygun et al. 2012). The particles showed increased substrate affinity and high specific activity of 85% even after 10 times of reuse. In another study, Khoshnevisan et al. (2011) obtained very less activity of the immobilized cellulase on magnetic nanoparticles. Temperature influenced the activity of enzymes. Therefore, with increase in temperature to 80 °C, the enzymatic activity was also enhanced by 0.1 unit (μmol/min mL).

Azo dyes such as azophloxine and Procion Red MX-5B are of deleterious nature in the native environment. Wang et al. (2013) used glutaraldehyde coupling to encapsulate laccase enzyme with Fe_3O_4/SiO_2 nanoparticles in their investigation. The results of the study showed that 80% of the dye was remediated using the constructed composite within 24 h. 95% (0.02 mmol L^{-1}) of Rhodamine B (RhB) was removed within 15 min due to catalysis of reaction by the ultrasound assisted breakdown of H_2O_2 using Fe_3O_4 MNPs, with specific consideration of pH and temperature of 5.0 and 55 °C, respectively. Wang et al. in (2010) evaluated the enzymatic activity of two different systems that showed 37.6 folds increase in ultrasonic US-H_2O_2 and 6.5-folds increase in catalytic H_2O_2–Fe_3O_4. Another successful study was conducted in 2013, where chitosan nanoparticles loaded with laccase enzyme were immobilized by using activated glass beads. The setup assisted laccase enzyme to act on the industrial dyes and hence remediating it. Even after prolonged durations, around 98% of the enzymatic activity was sustained (Sadighi and Faramarzi 2013). Other dyes such as phenol red, acid blue and reactive red 195, were also decolorized using magnetic iron nanoparticles and laccase enzyme (Jořenek and Zajoncová 2015).

A study conducted in 2013, used nano-porous silica beads with laccase enzyme to degrade 2,4-dinitrophenol. The results of the study concluded that within the first 12 h of the incubation period, the concentration of 2,4-DNP was reduced by 90%. Moreover, the structural and functional stability was maintained for more than 30 days of storage (Dehghanifard et al. 2013). Likewise, degradation rate of phenol in cooking waste water was two-fold higher for immobilized laccase. Even after repeated use of fabricated nanoparticles, functioning of the enzyme laccase was conserved by 71.3% (Wang et al. 2012). On the other hand, manganese peroxidase is immobilized on the nanoclay and studied for the degradation of aromatic compounds. The immobilized enzyme degraded pyrene (>86%), anthracene (>65%), fluoranthene (<15.2%) and phenanthrene (<8.6%) individually and in mixture. PAHs degradation was achieved in soil treated with immobilized MnP at optimum temperature and pH. Daumann et al. in (2014) isolated glycerophosphodiesterase enzyme from *Enterobacter aerogenes* to evaluate its role in organophosphate degradation. The enzyme was exposed to the carrier substrate bis(4-nitrophenyl)phosphate (BPNPP) for two different incubation period. First set of reaction mixture was assessed immediately after the immobilization that resulted in 3.55 μmol mg^{-1} min^{-1} specific activity. Whereas, the second set of reaction mixture was assessed after 1 week, resulting in negligible decrease in specific activity. Collectively, the study inferred that enzymatic activity was consistent even after 4 months, indicating the sustained activity of the GpdQ immobilized enzyme after multiple cycles and long storage period (Daumann et al. 2014).

Das et al. (2020) studied the effect of laccase immobilized magnetic iron nanoparticles in degrading chlorpyrifos under field conditions. A column with soil spiked with chlorpyrifos pesticide and laccase immobilized magnetic iron nanoparticles (on the subsurface) was designed to simulate the conditions of an agricultural field. The control column showed more leaching of chlorpyrifos as compared to column containing laccase immobilized magnetic iron nanoparticles. The sorption coefficient (Kd) value obtained for control and laccase immobilized magnetic iron nanoparticles containing column were around 21.6–112.3 L/kg, respectively, indicating the alteration of Kd values of soil by laccase immobilized magnetic iron nanoparticles. Higher the Kd value, lesser will be the leaching potential. Chitosan used for coating enzymes and soil organic matter resulted in the adsorption of chlorpyrifos. Batch studies conducted by Das et al. (2017) showed 99% chlorpyrifos degradation at pH 7 and 60 °C within 12 h of incubation with laccase immobilized magnetic iron nanoparticles.

17.6 Conclusions

The insight attained from the literature review indicated that pesticide usage since green revolution has created a havoc in the environment, ultimately affecting the living beings. Organophosphates are most commonly used pesticide after the ban on OCPs. Chlorpyrifos is the most commonly used pesticide among organophosphate pesticides because they are applied on numerous vegetables and crops for the purpose of pest control. Microbial remediation, an economical and eco-friendly method was considered to be a most suitable method for chlorpyrifos degradation. Enzymes which are the key players in microbial degradation can facilitate faster and effective degradation of chlorpyrifos. Among the several enzymes being exploited for pollutant degradation, laccase was most preferred by researchers due to its easy availability and broad substrate specificity. However, unlike other enzymes, laccase also suffered problems of reusability, stability and high cost of purification. Immobilization on suitable carriers could solve the problems of reusability, but selection of suitable and successful carrier is again a huge problem. Nanomaterials having a wide spread application in various fields can provide a solution to problems associated with carriers. Low cost, easy availability, easy separation with limited mechanical stress on enzymes and reusability made nanoparticles an ideal carrier to immobilize target enzymes. Studies showed that the magnetic iron nanoparticles can serve as a catalyst for pollutant remediation and carrier for enzyme immobilization with an application in various fields. To summarize, nanoparticles can contribute significantly and take the degradation to the next level with the enzymes especially the laccase enzyme.

17.6.1 Recommendations

Pesticides have greatly affected the quality of food, health and environment to a greater extent. Scientists across the globe are trying their best to tackle the persistence of pesticides and other problems associated with it. One such effort towards *in situ* pesticide degradation (i.e.) laccase enzyme immobilized nanoparticles for pesticide and other organic pollutant degradation is discussed in the chapter. The comprehensive review and analysis suggest that nanoparticles have acted as efficient carrier for the enzymes and showed better degradation efficiency at the laboratory levels. Scaling up to the field level and further commercialization requires more extensive studies to understand its behaviour under the natural conditions involving multiple cofactors. Further, studies are required to access the eco-toxicity of the nanoparticles on the microflora, insects, flora and fauna supported by the soil. Mechanism of pesticide degradation and stability of enzyme coated nanoparticles also needs a detailed investigation.

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Chapter 18
Deforestation and Forests Degradation Impacts on Livelihood Security and Climate Change: Indian Initiatives Towards Its Mitigation

Subhashree Patra, Amit Kumar, and Purabi Saikia

Abstract Deforestation and forest degradation are impairing the amplitude of forests to produce various ecosystem products and services, livelihood security, and its contribution towards mitigating the greenhouse gas emissions and climate change. Indian forests support the sustenance needs of ~300 millions of tribal people and forest dwelling rural populations. India is experiencing an increased pace of deforestation and destruction of forest resources leading to overall forest degradation in the past few decades. Around 40% of the Indian forests are degraded and over-exploited, 70% have lost the natural regeneration potential, and 55% are prone to fire. India is one of the parties to all the potentially notable world's agreements and conventions encompassing forests and their degradation prevention. India has committed to accomplish restoration of 21 Mha of damaged, degraded, and deforested lands by 2030 under the Bonn Challenge. The forestry sector constitutes an important part of India's Nationally Determined Contribution (NDC) and can be achieved through several ongoing programmes such as the National Mission for a Green India, National Afforestation Programme, compensatory afforestation, and plantations to increase the area under forest in the country. India's forestry sector is committed to establish a supplementary forest cover as a terrestrial carbon sink of 2.5–3.0 billion tonnes of CO_2 equivalent under the Paris Agreement by 2030. Besides, investment in natural ecosystems, through reduction in carbon emissions from deforestation and forest degradation (REDD), and reducing GHGs emissions from deforestation, forest degradation, and other forest related activities (REDD+) related strategies, contribute significantly to a reduction in GHGs emissions and improvement of carbon storage capacity of natural forests. It also helps in generating alternative income sources for the rural, tribal, and forest-dependent communities that will give essential financial inducements to avoid deforestation and to provide supplementary livelihood advantages from the protection and restoration of forest

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ecosystems. This chapter will particularly focus on the tropical forest, as it is currently experiencing the highest rates of deforestation and over-exploitation.

Keywords Forest destruction · Degradation · Livelihood security · Tropical forests · Indian initiatives

18.1 Introduction

Forests are the world's most critical terrestrial ecosystem that provides homes to 80% of terrestrial biodiversity (Popoola 2014). It is well-equipped with a range of ecosystem goods services from livelihood security to nutrient cycling and industry-related economic goods (Duguma et al. 2019) that help in sustaining different life forms on the earth. Besides, it provides multiple resources that are important to human beings (FAO 2003) and also as an option for environmental, economic, socio-cultural, and aesthetic profits (Olagunju 2015). Trees are considered the most dominant constituent of forests, some trees serve as a keystone species by providing food and habitat for different organisms through forest tree symbiosis (Steidinger et al. 2019) and other modes of biotic interactions. Tropical forests are considered the most diverse terrestrial ecosystems on the globe that are degrading and vanishing at a rate of 13.5 Mha forests Yr^{-1} globally (Kobayashi 2004). Tropical deciduous forests vary greatly from other tropical forests in terms of composition due to the strong seasonality (Sasaki and Putz 2009) and tropical forests occupy ~17% of the global tropical deciduous forests (Miles et al. 2006). Approximately 50% of tree species found in forests worldwide are being threatened with various levels of anthropogenic and natural disturbances (terSteege et al. 2015), which ultimately limits the ecosystem goods and services (van der Plas et al. 2016). These forests are also highly threatened, as most of these forests are located in areas with a very large population of forest-dependent people (Miles et al. 2006). Deforestation and ongoing anthropogenic pressure on the natural forests are considered a tremendous risk to worldwide terrestrial biodiversity (Barlow et al., 2016) as they can remove ~85% of the total inhabiting species of plants and animals (Baboo et al. 2017).

India is one of the 17 mega-biodiverse nations of the World (Mittermeier and Mittermeier 2005) with 21.67% forest cover of the country's total geographical area (FSI 2019). The Indian subcontinent has four global hotspots of biodiversity viz., Himalaya, the Western Ghats and Sri Lanka, Indo-Burma, and Sundaland which signifies the accelerated rates of habitat loss and degradation with high endemism in the region (Saikia and Khan 2018). The tropical forest in the region has been degrading at a very high pace (~88,000 km^2) during 1900–2019 (WWF 2019). Transformation of forest to other land-use pattern or long-term depletion of forest canopy cover to less than 10% threshold is known as deforestation (FAO 2005), while forest degradation is the retrogression floristic composition and structure (FAO 2007) that abiding depletion of the comprehensive supply of ecosystem goods and services (Olagunju 2015). Globally, ~55% of deforestation takes place in ~6% of the total tropical forest biomes (Hansen et al. 2008) of which 50% of deforestation in tropical areas occurs due to shifting cultivation (Somorin 2010). Besides, more than 40% of the Indian forests are degraded and insufficient in terms of ecosystem products and services and 70% have lost the natural regeneration potential (FSI 2019). Indian forests had faced tremendous pressure of over-exploitation and forest destruction (Davidar et al. 2010) due to increased population density, rapid industrialization, urbanization, high poverty, and economic growth (Karanth and Fries 2010). The growing stocks of Indian forests have been reduced by 12.26% (FSI 2019) which results in biodiversity loss and reduced ecosystem goods and services. Tropical forests are vigorously affected globally than any other forests due to rapid developmental activities and shifting agriculture, contributing more to canopy disruption (Gogoi et al. 2017). The tropical dry and moist deciduous forests in India are mainly overblown by the degradation and deforestation processes (Reddy et al. 2017) that impact the living systems (Rahman and Sumantyo 2010) by releasing locked carbon into the atmosphere. Human beings are responsible for the global environmental change by transforming the land and biota to a less feasible structure, where numbers of species are minimizing day by day (Chapin III et al. 2000). Extensive deforestation and degradation have notable impacts particularly on minor forest produces (MFPs) utilised by 50–90% of the forest dwelling populations for livelihood and income generation (Mipun et al. 2019). Forest loss and its destruction are worldwide phenomena having their peak in developing countries (Olagunju 2015) lead to warmer and drier climatic conditions (Davin and Noblet-Ducoudre 2010) and more GHGs emissions. The lack of a proper management system and the ongoing destruction and deforestation of tropical forests are creating tremendous pressure on the atmosphere by releasing CO_2 (Gebeyehu et al. 2019). Considering the forest cover change scenarios across the world, it has now become a matter of global concern and several national and international agencies have initiated several programmes aiming at protection, prevention of illegal activities, and sustainable management and utilization of forest products (Duguma et al. 2019) that will help in increasing the economic and social well-being of the forest (Agrawal et al. 2013). Most of the tropical forests across the world and in India are under great anthropogenic pressure due to the higher dependency on the forests for livelihood security and they require serious attention for biodiversity conservation, productivity, and sustainability (Kumar et al. 2006). Various international forums and organizations including United Nations Millennium Development Goals, UNFCCC, CBD, UNCCD Ramsar Convention on Wetland, World Heritage Convention, and CITES are taking various steps to resolve these issues related to environmental degradation. Simultaneously, various policies were introduced to control different forest degrading activities and their management for climate change such as REDD+ programs, Conference of Parties (COP), and Bonn Challenge targeting to restore 21 Mha of land by 2030 to make it productive, functional, and biodiversity-friendly landscapes (IUCN 2018). ~9.8 Mha of degraded and deforested land has already been restored since 2011 (Borah et al. 2019). Further, this approach encourages conservation, afforestation, and reforestation activities to control the emission in the developing countries under the clean development mechanism (CDM) (Alexander 2018). Moreover, they provide a well-known payment process for emissions reductions through projects of less carbon-intensive to both private and public sectors where payments are based on performance (Wunder and Wertz-Kanounnikoff 2009). The budget for forest management under the Union Budget (2020–21) of the Ministry of Environment, Forest, and Climate Change (MoEFCC), Govt. of India has increased from ₹26,579.4 million to ₹31,000 million (MoEFCC 2020).

18.2 Factors Driving Forest Destruction and Degradation of Tropical Forests

Deforestation is the transformation of forests through agriculture, infrastructure, forest fires, illegal timber felling, unsustainable logging, fuelwood harvesting, mining, and climate change (WWF 2020). Major contributing factors of deforestation and forest degradation are agricultural encroachment, settlement expansion, infrastructure development, forest fire, and mineral extraction (Jayathilake et al. 2021). Globalization also plays a vital role in forest degradation in developing countries (Rudel 2007). Shifting cultivation is the major contributor to forest degradation (Zonunsanga et al. 2014) followed by bush burning for grazing purposes, exhaustive grazing by livestock and wildlife, lack of fallow periods in between grazing activities, environmental pollution, the rapid expansion of agricultural lands, and intensive agricultural activities (Olagunju 2015). Population density (Tritsch and Tournrau 2016), cropland expansion (Carrasco et al. 2017), infrastructure development in the form of road networks, and land tenure systems also have a leading role in deforestation and degradation (Barber et al. 2014; Tritsch and Tourneau 2016; Jayathilake et al. 2021). Agriculture is identified as a major threat to 24,000 out of the 28,000 species included in the IUCN Red-List (Ritchie and Roser 2020). The pressure exerted by the growing human population (Camargo et al. 2019) in the form of consumption of food, fibre, and other agricultural commodities (Singh 2009) to fulfil the sustenance needs and for the economic development of the country by uncontrolled urbanization, industrialization, infrastructure development, mining operations, and intensified agriculture (Chopra 2016; Panwar and Pinkse 2020) leads to forests degradation. Illegal timber felling, hunting, encroachment of forest land, and poaching are some of the activities that are performed by the local communities for the fulfilment of basic needs and majorly to satisfy greed (Singh 2009). Over-grazing promoted soil erosion that ultimately decreased the quality and quantity of the vegetation cover and ultimately played a vital role in forest degradation and deforestation (Bisht et al. 2020). Similarly, forest fire also enhanced soil erosion (Inbar et al. 1998) by demolishing the microhabitat and terminating the growth of herbaceous ground vegetation in forests for a longer period (Spanos et al. 2010). It also causes serious health impacts (Koppmann et al. 2005) and warming of the local atmosphere (Vats 1996) by the emission of CO_2, CO, CH_4, hydrocarbons, NO_2, and NO_3. In India, a forest fire is mostly constricted to anthropogenic activities that were caused purposely or carelessly (Joseph et al. 2009) and ~55% of forests are prone to fire (FSI 2019). Mainly steep terrains, increased summer temperatures, increased wind velocities, and the presence of combustible materials in the forests are some of the characteristics that influence the spread of fires (Roy 2003). Most of the time, fires are initiated in the forests for the collection of seeds, masking of illegal timber felling, to initiate the growth of grasses as resprouted grasses are palatable to livestock, to scare away wild animals, and also to collect honey (Bhandari et al. 2012), mahua flowers for local alcoholic beverage preparation mainly by the tribal (Kumar and Saikia 2020). The recurrence and contiguous extents of fires are increasing over time (Reddy et al. 2017) in most of the tropical dry deciduous forests which hold 40.86% of India's total forest cover (FSI 2019). Tropical forests are considered as most suitable places for any developmental projects like enlargement of infrastructure for oil exploitation, allowance of logging activities, construction of dams to produce electricity, ultimately leads to expansion and construction of roads networks thus, results in opening up the dense forests and destruction of vegetation cover (Kaimowitz and Angelsen 1998). Mining is a profitable economic activity promoting development booms with consequent deforestation (Biswas and Biswas 2018), environmental impacts (Bell et al. 2001), enormous landscapes degradation, and biodiversity loss (Bradley 2020). Land-use change at mining locations, environmental pollution, and degradation are some of the direct impacts of mining but the indirect and cumulative impacts are much more significant (Bradley 2020). Mining and logging are considered as the major factors that influence the forest cover loss in India (Docena 2010) with the associated development of transportation infrastructure for the export of minerals, and other economic activities that are responsible for opening up the forests (Bradley 2020). Although logging activities are not the direct cause of deforestation rather act as a stimulant for deforestation (Chomitz et al. 2007) by providing access for roads and to subsidiary forest destructive activities which accelerate the damage of natural forests (Putz et al. 2001). The majority of logging activities in tropical forests are unsustainable, resulting in illegal logging, illegal trading, and corruption (Olagunju 2015). Rigorous and most catastrophic ways of logging are found in Southeast Asia (Chakravarty et al. 2012). Lack of good governance affects the life of people that depend on forest products (World Bank 2006). In the last three decades, the rate of global deforestation is almost 1.5–2.0 times higher as compared to the rate of forest expansion (Fig. 18.1) (FAO and UNEP 2020).

18.3 Deforestation and Forests Degradation Impacts on Livelihood Security: A Case Study from Jhum Affected Northeast Indian Forests

Shifting cultivation is the major contributor to forest degradation (Zonunsanga et al. 2014) and is responsible for ~50% of tropical forest deforestation (Somorin 2010). Jhum cultivation is a traditional method of shifting cultivation practised by the local

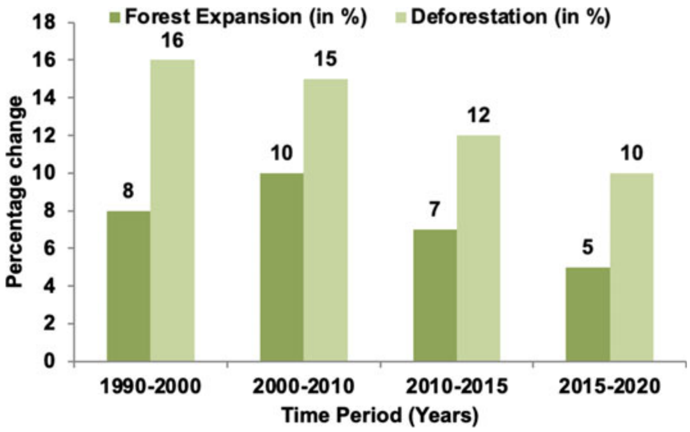

Fig. 18.1 Percentage of global forest expansion and deforestation during 1990–2020 (2020 *Source* FAO and UNEP)

tribal people of Northeast hill regions and considered the main source of livelihood security for a major group of the global population (Parrotta and Trosper 2012). It is one of the major land-use practices in Northeast India (Ramakrishnan 1984) and well adopted by the indigenous tribes and local communities living in hilly terrains due to its polyculture system and greater economic benefits (Thong et al. 2018). It comprises two phases viz., a cropping phase and a fallow phase where the abandoned land regenerates naturally (Fig. 18.2) (Thong et al. 2018). The majority of shifting agricultural related activities (70%) including clearing of land, crop selection, weeding, harvesting, processing, and selling the surplus in the market are performed by indigenous tribal women, while men are responsible for the identification of suitable land and the laborious physical activities related to preparation of land, and both men and women together make the firebreaks, harvesting, merrymaking feasts, and the religious ceremony performed during the shifting cultivation (AIPP and IWGIA 2014). Jhum cultivation results in an ecological succession of some fast-growing plant species with a higher potential of natural regeneration and plant diversity than any other traditional agroecosystem (Ferguson et al. 2001). Traditional jhum is associated with a socio-cultural organization based on communal rights and reciprocity and is considered a suitable life support system (Gupta 2000). On the other hand, it is considered as one of the primary causes of forest destruction and degradation (Roy et al. 2015) due to adverse impacts on biodiversity, carbon stock, greenhouse gas emissions, habitat fragmentation, the disappearance of native species, increased soil erosion, and soil fertility loss in the topsoil (Mishra and Ramakrishnan 1981). Approximately, 50 acres of land are degraded globally per hour due to shifting cultivation (Hays 2011). Basically, the problem of jhum cultivation is due to the spread of fires all over the forest, sometimes unintentionally (Lindsey 2004), which results in huge forest cover loss very fast (Bennett 2017). Due to the burning of huge land masses, the habitat of several species has been lost and others are pushed out of

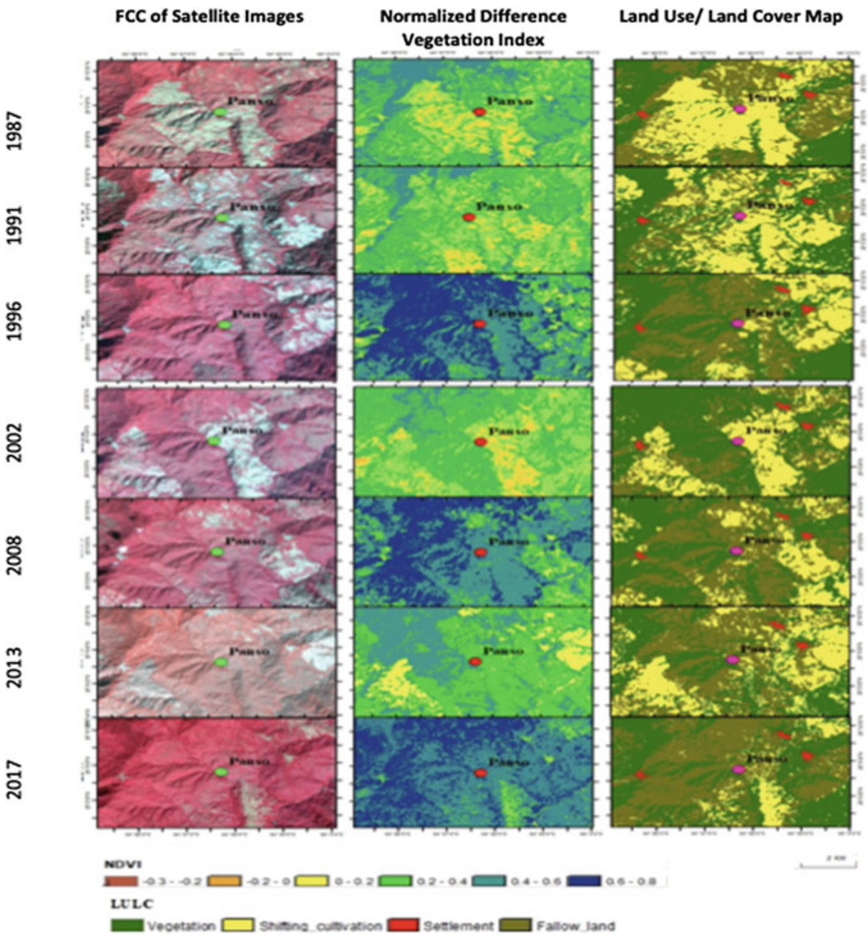

Fig. 18.2 Impact of jhum cultivation on land surface as monitored over the years (1987–2017) in parts of Nagaland (Panso), Northeast India

the forest, thus leading to biodiversity loss (Stief 2021). There is a projection of dense forest cover loss from 60.1% (in 2000) to 16.8% (in 2100) in Western Himalayas, while the same had reduced from 76.2 to 38.7% in the Eastern Himalayas (Pandit et al. 2007). The increasing trends of forest degradation in the Western Himalayas are mainly due to higher population density compared to the Eastern Himalayas (Pandit et al. 2007), while the major reason for the decline in dense green cover in Eastern Himalaya is attributed to the Jhum practices and other sustenance oriented exploitation (Roy et al. 2015). The exploitation of forests for jhum cultivation leads to forest cover loss and that ultimately limits the forest's goods and services. The major reasons behind the continuation of jhum cultivation in the Northeast region are poverty, inadequate land for traditional farming, and lack of scientific and technical knowledge of agriculture (Rahman et al. 2012).

18.4 Deforestation and Forest Degradation Impacts on Climate Change

Tropical forests perform a vital role in the mitigation of climate change through their global carbon cycle and CO_2 sequestration processes (Gebeyehu et al. 2019). It is a major sink for atmospheric carbon and accounts for 50% of the above-ground terrestrial vegetation carbon (Hunter et al. 2013). The exchange of energy, interchange of mass, and change of momentum fluxes in the middle of the geosphere and biosphere is influenced by the forests (Longobardi et al. 2016), which can be measured by evapotranspiration, surface albedo and roughness (Bounoua et al. 2002), as well as latent heat exchange (Brien 1996). Vegetation is the major factor in impacting the exchange of photons, momentum heat at the locality, and the microclimate of the locality (Sellers 1987). Vegetation and climate have bifacial interconnection on discrete temporal and spatial scales, thus changes in the composition and arrangement of vegetation have a great influence on the climate (Canziani and Benitez 2012). Vegetation structure, patterning, and physiology are largely influenced by the transformation of tropical forests to cropland, which results in climate modification (Brien 1996). The hydrological cycle is directly linked with the local weather patterns of a region and plants play a prominent role in this phenomenon. Thus, a change in plant diversity or a decrease in their number ultimately influences the climate (Bennett 2017). The sun insolation is more frequently engrossed by croplands compared to forests hence, they have a higher albedo than forests (Longobardi et al. 2016) by decreasing the rate of evapotranspiration (Kleidon and Heimann 2000). In forests, reduced albedo increases the warming effect by absorbing high amounts of shortwave radiation, however, it can be balanced by the loss of latent heat through increased evapotranspiration process in the forests (Bright et al. 2017). CO_2 is stored in the forests more than the amount stored in the atmosphere (Bennett 2017). Deforestation is responsible for around 24% of the world's total GHG production (IPCC 2014) which affects productivity, biodiversity, climate, and becomes a menace to the global carbon cycle (Harris et al. 2012; Gautam and Mandal 2016). The increasing influence of invasive species impacts the loss of biodiversity and modifies ecosystem composition and structure (Bennett 2017). The evacuation of tropical forests demolishes global carbon sinks that sequester CO_2 from the air and play an important part in future climate adjustment (Stephens et al. 2007). Every year approximately forests absorb 2.6 billion tonnes of CO_2 from which ~33% is released by the burning of fossil fuel and ~5–10 Gt CO_2 equivalent annually comes from degraded forests and deforested areas (IUCN 2021a). As long as the concentration of GHGs and outflow of ozone-depleting substances continues to rise, the threat for climate change will persist until equilibrium conditions are achieved (IPCC 2007).

18.5 Approaches to Combat Deforestation and Degradation of Tropical Forests (Nature-Based Solutions and Ecosystem-Based Adaptations for Forest Landscape Restoration)

Tropical forests are considered to have a high degree of resilience and the fastest recovery potential of their structure, function, and productivity after any natural or anthropogenic interruption (Parrotta et al. 1997). Several ways have been introduced to combat degradation and deforestation such as soil erosion regulation through modification and improvement of agricultural practices. Encouragement of agroforestry practices helps in increasing vegetated land and reduce the obsession pressure over the natural forests, simultaneously helping soil management (Popoola 2014). Similarly, increasing the protected areas may also help in biodiversity conservation and halt further forest degradation. Damaged tropical forests can be effectively restored through the strategy of rehabilitation as it is the most naturalistic way to deal with the complex tropical system (Lugo et al. 1993). Sustainable forest management (SFM) has been introduced to augment the resilience, energy storage, and biodiversity to balance social, economic, and ecological perspectives of the forests (Holvoet and Muys 2004). Another solution is the enhancement of areas for forest plantation in the deforested areas by replantation programmes (Williams 2002). According to UNCCD (2004) forests and tree cover have the capability to prevent land degradation and desertification by balancing nutrient cycling in soil, stabilizing the soil, and lowering the erosion by wind and water (Tomar et al. 2021).

Modification and enhancement of agricultural practices in place of shifting cultivation practices may act as a solution to reduce the rate of soil erosion (Zonunsanga et al. 2014). Agroforestry alternatively helps in managing the extant forest in areas of the predominance of shifting agricultural practices (Rahman et al. 2012). Some of the measures that can improve the economic and cultural viability are bamboo plantation across the slopes to reduce the velocity of the runoff and to increase surplus, leasing of trees with large canopies during the shifting cultivation practices for certain intervals increases the productivity and the water and nutrient holding capacity, etc. (Zonunsanga et al. 2014). Nature-based solutions like adopting the farm forestry, forestry plantation, and horticulture plantations, viable agriculture practices are being considered fruitful (Lallianthanga and Sailo 2013). Restoration Opportunities Assessment Methodology (ROAM) helps in sustainable agricultural systems to address food insecurity, rehabilitation, and restoration of forest landscape (Beatty et al. 2020). International programmes like REDD+, CITES, and the European Union's Forest Law Enforcement, Governance, and Trade (FLEGT) programme, and its Voluntary Partnership Agreements (VPAs), help in sustainable forest management, conservation, and utilization. The Bonn Challenge is emphasized on the restoration and reclamation of degraded and deforested landscapes (UN 2021).

18.6 Indian Initiatives and Commitments Towards Forest Degradation Prevention

The introduction of irrigation schemes, initiation of training and extension programmes, seeds and fertilizer subsidies, encouraging mechanization, and better market access (Maithani 2005) are some of the processes that help in the protection and maintenance of forests. India in partnership with USAID put forward different sustainable forest programmes such as Forest-PLUS 1.0 (2012–2017) and Forest-PLUS 2.0 (launched in December 2018) to improve forest management in targeted forest landscapes for the conservation of wildlife, strengthening ecological health, and ameliorate the livelihood of the forest-dependent population (USAID 2021). The policies and programmes introduced by the Indian government through afforestation and reforestation strategies are National Mission on Green India, the National Afforestation Programme for regeneration of degraded forests and adjoining areas by community participation (PIB NAP 2019), compensatory afforestation, social forestry, and plantation drives across the states. MoEFCC escalated the amount from ₹26,579.4 million to ₹31,000 million in the year 2020–2021 as compared to 2019–2020 for the overall process (Parliament of Rajya Sabha 2020) under the Union Budget 2020–2021 (Union Budget 2020–21) related with the augmentation of forest ecology (Roy 2020). Further, in 2019 (October), ₹47,436 crores have been transferred by MoEFCC to 27 states for effective implementation of afforestation efforts under the Compensatory Afforestation Fund Management and Planning Authority (PIB 2019). However, to reduce emissions from forest degradation and deforestation and to increase carbon stocks were also bound in the REDD+ programmes in the Paris Agreement (Bos et al. 2020). Forests are the major sink of carbon as acknowledged by the Kyoto Protocol and the afforestation programme and reforestation programme carried under the CDM of the Kyoto Protocol helps in mitigating the GHGs influence on the atmosphere (Singh and Sahoo 2011). The net forest loss gradually declined during 1990–2020 due to reduced deforestation and increase in forest areas in various parts of the countries through natural regeneration potential of forests and successful implementation of various afforestation programmes (FAO and UNEP 2020). Without the involvement of forest resilience in the mitigation plan for climate change, there will be no other way to combat the effect of GHGs and global warming. Therefore, to enhance the afforestation process a specified programme known as reducing emissions from deforestation and forest degradation is introduced by the United Nations Framework Convention on Climate Change (UNFCCC). These initiatives are introduced by the developing countries to provide monetary incentives to reduce GHGs emissions from the deforested and degraded forests (Gibbs et al. 2007). For the successful implementation of policies in developing countries, the REDD programmes are carried out through the estimation of forest carbon stocks (Saatchi et al. 2011). Indian Government in association with global conventions and agreements related to forests and their degradation implemented various programmes such as.

IUCN (1948): It is the first and mega global international environmental union that inspires, motivates, and guides society worldwide for the conservation of the integrity and diversity of nature, while simultaneously conforming to their equitable and sustainable use. It deals with the protection and conservation of forests through NBSs that act as a catalyst to climate change. The main focus of this Convention is to work on forest resilience to prevent deforestation and forest degradation of the highly rich biodiversity areas having cultural values. IUCN played a foundational role in the formation of various conventions viz., the Ramsar Convention on Wetlands (1971), the World Heritage Convention (1972), the Convention on International Trade in Endangered Species (1974), and the CBD (1992). It also helps in capacity building for initiation of restoration projects, engaging the private sectors, and ensures the beneficiaries to forest-dependent communities and local landowners for equal sharing of REDD+ initiatives.

The Bonn Challenge along with the New York Declaration on Forests 2014 committed to restoring 350 Mha of degraded and deforested land till 2030 (IUCN 2021b). ~210 Mha has been restored by 74 governments, private associations, and companies to date (IUCN 2021b). India as part of this commitment has pledged 13 Mha under Forest Landscape Restoration by 2020 and an additional 8 Mha by 2030 (IUCN 2021c). The Green Carbon Fund, the Forest Carbon Partnership Facility (FCPF), and the Climate Investment Fund are some of the funding sources for mitigating and adapting to climate change (UN 2021). The United Nations initiated the Decade on Ecosystem Restoration (2021–2030) programme to combat deforestation and degradation of ecosystems worldwide and also to work on various aspects of conservation (UNEP, FAO 2020).

CITES (1973): It is an international agreement between governments that deals with the protection, regulation, control of wild plants and animals to prevent international trade for the survival of endangered species. India had signed the CITES agreement in 1976 and a total of 1658 Indian species have been protected by CITES (India Biodiversity Portal 2019). Its main objective is to ban several illegal activities of logging, poaching, exporting, etc. by strengthening training forces, arming the rangers, and providing skilled prosecutors to manage the forests that lead to the protection and conservation of forests and biodiversity (UN 2021).

UNFCCC (1992): The UNFCCC introduced at Earth Summit (1992) came into force in 1994 with the objectives to regulate the emission of GHGs through global cooperation and to prevent anthropogenic interference to the climate system (UNFCCC 2021). Although India has been an active partner of the Convention since 1993, it is not tied to GHGs emission reduction goals as a measure of mitigation. However, the Paris Agreement (2015) enforces a way for developed countries to assist developing countries with climate change mitigation and adaptation strategies (UN 2015). India is a leading participant in multilateral negotiations including the introduction of policies and frameworks for combating deforestation such as the National Environmental Policy (NEP) and the National Action Plan on Climate Change (NAPCC).

It includes various programmes like Nationally Determined Contributions (NDCs), CDM, and Nationally Appropriate Mitigation Action (NAMA) (UN 2021).

CBD (1992): CBD was the first global agreement on the conservation and sustainable use of biodiversity with equitable sharing of benefits and knowledge arising from genetic resources (Secretariat of the CBD 2000) through the general provisions of national-level approval (Chaytor et al. 2002). Governments are required to adopt all prior steps including the formation of national strategies and action plans to conserve and protect the biodiversity of the nation under this Convention (Secretariat of the CBD 2000). Under Article 6 of CBD, the parties have been instructed to integrate all strategies and programmes into national policies and developmental plans (Secretariat of the CBD 2005). Under this Convention, Nagoya Protocol was introduced in 2010 for genuine and equitable sharing of ecosystems' benefits to achieving the goal of conservation and sustainable use of biodiversity by creating legal bindings and transparency for both contributors and users (CBD 2015). The Biological Diversity Act (2002) was passed in India to provide appropriate mechanisms for equitable sharing of resources and preservation of biodiversity-related issues in the country. India has adopted and implemented several other policies including the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) and the Trade-Related Intellectual Property Rights (TRIPS) (1995) for the conservation of forest biodiversity under different governmental regulations.

Other agreements including the International Tropical Timber Agreement (ITTA), the International Tropical Timber Organization (ITTO) (1986), which was signed by India were ratified in 1996. India has also signed and ratified several other agreements for the conservation of biodiversity such as the Convention concerning the World Cultural and Natural Heritage (1972), the Convention on Wetlands of International Importance that is Ramsar Convention (1971), the Convention Relative to the Preservation of Fauna and Flora in their Natural habitat (1933), the Convention on International Plant Protection (1951), the Conservation of Migratory Species of Wild Animals (Bonn 1979), Indigenous and Tribal People Convention (1989), World Trade Organization (1995), United Nations Forum on Forests (UNFF) (2000), Sustainable Development Goals (SDGs) (2015), etc. India's NDC can be achieved through the National Mission for a Green India (GIM), National Afforestation Programme, and compensatory afforestation and plantations to increase the forest cover in the country. India's NDC target is to minimize the emissions of GDP by 33–35% by 2030 from the 2005 level and to pull off 2.5–3.0 billion tonnes of CO_2 equivalent in the forest by 2030 (Jaiswal 2020). The Green India Mission Programme implemented afforestation programmes to enhance 5.0 Mha of forest and 5.0 Mha of tree cover to support livelihood security with a target of sequestering 100 MT of CO_2 equivalent annually (GIM 2010). The 42nd Amendment to the Indian constitution introduced Article 48A and Article 51A(g) to deal with environmental protection and conservation after the Stockholm Conference in 1976. Article 48A states that 'The conservation, management, and improvement of the environmental conditions and to safeguard the natural resources of the country is the responsibility of the States', whereas Article 51A(g) states that 'The conservation and management of the natural ecosystems for all living beings shall be the responsibility of every Indian citizen (CoI 2020).

18.7 Alternative Livelihood Opportunities Through Poverty Alleviation Programmes

Some of the international jurisdictional perspectives to deal with forest protection, conservation, and to counteract issues related to climate change through nature-based solutions include the reduced deforestation activities (IPCC 2019) by the implementation of sustainable commodity supply chain programmes and REDD+ programme (Stickler et al. 2018). NGOs, businesses, governments, and local stakeholders having a common interest in mitigation of forest degradation-related issues align with national, sub-national, and local operational units, but the major initiative was taken by the countries with sub-national jurisdiction as a concerned authority (Busch and Amarjargal 2020). Such programmes have a various centres of attention like commitments of zero-deforestation that are dissociated from the activities of governments (WWF 2016), jurisdictional approaches dealing with multi-stakeholder programmes (Hovani et al. 2018), administrative strategies to REDD+, and lower GHGs emissions strategies (Boyd et al. 2018). Indian Government in association with the World Bank initiated many programmes like industrial forestry, social forestry, Joint Forest Management (JFM) in developing countries by targeting poverty alleviation and sustainable development. In India, local communities have benefited from several rights by accessing and maintaining the forest patches through JFM and Indian Forest Rights Acts (Ghate and Nagendra 2005). State forest departments had taken different measures viz*.,* JFM policies, plantation, and buffer zone management for protection and conservation purposes (Torri 2011). Through JFM, locals can be economically benefited and the forest is also protected by giving the right to utilize the forests as long as it is not damaged or altered, which ultimately provides employment opportunities to the forest dwellers and the indigenous people. India with founder member of International Labour Organization (ILO) or Indigenous and Tribal Peoples Convention (1989) targets to provide protection to the socio-economic and cultural rights of indigenous tribal populations and put forward land rights v*iz.,* Article 14, 15, 2, and 7 (ILO 1986).

ILO does not centralize on forest related issues but its application includes activities like ancestral domain management and governance of natural and environmental resources (ILO 1986). Mahatma Gandhi National Rural Employment Guarantee Act (MNREGA), 2005, is another poverty alleviation programme initiated by the Government of India that provides employment of 100 days to all poor adult Indian citizens. Forests provide a large number of NTFPs that have enormous nutritional, medicinal, and other useful values that sometimes sell in the markets at a very nominal cost by the locals for economic security. Proper value addition can increase the market value of the products, which will enhance the income and the employment opportunities of the people residing in proximity to forests. By adopting the new generation plantations (NGP) programme, ~ 11.1 Mha of land is being managed which results in forest conservation and socio-economic development of the locals (Silva et al. 2019). The introduction of CARE (1994) on poverty-stricken and the most sensitive groups emphasizes capacity building for the poor based on the concept of livelihood security (Krantz 2001). For the protection and management of forest, several initiatives had been taken like community forestry, environmental and cultural forestry to support the local community. Implementation of policies prioritizes individuals with land and livelihood assets through forest supplements that give benefits attached with responsibilities to each and every individual for their sustenance, thereby protecting the forests and the community through fundraising and increased production (GEF SGP 2017).

18.8 Recommendations and Future Research Prospects

Forests are considered as a sustainable strategies to mitigate the impacts of changing climatic conditions and management of biodiversity for its conservation and sustainable utilization for the human well-beings. Biodiversity helps in enhancing the ecosystem productivity, goods and services and maintaining the ecosystem stability in the changing environmental conditions. A detailed study of the complex interactions of biodiversity and ecosystem stability in changing climatic conditions is the need of time. Besides, an in-depth study of the role of forest biodiversity in ecosystem management and their response to climate change, abiotic stresses, and fluctuations in the environment is necessary to understand these complex processes. The world's forests may provide us a more sustainable, equitable, and greener future as healthy forests ensure us with clean air, fresh water, shelter, and food. Therefore, restoration activities are needed from time to time to mitigate the ongoing forest degradation and also to make use of it for a better future.

18.9 Conclusions

Forests are indispensable resources for mankind and are exploited by anthropogenic actions that tend to deforestation, forest degradation, habitat loss, and forest fragmentation, which directly or indirectly affect livelihood security. Deforestation and forest degradation are aggravating with the increase of human population and their rising dependency on forests thus necessitating management strategies to sustain the biodiversity and its sustainability. Looking into the present forest cover change scenarios across the world, it has now become a matter of global concern and warrants immediate policy interventions aiming at protection, sustainable utilization, and management of forest resources. Therefore, it is essential to aim at mitigating measures and implementation of various strategies, policies, and laws with global collaboration to control the increasing anthropogenic impacts over the forests. The commitment of local communities to different levels of policy formulation and implementation will strengthen the sustainable forest management programmes and agroforestry practices meanwhile enhance employment opportunities. Integrated national financing frameworks (INFFs) can help the developing and under-developed countries to increase forest investments and to achieve long-term sustainable development goals.

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Part V
Socio-economic Framework

Chapter 19
Sustainable Technologies for Value Added Product Recovery from Wastewater

Pallabi Das, A. K. Singh, and K. K. K. Singh

Abstract The problem of wastewater and solid waste disposal is ubiquitous in today's world. Different technologies are being researched upon for the treatment of wastewater. The backdrop of resource crunch and stricter environmental norms has generated the impetus for a paradigm shift in wastewater management. Greener and sustainable approaches are being explored that focuses on resource conservation and recycling of water. The waste-to-wealth technologies scoring high on technological viability and economic feasibility fronts provide a fresh research avenue for practical implementation. In this chapter, the efficacy of some of the most promising conventional and novel separation options for value added product recovery from wastewater have been discussed. The crux of the technology, applicability and the possible resources that can be recovered was studied vis-a-vis the pros and cons. Finally, evaluations of the industrial scale up potentially and commercialization status of the technologies was reviewed.

Keywords Waste to wealth · Sustainable technology · Valorization · Membrane separation

19.1 Introduction

The growth of industrialization and population over the past few decades have greatly stressed the available mineral, water, air, and soil resources. As a byproduct of the multifarious human and industrial activities, solid waste and wastewater are produced. Treatment technologies focusing on wastewater remediation are not sufficient to meet the challenges. There is an acute shortage of raw materials and minerals for different industrial processes which is responsible for their escalating prices. Furthermore, the solid waste and concentrates generated during such WWT steps also necessitate management. This serves to incentivize the process of environmental remediation, conserve resources and also mitigate environmental pollution.

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Several physicochemical techniques are used to recover value-added products from wastewater. These technologies concentrate the solid content which comprises of different "pollutants" or simply components depending upon the source like heavy metals, nutrients like PO_4^{3-}, $NO_3^{(-)}$, or ammonical, sulfate compounds, and a host of others. All of the aforesaid individually possess immense value in different industries like fertilizers, chemical synthesis, semi-conductor industries, and metal processing industries. Hence the question of their isolation or selective separation arises. Some compounds may be separated by the combination of two compounds or by the formation of a ternary compound. For example, ammonium present in wastewater is recovered by the addition of magnesium phosphate in the form of a complex compound called struvite (magnesium ammonium phosphate) (Cao et al. 2019). Sulfate present in acid mine waters can be recovered by the addition of calcium and aluminum hydroxide leading to the formation of calcium aluminum sulfate commonly called ettringite (Rooyen and Staden 2020). Recovery of valuable components can be in the gaseous phase as well; such as ammonia or H_2S stripping (Promnuan and O-Thong 2017). Apart from valuable product recovery, the waste loading can be utilized for electricity production via fuel cells, or syngas CH_4 produced using microbial cells. Wastewater valorization encompasses all of the above and more (Sivasankari et al. 2021; Huang 2018; Lu et al. 2020; Kopke et al. 2010). Table 19.1 lists some of the products that have been successfully recovered from different wastewaters and effluents.

Several stages are involved in the waste-to-wealth recovery techniques. The primary step is concentration, followed by selective separation. The techniques that aid in selective degradation can also be utilized for the breakdown of the non-target compounds facilitating the recovery of the target compounds. Several physicochemical techniques like precipitation, ion exchange, membrane separation, or integrated options like membrane crystallization have been used in this domain. Electrochemical processes and their hybrids have also been used for the breakdown of resistant, electrostatically bonded compounds to release and precipitate heavy metals and other valuables (Maarof et al. 2017). Microbial technologies also offer a fresh perspective into the selective value addition paradigm. Methanogenic, light-capturing phototrophic purple bacteria, chemoautotrophs, substrate selective to the major components present in wastewater can be functionalized with multifarious pathways to tailor the final product as per the user's requirement (Hülsen et al. 2014; Das et al. 2018; Karthic et al. 2020).

This chapter focuses on a detailed discussion about the various technology options available for wastewater valorization. All the techniques were studied from the point of view of their applicability, selectivity, pros and cons and overall viability. Conventional physicochemical options, biological alternatives as well as novel developments like membrane technology has been covered in this chapter. Sustainability quotient of the process, scope for research innovation, and future research directions were highlighted. Integrated technology options aiming at simultaneous wastewater treatment and value-added product recovery were discussed for complete standalone technology development.

Table 19.1 Value added products that can be recovered from effluents

Product recovered	Feedstock	Method employed	Yield/conversion	Reference
Sodium sulfate	Simulated acid mine drainage water	Seed crystallization in a fluidized-bed reactor	79%	Luna et al. (2017)
Acetic acid	30% aqueous solution	Reactive distillation: esterification with *n*-butanol	Close to 100%	Gangadwala et al. (2007)
Succinic acid	Whey and lactose solutions representing dairy effluents	Batch fermentation	65% with lactose feedstock 62.5% with whey	Louasté and Eloutassi (2020)
Acetic acid and methanol	Dimethyl terephthalate process wastewater	Pressure membrane and membrane distillation processes	95% methanol	Yasin et al. (2020)
Zinc and phosphate	Phosphating wastewater	Struvite crystallization	Zinc: 99% Phosphate: 98%	Huang et al. (2017)
Chromium	Tanning wastewater	Sonication sedimentation	60%	Guo et al. (2006)
Nickel	Nickel electroplating wastewater	Electrodialysis	90 mg A^{-1} h^{-1} cm^2 of Ni^{2+}	Benvenuti et al. (2014)
Struvite	Sewage sludge anaerobic digester effluent	Chemical precipitation	NH_4–N: 89.35%, PO_4–P: 95%	Uysal et al. (2010)

19.2 Recovery Techniques

Different conventional and novel recovery techniques have been grouped into two subsections and studied individually below:

19.2.1 Conventional Options

19.2.1.1 Hydrothermal Treatment (HT)

Hydrothermal treatment as the name suggests is a process where a reaction occurs in the presence of water driven by both high temperature and high pressure. In the laboratory it is usually carried out in an autoclave/Teflon bomb in a high-pressure vessel.

The presence of water distinguishes hydrothermal techniques from solvothermal techniques that occur in the presence of a solvent (other than H_2O). This technique has been used for product recovery from both solid and liquid streams. The high temperature, pressure needed for the process ensures the activation of relatively inert feedstocks such as fly ash, slag (Sahoo et al. 2016; Binnemans et al. 2020). Similarly, the process has been harnessed for product recovery from recalcitrant liquid feedstocks viz. wastewaters like municipal effluent which are a complex mixture of a different chemical, biological and physicochemical components. HT does not necessitate pre-drying or pre-concentration as has been applied for the extraction of fuel and chemical compounds from the municipal sewage produced during municipal wastewater treatment (Djandja et al. 2021). The potential of HT in recovering energy-dense fuels like bio-char, bio-oil, organic acids, fertilizers, and other nutrients from organic-rich streams has been studied widely wherein compounds like, acetic acid has been extracted from waste streams (Baroutian et al. 2013, 2015). The Schematic is shown in Fig. 19.1.

Inorganic components like phosphorus and nitrate represent valuable feedstocks for a host of chemicals like fertilizers, explosives, cosmetics among others. Hence their selective recovery deserves research attention. Hydrothermal synthesis coupled with chemical-thermal mineralization via $Ca(OH)_2$ addition was able to precipitate calcium phosphate from a simulated WW containing a mixture of phosphate hypophosphite, dihydrogen phosphate (Itakura et al. 2009). Interestingly, harmful compounds like boron can also be converted into value-added chemicals $Ca_2B_2O_5 \cdot H_2O$ hydrated boron oxide with HT. The product is also recyclable which adds to its value. The process of HT has demonstrated high efficiency of 99% while extracting boron via the calcium mineralization route (Itakura et al. 2005). The mechanism of hydrothermal synthesis routes includes oxidation, carbonation, liquefication, and hydrolysis. Hydrothermal acidolysis is a patent technique to break down metal-containing ionic compounds from solid matrices. The processes of hydrolysis and carbonation consist of non-oxidative propagative steps while the other two occur in presence of O_2 and include mineral solubilization. Combination of hydrothermal treatment with sulfuric acid addition in a wet ball mill treatment was able to precipitate 99% Pb from $PbZrO_3$ matrix in the form of $PbSO_4$ (Kamiya et al. 2006).

Hydrothermal carbonization in many cases partitions the feed into solid and liquid fractions. This helps to recover aqueous nutrients like potassium and nitrogen present in sewage (Saetea et al. 2013). HT also makes it possible to simultaneously recover phosphorus and produce hydrogen from waste feedstreams (Ekanthalu et al. 2021). Competitive phosphate salt precipitation rates can be attained through this technique with serial acidic and alkaline leaching (Lühmann and Wirth 2020).

Despite the promising applications across multifarious domains, this technique has several shortcomings. The principal among them is the high energy consumption associated with the process. The usage of acid and alkalis in the process also necessitates stringent monitoring to prevent any secondary contamination from the spent wash. The aforesaid operations also entail considerable energy expenditure. Hence these processes need a robust cost–benefit analysis and possible pairing with more novel advanced separation processes to increase the overall sustainability.

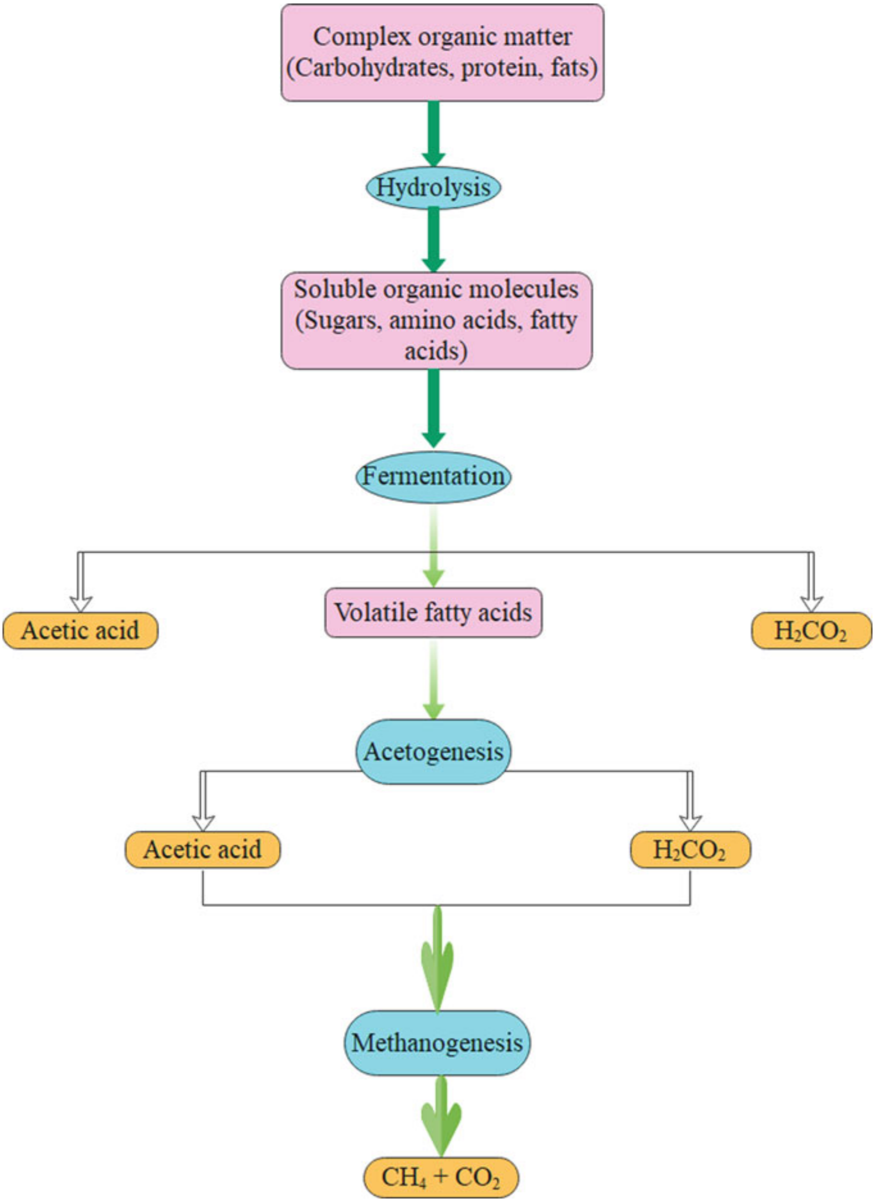

Fig. 19.1 Reaction schematic (Elalami et al. 2021)

19.2.1.2 Microbial Techniques

The application of microbes for value-added product recovery from effluents is widely researched and implemented. These technologies projected as eco-friendly options offers a broad range of choice to control the composition of the output formed, depending upon the process conditions, choice of microorganism mechanism of the reaction pathway. Biogas, biomethanol, syngas, metal precipitation, nutrient recovery like (PO_4^{3-}, NH_4^+, $NO_3^{(-)}$, fertilizers, soil conditions are some of the different value-added products from wastewater that can be recovered using the biological and microbiological methods. Among the different techniques, anaerobic digestion has already been commercialized and implemented at the industrial level. In this process, naturally occurring anaerobic microbes break down organic carbon present in biological feedstocks in the absence of O_2 into solid, liquid, and gaseous products. Industrially operating anaerobic digestors are categorized into "wet" and "dry" types depending on the solid loading processed (Elalami et al. 2021). Mesophilic and/or thermophilic bacterial culture is commonly used for this purpose (Shaw et al. 2017). Large-scale anaerobic digestors often consist of two stages: in the first stage bacterial treatment is administered to produce methane and CO_2 enriched biogas and a secondary stage is undertaken for the separation of solid–liquid digests from the process (Jingura and Matengaifa 2009; Gunaseelan 1997). The series of chemical reactions involved include hydrolysis, acidogenesis, and methanogenesis (Metcalf et al. 2003).

The treatment of municipal wastewater also often includes aerobic digestion besides anaerobic digestion. It is an endogenous respiration state when the organic matter is rapidly degraded by aerobic bacteria to produce single-cell proteins (SCP), CO_2, and H_2O. Feedstocks containing polysaccharides, sugars, lignocellulose in biomass are utilized in the reaction pathways as substrates (Kosseva 2020). It is more commonly used for waste volume reduction and preconcentration before anaerobic digestion. The products obtained are largely dependent on the composition of the effluent. For instance, proteins are degraded into ammonia, high COD results in high biogas generation and VFA formation. Some of the important parameters that govern the process apart from feed concentrations are the operating and environmental factors, Hydraulic Retention Times (HRT), feed COD loading (Maharaj et al. 2001).

Different classes of bacteria have been used for resource recovery from wastewater. Purple phototrophic bacteria functioning under anaerobic condition has been extensively used due to its high efficiency in resource recovery. The biomass residues produced from such bacterial stirred reactors are rich in nutrients. Consequently, it can be used as a biofertilizer. The liquid component contains polyphosphates and 5-aminolevulinic acid and can be used in PPB culture (Capson-Tojo et al. 2020). Autotrophic bacterial cultures like hydrogen oxidizing bacteria knallgas capable of electrolytic splitting can be used for wastewater treatment and value-added product recovery (Matassa et al. 2015). Some of the value-added products formed using such bacterial processes include single-cell proteins (SCP), polyhydroxybutyrate apart from molecular H_2 (Robinson et al. 1999; Repaske et al. 1976). Stoichiometry of the bacterial reaction and molar ratio of gases plays a key role in the yield and overall reaction pathway governing the kinetics (Ishizaki and Tanaka 1990).

$$21.36\ H_2 + 6.21\ O_2 + 4.09\ CO_2 + 0.76\ NH_3 \rightarrow C_{4.09}H_{7.13}O_{1.89}N_{0.76} + 18.70\ H_2O$$

Another interesting advantage of this bacterial class is the emergence of co-tolerant species that can be used in adverse conditions (Tanaka et al. 2011). A process that is used in conjunction with the anaerobic digestion processes is composting. It is a biochemical pathway for organic carbon degradation, using a combination of mesophilic and thermophilic bacteria. This process essentially produces organic compost which is used as a soil conditioner as it contains a host of nutrients like C, N, K, P (Richard et al. 2019; Babu et al. 2021).

The progress in the field of biotechnology has in recent years led to the development of innovative microbiological-hybrid processes that are being used for simultaneous wastewater treatment, energy production and recovery of value-added products. Microbial electrolysis cells and microbial fuel cells are examples of such process intensified, novel technology solutions. The microbial electrolysis cells (MEC) resemble a conventional electrolytic setup. There is a cathode and an anode. The electrolyte is replaced by an organic substrate. Exoelectrogenic bacteria present in the anode break down organic matter to release protons (H^+) and electrons. The electrons reduce the protons in the cathode to yield hydrogen (H_2) to drive this non-spontaneous endothermic reaction; a small amount of voltage (0.2–0.8 V) is applied between the electrodes to create a potential difference (Lu et al. 2016). This process yields different products like methane, formic acid, H_2O_2 apart from hydrogen (Wang et al. 2013). The low voltage requirements can be easily met by coupling renewable energy sources like solar panels, apart from combining any source of waste heat or low-grade heat (Kadier et al. 2016). The schematic is shown in Fig. 19.2.

Similar to the MEC's are the Microbial Fuel Cells (MFC), which are utilized to generate electricity from the organic fraction of the wastewaters. Here similar low Gibbs free exergonic reactions take place. In an MFC, the cathode and anode are separated by a proton exchange membrane. The entire assembly is fabricated in a way to have contact with air on the upper side and contact with water on the lower side. This ensures the movement of electrons which can be converted into clean energy (Meena et al. 2019; Kook et al. 2016). There are also wastewater-specific variations of the MEC's. For instance, microbial desalination cells which besides generating electricity also desalinates the water. Here an additional desalination chamber comprising of ion exchange membranes is provided in the middle of the cell between the cathode and the anode (Zuo et al. 2016). Despite the multifarious benefits of environmental friendliness, there are several challenges and complexities that these microbial systems face. Firstly, the operation and maintenance of such systems require highly skilled manpower. Secondly, the microbial colonies possess high sensitivity to pH, temperature, feed concentration and are easily degenerated. They are often unsuitable to treat fluctuating feedstock. Thirdly, the magnitude of the electricity generated from the MEC's and MFC's are often less in terms of

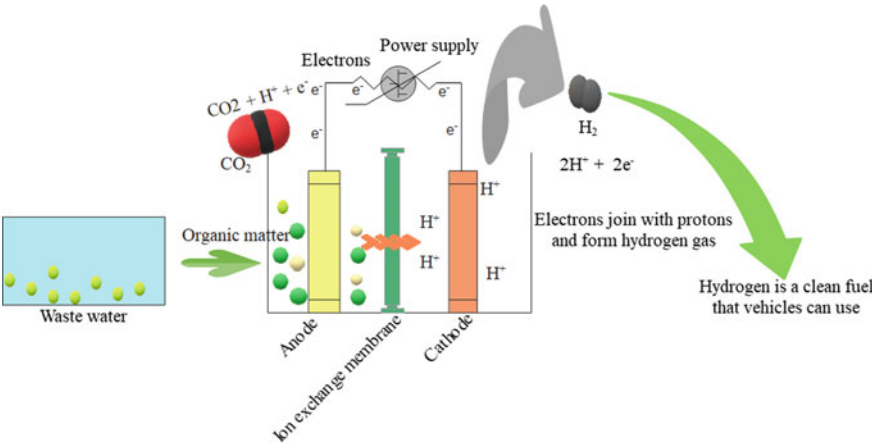

Fig. 19.2 A simplified schematic of electrochemical processes (Kadier et al. 2016; Escapa et al. 2016)

cost–benefit analysis. Nevertheless, these represent futuristic technologies and active research must be pursued to make these techno-economically viable.

19.2.1.3 Electrochemical Route

Electrochemical techniques classified under advanced oxidation processes are used for effective and fast degradation of organic and inorganic components present in wastewater. These techniques are also used for selective recovery of the compounds via redox reactions. Different integrated variants used in resource recovery are electro-adsorption, electro-oxidation, electro-reduction, and electro-precipitation. The electro-adsorption process functions by a double layer formation on the electrodes. Common adsorbents like activated carbon are used with the electrodes for selective separation of components such as heavy metals from the feed. These contaminants can be reduced/precipitated with the help of the electrodes (Foo et al. 2009). Researchers in the field have studied the use of carbon nanoelectrodes, activated carbon fiber electrodes, and graphene electrodes for increased surface area, selectivity, and efficiency (Yang et al. 2021). Various heavy metals like Cs, Ni, Cr designated as toxic and hazardous pollutants serve as a valuable feedstock for the chemical industry. Such metals can be recovered using this technique (Su et al. 2018; Ho 1987; Chen et al. 2013). The electrochemical techniques have also been employed to successfully break down resistant arsenic and chromium ions (Fan et al. 2016).

Besides heavy metals, anionic groups and also compounds present in wastewater have been extracted using electrochemical means. Ubiquitous pollutants present in WW when isolated serves as a resource for different chemical processes. For instance, sulfate widely occurs in pond waters as a contaminant. Using a combination of microbial electrolytic cells H_2S gas with a significant calorific value can be produced using sulfate-reducing bacteria. Alternately the H_2S can be alkali scrubbed to yield sodium sulfide. Apart from standalone use of sodium sulfide, it can also be oxidized to inorganic sulfur as an anolyte (Selvaraj et al. 2016). Other feedstocks from which sulfate has been recovered include SO_4^{2-} rich, acid mine waters and even urine (Lu et al. 2019a, b; Chartrand and Bunce 2003). The sulfur content present in wastewaters can also be recovered via the sulfite route using a fuel cell-redox reactor (Zhai et al. 2012). Nutrients present in wastewater such as phosphate, nitrate, and their compounds can also be selectively separated by combining chemical precipitation with electrolytic techniques. Advanced research in the domain of MEC has led to the use of methanogenic bacteria for producing methane in a membrane bioreactor-electrolytic setup. The system allowed simultaneous separation and production of methane (Yang et al. 2018).

The electrolytic processes can be coupled with novel developments like photocatalysis to tailor the product formation and yield. It also enables greater flexibility of utilization of renewable energy sources. During the process of photocatalysis, electron–hole pairs are generated which enhances the oxidative power of the process (Jiang et al. 2020). It also increases the selectivity of the process, leading to the extraction of valuable components like uranium, tellurium, tin with efficiencies in the range of 80–85% (Jin et al. 2018). Other process combinations include electro-membrane and electro-fuel cells which are promising options for sustainable wastewater treatment, energy production, and waste valorization.

The aforesaid technologies are viable developments that can truly incentivize waste-to-wealth technologies. The energy requirements of the electrolytic cells and the cost of the cathode and anode can be trade-offed with the product (yield and quality). If the wastewater is also simultaneously treated, then it can further shift the process economics favorably.

19.2.2 Membrane Separation Techniques

In the domain of novel separation processes, membrane technology has received heightened research attention for WWT. It is also widely commercialized for domestic and industrial sectors. The main benefits offered by the membrane separation process include ease of operation, high separation efficiency, environment friendliness, and compact process design. The process intensified membrane systems offer operational flexibility and can be tailor-made to suit the process needs. It also makes them candidate technology for hybrid operations integrated with the conventional and novel options. This has given rise to numerous spin-offs such as membrane adsorption, membrane photocatalysis, membrane crystallization, membrane distillation, and several others (Khulbe and Matsuura 2018; Pramanik et al. 2016; Alkhudhiri et al. 2012) These represent specialized applications that have the potential to be developed into complete standalone applications for wastewater treatment and value-added product recovery. Some of the most promising ones are described below.

19.2.2.1 Membrane Crystallization (MCr)

Membrane crystallization is an integrated technology where the membrane aids in separation and crystallization. The membrane provides a large surface area for the process of crystallization by lowering the free energy needed to reach the nucleation stage. It also promotes heterogeneous nucleation which increases the probability of nucleation and crystal growth. The membrane surface can be used for direct crystal growth or concentrative crystallization (Das et al. 2021).

In either case, the membrane aids in separation and also promotes crystal formation by providing a large surface area. The presence of the membrane lowers the energy barrier needed to reach the spontaneous nucleation stage. It also facilitates nucleation by concentrating the feed to its supersaturation ratios this increases the probability of crystal formation (Das et al. 2019a, b). The process of MCr has demonstrated marked lowering of induction times (Drenth et al. 2003). The process offers benefits like good yield, selectivity, crystal quality. The use of ambient conditions prevents any thermal or shear degradation.

The technology of MCr has been used for selective separation of valuable components from wastewater. It has been used for the recovery of individual components like lactose as well as form compounds like struvite for the separation of phosphate from wastewater (Das et al. 2019a, b). Different classes of wastewater like electronic industry effluent, desalination brine, and pharmaceutical wastewater have been used as feedstocks for this process, to recover valuable compounds like sodium carbonate, sodium chloride, and even enzymes like lysozyme (Edwie and Chung 2012; Todd et al. 1991; Martínez et al. 2014; Nariyoshi et al. 2016). There are several variants to this process like concentrative crystallization, antisolvent crystallization, membrane distillation crystallization, osmotic crystallization, and others (Salmón et al. 2018; Nowee et al. 2008). In concentrative crystallization, the membrane surface is not directly used for crystal growth. Using pressure-driven membranes like NF and RO, it concentrates the feed till the initiation of supersaturation (Calabrò and Basile 2011). In antisolvent crystallization, the solubility of the target feed in the solvent is decreased by the addition of the antisolvent. This leads to precipitation of the target compounds on account of reduced solubility which eventually leads to crystallization. The decrease in solubility is connected to the rapid attainment of supersaturation conditions. Commonly used antisolvents include methanol, acetone, propanol, polyethylene glycol which exhibit greater miscibility with the solvent: water and decrease the solubility of the particular compound (Yang et al. 2018; Kumar et al. 2014). In membrane distillation crystallization, initially, the feed/wastewater undergoes membrane distillation wherein the feed is heated to generate vapors that receive preferential passage through the hydrophobic, non-porous membrane. The vapors are then subsequently condensed on the permeate side by bringing them into contact with a coolant. The concentrated feed bearing the compounds are then subjected to selective membrane crystallization/integrated chemical precipitation-crystallization to extract the target compounds (Tun et al. 2005). The process can also be used to recover the solvent by selective condensation and crystallization. Membrane distillation crystallization (MD-MCr) has been used to recover compounds like sodium sulfate, struvite characterized by a high degree of separation, and pure thenordite crystal formation (Quist-Jensen et al. 2017, 2018). This process of MD-Mcr uses thermal and pressure gradients as the driving force. Another alternative is Osmotic Membrane Crystallization (OMC) wherein the concentration gradient is used as the driving force. A synthetically prepared solution called the draw solution having a greater osmotic concentration than the feed is circulated in the permeate side while the solution to be concentrated is circulated on the feed side. The feed and the DS are separated by a semi-permeable membrane, which allows selective solvent transport. The difference in the concentrations of the two solutions creates an osmotic pressure gradient between the feed and the DS. Resultantly, the solvent moves from the feed to the DS via the semi-permeable membrane. As the process progresses there is a gradual increase in feed concentration due to solvent removal. Consequently, the concentration of the DS decreases and it progressively becomes dilute. The process continues till the osmotic equilibrium between feed and DS is reached. The process of OMC provides a sustainable means of crystallization with reduced energy expenditure. The process suffices with thinner membranes due to reduced transmembrane pressure differences. This decreases the mass transfer resistances leading to higher separation fluxes (Das et al. 2021). Owing to its multifarious benefits, it has received increased research attention in the recent past. Several studies have researched on OMC for value-added product recovery in diverse feedstocks ranging from fruit juice concentration to saline brines (Kujawa et al. 2015). The operational flexibility of the process has been translated to gas–liquid contacting wherein preferential separation of CO_2 and SO_2 from flue gas and its subsequent crystallization was carried out. The process demonstrated competitive flux and crystal yield (Ye et al. 2015; Salmón et al. 2017; Lee et al. 1997; Ye et al. 2016). Notwithstanding the benefits of each type of MCr, there are several hurdles before researchers which need to be addressed before field implementation. Areas like recovery of antisolvents, draw solutions, temperature polarization in MD-MCr require a greater degree of focused interdisciplinary and pilot level studies. Nevertheless, these are promising sustainable technology options that need to be actively pursued.

19.2.2.2 Membrane Bioreactors (MBR)

As the name suggests, the MBR's offer a unique combination of membrane separation technology with biological treatments and more specifically biological reactors. The most basic configurations in an MBR are the submerged type where the membranes are immersed insitu in the bioreactor and the side stream type where the membranes are housed in a separate arrangement downstream of the bioreactor (Fane 2002). These configurations using commercial UF and MF membranes, initiated by Dorr–Oliver Inc have received ubiquitous usage in sewage water treatment plants (Sutton et al. 1983). The submerged MBR is more commonly used due to its ability to handle higher mixed liquor suspended solids. The aerators installed below the membrane modules in submerged MBR serves the dual purpose of cleaning the membrane modules and providing oxygen for the process. Alternatively, there is anaerobic

MBR remediation. These are capable of treating organic and inorganic components including heavy metals and trace organic components (Troc's) (Torre et al. 2015; Arevalo et al. 2013). The additional benefit of the anaerobic MBR's is the generation of methane-rich biogas from the organic loadings of the feed. This offsets the energy requirements for the process.

The MBR's represent a huge potential technology for value-added product recovery from wastewater. The high P and N loadings present in biological origin effluents are converted into NH_4^+ and PO_4^{3-} compounds which can be recovered separately or co-precipitated as in struvite (Deng et al. 2014). Comparative life cycle assessments have established anaerobic MBR's to be more energy-efficient and sustainable than conventional aerobic activated sludge processes. Furthermore, product recovery rates in terms of dissolved methane yields were found to be higher in the latter (Harclerode et al. 2020). However, recent research works carried out by Jiang et al. (2021) have highlighted the efficiency of anoxic MBR's in terms of sludge denitrification, phosphorus uptake, higher nutrient storage and release potential of the resultant MBR sludge (Jiang et al. 2021). Combination of anaerobic hydrogen fermentation and MBR using synthetic brown and grey wastewaters representing sanitation effluents established stabler wastes and competitive hydrogen generation efficiency (Paudel et al. 2014).

There are several novel innovations in the MBR technology which represent potentially process intensified, sustainable resource recovery options from wastewater. One such example is the osmotic membrane bioreactor which incorporates the principle of forward osmosis. Here the UF/MF membrane is replaced by a dense FO (Forward Osmosis) membrane. A synthetic solution called the draw solution is circulated on one side of the membrane and the other side is the activated microbial suspension. This creates an osmotic gradient across the membrane. Due to this, the selectively permeable membrane dewaters the sludge suspension. The driving force for the solvent transport is the concentration difference powered osmotic gradient (Blandin et al. 2018). The diluted draw solution that is produced can be reused. It can be subsequently treated to recover clean water and recover draw solutes. Concentrated brines and fertilizers as draw solutes provide the flexibility of direct end-use. Owing to the high concentration attained in this process, there is scope for selective extraction of the desired components from the concentrate, such as precipitation of phosphate by addition of calcium salts (Li et al. 2018). Other hybrid configurations of membrane bioreactors include electrochemical MBR, algal MBR, fungal MBR among several others. The algal and fungal MBr's utilize different species of fungi and algae for WWT. Fungal MBr's can also be coupled with other novel separation techniques like photocatalysis for complete wastewater treatment (Deveci et al. 2016). The use of microalgae in algal MBr's has demonstrated reduction of WW BOD levels with a simultaneous yield of biofuel, bioplastic, epoxy polysaccharides, and other carbon–neutral products (Arora et al. 2021). The utilization of biocatalysis potential of the microorganisms can is effective for selective product formation. The combination of biocatalysis and WW degradation kinetics of MBr's can be integrated with electrochemical cells for electricity production. The MBR's provide a robust and sustainable option for wastewater treatment and scope of value addition by way of product formation or energy production. However, there are challenges like biofouling of membranes, low fluxes, and high energy consumption for activated sludge layer production, maintenance and operation of the MBR. The process design is also fairly complex necessitating skilled manpower for running the MBR facilities. There are also aspects of loss of nutrients from wastewater by way of gaseous release in the form of CO_2, H_2S, NO_2, etc. which need to be addressed. If the gases are of a substantial amount, then a recovery unit operation can be added to the process downstream. However successful operation of commercial level MBR plants bears testimony to the fact that the problems described above can be ameliorated.

19.2.2.3 Ion Exchange and Electrodialysis

Ion exchange membrane transport is a selective hybrid application that is manifested in preferential ionic transport across the membranes. Here, the membrane surface is coated with ion exchange resins (cation on anion exchange resins) depending upon the feed composition, or charged ionic groups are incorporated into the polymeric structural framework of the membrane. As a means of wastewater treatment, it helps in selective removal of ions by replacement from its matrix before uptake of ions from the solution. This is supplemented by membrane separation where the movement of other ions or molecules are impeded due to their selectivity and high separation efficiency. Ion exchange membranes have been used in desalination, electrodialysis, industrial WWT, and chemical industry as a whole (Strathmann et al. 2013; Tanaka 2011; Khoiruddin et al. 2017). On exhaustion, the membranes can be regenerated to release the adsorbed ions.

This property of selective separation by ion exchange membranes has the potential to be applied in the extraction of target compounds from real-life wastewater which is a complex mixture of diverse constituents. Researchers using clinoptilolite zeolite columns and commercial dow resins were able to selectively precipitate >98% P and 95% N from complex wastewater. The process was also able to precipitate other impurities present in the feedstock such as Al3+, Ca2+, and Fe (Williams et al. 2015). Modified electrodialysis, an evolved application of ion exchange membranes can be used to recover different compounds from heavy metals bearing feedstocks and saline effluents (Devda et al. 2021).

The high efficiency of the ion-exchange process can be used to separate micropollutants from wastewater, thereby facilitating the process of recovery of major contaminants from the effluent. An innovative combination of biochar produced from biosolids and integrated ion exchange resin zeolite has demonstrated effective reduction of micropollutants followed by recovery of PO_4-P and NH_4-N from nutrient-rich anaerobic treatment effluent (Tong et al. 2018). In comparison to conventional biological nutrient removal plants that are operated to recover nutrients from municipal wastewater, ion exchange processes have shown to reduce projected plant cost by 17% by simple integration of IEX processes with conventional activated sludge technique. The process was able to recover nutrients in the form of ammonium sulfate $(NH_4)_2SO_4$ and hydroxyapatite $Ca_5(PO_4)_3OH$ (Huang et al. 2020).

In electrodialysis cation and anion exchange membranes are arranged alternatively forming a stack. This stack is subjected to a differential potential gradient. Under the influence of this driving force, the anions present in the feedstock will pass through the anion exchange membranes and try to migrate to the anode (positively charged electrodes). However, the movement of the anions will be intercepted by the cation exchange membranes. The same principle is applied for the cation transport which possesses a tendency to migrate to the cathode (negatively charged electrode) but are intercepted by the anion exchange membranes. As a result, it can be applied for the complete removal of the different ionic contaminants present in the effluent. Furthermore, if the contaminants are of a sizeable quantity, they can be recovered by selective ionic release and subsequent regeneration of the ion exchange membrane (Yang et al. 2016; Das et al. 2017). Bipolar membrane electrodialysis working on H^+ releasing mechanism has been used to recover organic acids by ionic exchange with H^+ ions from fermentation broth. These include acetic acid, sebacic acid, succinic acid among others (Yu et al. 2000, Zhang et al. 2009; Szcygielda et al. 2017). Novel metals like arsenic, zinc, and copper could also be simultaneously recovered using "electrodialysis" which separates movement and bivalent ions from a mixed feed solution (Reig et al. 2018).

There are numerous other variations of electrodialysis to produce valuable compounds and generate electric power. Reverse electrodialysis is one such application where electric current causes changes in the direction of ionic migration of the electrolyte across a stack of cation and anion exchange cells. The difference in the electrochemical potential is harnessed to generate electricity (Zhao et al. 2018). The interesting and innovative applications of ion exchange and electrodialysis across diverse domains represent potentially scalable applications for selective wastewater valorization.

19.3 Pilot-Level Studies and Industrial Applications

The different resource recovery technologies discussed in this chapter are in various stages of research and field implementation. While some are in nascent research stages others like struvite recovery have been studied industrially. Let us look at some of the pilot-scale and commercial-scale applications to understand the technology readiness level, challenges faced in practical implementation, and potential of waste valorization. Membrane bioreactors and anaerobic digesters have been implemented on a commercial level to utilize effluents like biomedical wastewater, municipal wastewaters for the generation of bioelectricity (Souza et al. 2011). These systems successfully convert the COD loadings of the organic-rich wastewater into electricity (Shin and Bae 2018). Pilot studies conducted on a photosynthetic bacterial membrane bioreactor for treatment of complex COD wastewater to recover multifarious compounds like protein, polysaccharides, bacteriochlorophyll, carotenoids, demonstrated satisfactory product yield while maintaining the output water quality standards when operated at the pilot level for a continuous period of 440 days (Lu et al. 2019a, b). Several compounds like volatile fatty acids (VFA), Polyhydroxyalkanoate (PHA), cellulose, nutrients like nitrogen and phosphorus recovered from wastewaters have been an alternative source of supply at the industrial level. These compounds recovered by biochemical means are often more sustainable than their industrially synthesized counterparts in terms of biodegradability, cost-effectiveness, and overall eco-friendliness. Comparative performance and economic analysis of products like acetate, propionate, struvite production have established the possibilities of increasing market potential (Crutchik et al. 2018; Akyol et al. 2019). Pilot level studies conducted in Trapani (Italy) on a 400 m^2 membrane powered reverse electrodialysis was able to achieve a power output of 1 KW using saline wastewaters and concentrated brines as feedstocks (Tedesco et al. 2017). Struvite recovery from the ammoniacal and phosphate-bearing wastewater fractions is the only avenue that has received intense research focus. Numerous laboratory, as well as pilot-scale studies, have been conducted for struvite recovery applications. Diverse integrated pilot-level studies have been undertaken in this domain. A combination of ferric chloride-polyacrylamide followed by coagulation-flocculation technique for WWT with simultaneous precipitation of struvite from a raw swine effluent was undertaken in the pilot-scale batch facility, demonstrated 98% PO_4-P removal and 15% NH_4-N removal from the effluent by producing struvite (Laridi et al. 2005). A pH of around 8.2 and CRT of 8–12 days yields struvite crystals of commercial quality (Adnan et al. 2003). Even struvite has been successfully isolated from a pilot-scale system using NH_4^+ and PO_4^{3-} bearing urine as a feedstock. The plant operated continuously for one year demonstrated 90% PO_4–P purity struvite pellets with 0.3–6 mm in diameters in the Netherlands (Zamora et al. 2016).

Industrial applications of reverse electrodialysis and ultrapure water production in the USA by saltworks technologies and XZERO system technologies have been undertaken towards simultaneous water treatment and energy production (Panagopoulos and Haralambous 2020). Various commercial level zero liquid discharge techniques in different fields in countries like China, Japan, India also stress on the potential and feasibility of wastewater valorization techniques.

19.4 Conclusion and Future Work

The following are the major conclusions that can be drawn:

(1) Waste-to-wealth technologies focusing on selective recovery of valuable from waste streams represent a paradigm shift in the domain of wastewater treatment that simultaneously offers economic incentivization and resource conservation.
(2) The compounds present can be recovered singularly or separated in the form of a tertiary compound for additive dosing.
(3) The conventional techniques of leaching, electrochemical methods have been successful for solid and liquid waste streams. The microbial techniques

specially those following the bioreactor route have already been implemented in fields like municipal wastewater treatment

(4) Membrane separation techniques are particularly useful in selective recovery characterized by sustainability and operational flexibility. They offer easy integration across different technological platforms leading to intensified hybrid process development.

(5) Novel developments in the fields of nanotechnology, photocatalysis are promising for quick and high precision waste valorization. However, more pilot level studies are required for ascertaining the techno-commercial viability.

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Chapter 20
Socio-economic Environmental Sustainability and Indian Mining Industry—A Perspective

Abhay Kumar Soni

Abstract Environmental degradation and socio-economic issues are the most significant areas of great concern. In an industrial area, it has direct linkages and visible results on the social fabric. An in-depth understanding of the environment and its degradation reveals that the impact could be caused on air, water, land and any other contributory component of the earth system, either biotic or abiotic. Since the socio-economic impacts are from among the many, in this chapter of book, the author has tried to concentrate and describe the socio-economic aspects only that deals with the sustainability concerning the Indian mining industry. In recent decades, rapid industrialization, progressive development has left innumerable and alarming impacts on the ecology and environment and it is evident that to progress holistically, environment protection and societal development must go hand-in-hand. No strategy to tackle the environmental challenges is complete without the coverage of societal parameters; hence, this topic in the book has relevance and benefits. The socio-economic dimensions of the environment are immensely helpful in terms of raising the standard of living, employment generation and literacy enhancement which are, of course, very serious issues for society. As evident, different regions have different parameters for the community and region development, it is necessary that an in-depth and site-specific understanding shall be made. In this chapter, the author has defined the methodology of socio-economic impact assessment and evaluation, the framework for environmental sustainability to tackle the environmental degradation menace, industry–community relation, etc., emphasizing that mining enterprises are useful for the societal development of rural areas, where mines are generally located. To cater for the progress of society, we must address the social issues and challenges more diligently. By doing so, the major issues of industrial unrest can be addressed properly for the masses. It should also be realized that socio-economic environment impact evaluation and analysis, ignored mostly, shall be handled on priority.

Keywords Environment · Socio-economic impact · Sustainability · Mining · Indian mining industry

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20.1 Introduction

The social environment includes an individual's social, economic and political condition wherein he lives. The moral, cultural and emotional forces influence the life and nature of individual behaviour. Interlinkages between the environment and society, which may be, 'an open society' or 'a closed society', are already established and known. An *open society* is very conducive for individual development, whereas a closed one is not that conducive for development. Together with the social environment, the *physical environment,* common to any individual in specific circumstances or situations, is also a key. A person when getting a good milieu (natural environment) or society feels cheerful and satisfied, which is the part and parcel of a healthy and good societal environment. Hence, *the social environment* is immensely important to humans as well as human enterprises (industry), from among all other environmental component types, namely air water or land, that cause environmental degradation. It is the society and its immediate social surrounding which helps him/her to adjust every individual in achieving the targeted goal and overcoming the barriers of life.

Mining, an important economic activity, has major societal impacts. It affects the different spheres of industrial society right from income to daily routine life. Focusing, mines and mining regions it is always desirable that development should be environment-oriented. Regional development and economic progress, if both moves together the green environment is protected and saved naturally. Population dynamics (age groups, birth/death rate, sex ratio, life expectancy, dominant religion and popular language) literacy, health status, communication services, land holdings, per capita income, unemployment, occupational structure define the socio-economic progress of development in a particular region or for a group of people in that region. In India, it is experienced and observed, that the coal mining regions often lack in social development compared to that of metal mine regions, despite better spending capacity of the former region i.e. coal mines.

The Indian mining industry produces varieties of 'minerals', about 95, of fuel (4), metallic (10), non-metallic (21), atomic minerals (5) and other minerals of minor and industrial category minerals (55) from across the 29 states and 7 union territories[1] (IBM 2018). The industry encompasses opencast, open-pit as well as underground mines of all sizes-small, medium, large and very large production categories. It is well known that many regions and their local economy are dependent solely on mines, hence mining and ancillary industries which are very big to play an important role in regional development. *Labour* and *trade* are at the centre stage of the growth, employment, transaction and distribution of these regions. Therefore, the social dimension of the environment is extremely essential to make progressive improvements. The industry and the government(s), from time-to-time advocate several guidelines for upliftment and rehabilitation of the people that affect the society and living in the mining areas. Needless to say with technological and educational interventions, better progress results are achievable.

[1] Now changed (28 states and 08 UT's).

Fig. 20.1 Interlinkages of society, economy and environment

The minerals, as a raw material for the industry, plays and drive quality of life not only in the whole society. Figure 20.1 shows the interlinkages that exist between society, economy and environment for sustainable development.

In industry and society social impacts, environmental degradation, its evaluation, assessment, causes and remedies is a major and significant point of discussion which in turn leads to improved quality of life of that area/region. In this chapter, an attempt has been made to describe and address them briefly.

20.2 Defining the Impact and Degradation

Scientific interpretation of the impact(s) is a good way to define. When the industrial investment is made and a mine is opened, environmental degradation is most likely a consequence that is often questioned too. On the one hand, people demand the development of the area by sitting industry, whereas, on the other, the hullabaloo of locating the industry in the area (negative impacts) start surfacing. Managers of mine and decision-makers have to handle it in reality and most significant among them is the industrial unrest caused either on one or another pretext. The environmental ground is the first reason followed by other social and economical reasons. To define the causative effect on the socio-economic front, the impact categorization has been done according to the different phases of the mining life cycle (Table 20.1). These are first examined and impact evaluated.

Table 20.1 Direct and prominent social impacts of mining in various phases of the mine life

Phases of mining	Name of phase	Direct impacts
Ist phase	Exploration and development stage	Immigration from other areas, job opportunities, infrastructure development, welfare amenities development and relocation, land-use changes, tax regime changes, business development for the local population
IInd phase	Exploitation stage	Environmental degradation, pollution and its different forms, accidents due to mining and ancillary operation, social unrest, e.g. strikes, lockouts, employee-related matters such as wage cut, welfare, perks and dismissal
IIIrd phase	Decommissioning/closure stage (Rao and Pathak 2009)	Job loss, insecurity and social tension, increased migration, polluted air and water environment, contaminated land, salvaging and social issues

20.2.1 Environmental Indices

The 'environmental indices' provide a condensed description of multidimensional environmental states by aggregating several variables (or indicators) into a single quantity. A meaningful environmental index is defined as an index or a tool to examine trends, highlight specific environmental conditions and help government decision-makers evaluate the effectiveness of regulatory programs. *Environmental indices* are not the only source of information but a researched methodology for an easy decision. If the variables, which describe environmental status, have easy measurability and comparability, they are meaningful (Udo and Heinz 2000).

Numbers of environmental indices had been developed and proposed in the literature (Ott 1978). Many researchers claimed and applied them to fulfil the need for environmental evaluation. SEI and QOL indexes are also one of them and if explained or quantified, they are representative of the socio-economic side of the environmental scenario that serves as meaningful decision-making tools for the best solution.

20.2.2 Impact Predictions

Extrapolative methods, intuitive forecasting (Delphi techniques), trend extrapolation and correlation, metaphors and analogies, scenarios, dynamic modelling (input–output model) are some known techniques to predict the socio-economic impacts.

Both primary data and secondary data may be used for the analysis. Based on the surveyed data, the interrelationship of society and industrial activity may be explained, and the quality of life in the area can be predicted in advance to assess the future trend. A predictive assessment can also be made that is consistent with the past and the present socio-economic scene of the study area.

In this book chapter, QOL as an index has been advocated which is a 'single number index' easy to present and communicate. This index being discussed is a societal tool based on the multidimensional approach and has tremendous scope for further development that may be refined and made penetrating for the industrial need of the mining industry to be acceptable to a maximum.

20.3 Socio-economic-Based Framework for Environmental Sustainability

The socio-economic-based environmental sustainability framework is a framework capable to deliver the fruits of development that reaches the grassroots level in the far-flung areas. These contribute to the human development work for the poor people (WDR 2004). It is a well-known fact that mining activity causes an impact on the environment and ecology of a region. When a mine becomes operational, environmental disturbances either *positive* or *negative* become perceptible and being noticed by many (Canter 1996). To assess such impacts, at various stages in the life of a mine, we have a set of environmental impact assessment (EIA) procedures. Based on the number of parameters of air quality, water quality and land quality, environmental degradation is assessed. Whatsoever may be the impact, it is the society and the economy which are directly or indirectly affected and the concerned industrial activity is blamed for it. If we address the fallout of industrial activity, correctly 'project-affected people (PAPs)' and the society feel that justice is caused and measures taken are adequate to nullify the negative impacts. This also balances the economy indirectly.

Though a plethora of rules, acts, regulations and bye-laws exist to evaluate and regulate the environment scenario of a site or project, either pre-project or post-project, convincing the PAP's and individuals are the first and foremost requirement to get a green signal for smooth industrial operation. This has a direct link only when sound and satisfactory criteria are in place. By and large and as a general common approach, to reduce the operational difficulties of the industrial enterprises' environmental parameters, viz. air quality, water quality or land quality are well-attended. Their management is done through science and technology in such a manner that degradation is nullified, and pollution problems are solved to the maximum. In this perspective, the socio-economic parameter's-based evaluation procedure has been focused here in this chapter for evaluation and assessment. The socio-economic parameters are since directly attached with the 'PAP's and individuals well-beings, its penetration is direct. The acceptability of such an evaluation procedure, including its decision for the industry and public, is not that easier because of its manipulative nature. Sometimes its result in society is irreversible and irresistible causing even industrial unrest too.

During the monitoring of the environment and review of the status of socio-economic factors, it was found that these factors are both direct (tangible) and indirect (non-tangible) (Dhar and Saxena 1994). The biggest difficulty is the circumstance encountered, and the variety of measurement units in which environmental variables can be expressed, e.g. kilograms and pounds in the case of pollutant loads, economic prosperity in terms of the currency earned in rupees or land holding in terms of hectares, etc. This may cause difficulties for the comparison of environmental states as the units of expression are avidly different. Therefore, to devise an index that fits statistically into a single number (common unit) and at the same time, a true representative of the scenario as well should be overcome. To assign weightage in indexing methodology in acceptable manner approaches in three classes, namely 'data-driven', 'normative' and 'hybrid weighting', were possible for various parameters (Koen and María 2013). A comparison of advantages and drawbacks for the respective category can be done accordingly. It is necessary, if not essential, that the designed index should pass the rigorous test of 'acceptable to the maximum'. Here, it is significant to mention that the socio-economic framework is an easily understandable approach provided unanimity is achieved. Socio-economic-based indices have flexibility, versatility too to serve the very purpose of evaluation and assessment of the environment in both pre and post-project periods. If designed properly, the framework is apt for the local as well as regional needs and may prove to be a beneficial 'decision-making tool' for the environment, society and industry (mining). But, for improved work performance, all major domains of the environment are a must and need to be studied.

However, a strong need is always felt to design and develop a methodology, which can prove scientifically and correctly, the existence of the industry. Having such a framework, an assessment of the not, an easy impact and degradation can be defined by—(a) Socio-economic Index (SEI). (b) Quality of life Index (QOLI). One may consider these as a norm or criteria or a factor for an individual mine or a community/society. Despite criticality, the 'well-beings' of people/citizens, governments and industry can be measured and the progress of the mining areas/regions elaborated in an integrated manner.

India is a developing country, with its vast mineral resources and human resource capabilities. Its mining industry, socially different from the rest of the World, is an industry that is rural area-based, with corporate in cities. Research studies indicated that developmental agenda and societal schemes of government can be accelerated, applied quickly, and benefits are extended to the common masses of a mining region by

(a) Employment generation in rural areas and ancillary employment opportunities in both rural and urban areas.
(b) Ensuring and enabling the local people involved in the monitoring of developmental activities.

(c) Infrastructure development including development of public facilities/utilities.
(d) Enhancement of literacy rate and educational facility.
(e) Positive impact on the development of health care facilities.
(f) Cultural changes and measures that provide freedom.
(g) Reduction in-migration from rural to urban areas (relocation, resettlement, rehabilitation and displacement of tribals and PAPS).
(h) Encouraging measures that reduce poverty, i.e. land holding capabilities, shelters/settlement, economic well-being and business growth.
(i) Improved lifestyle and its quality.

In the foregoing paragraphs, it will be discussed how these are applied for the project assessment and how the assessment criteria are decided.

20.4 Measuring Quality of Life: The Methodology

Before the 1970s, traditional objective indicators were accepted as suitable predictors of human welfare worldwide (George and Weitz 1977). However, in the late 1980s, social scientists concluded that quality of life (QOL) and the country's Gross Domestic Product (GDP) could better describe the financial position of the society. The same was adopted in India, and factors such as personal income, housing, education, health and family welfare were recognized as indicators to define the quality of life, which is none other than a socio-economic factor. Later, in the late 1980s and into the 1990s, progressive development took place to monitor and measure it. Over the years, how QOL should be defined and measured has been focused. It was recognized that both subjective indicators (demography, health) and objective information (wages and housing expenditure, infrastructure) are necessary to measure QOL, and accordingly, measures/parameters were considered in assessing QOL of mining communities using the economic, social, political, and even spiritual dimensions, though physical environment (air, water, land and noise) still dominated the assessment scene in industrial companies and organizations.

QOL can be defined as a function between the objective conditions of life and the subjective attitude. The objective conditions are those factors that can be assigned a numerical value, e.g. housing, food, health, education, assets, recreation, fuel and energy consumption, to determine the life quality. For assessing the quality of life, an index called the quality of life index (QOLI) has been suggested by Saxena (Saxena 2002) for coal mining areas. Similarly, for iron ore mines of the Goa region, Ligia Noronha also suggested an index (Ligia 2001) which were purely based on social and economical parameters. The QOL method is a value function-based empirical methodology that takes the course of data collection from a specific site through a structured questionnaire prepared for the families or individuals. To know the ground reality, a survey based on a questionnaire in a pre-designed format needs to be conducted (Annexure I). Based on the real-time data, a detailed analysis is done. Available statistical methods and software tools are helpful to evaluate the interrelationship between QOL parameters and validate the analysed data as well.

This has been observed that the QOL methodology is very easy to use and describe. It is a tool for assessment and monitoring of the conditions that affect the living and working conditions of people. Whether we measure the quality of life in terms of ‘subjective variables’ or ‘objective variables’, one has to ameliorate the objective variables for improvement. To improve the life quality of a community or group of people, it is necessary to establish a relationship between subjective and objective dimensions of QOL. These dimensions in a mining site/complex vary significantly with the industry performance during the different phases of the mining operation. Adequate measures are required for a better and improved quality of life in the mining region if not taken, the situations may berserk from better to worse. Quality of life (QOL) measurement is thus meant to provide a tool for community development that intends to monitor social status in an understanding manner very aptly, hence recommended for future use. To estimate the QOL, the individual/families and mining complexes (group) are assigned scores (or weightage) on a 1–100 scale. The scores so chosen are based on the empirical approach (arbitrary) and may be changed/altered/fixed afresh to suffice the evaluation purpose. For different parameters, value function curves are plotted (Fig. 20.2) and the trend is established. These value function curves are based on the primary parameters (housing, water, food and nutrition; QOL score = 2) and secondary parameters (sanitation, health and safety, education, medical facility, public transport and communication, fuel and energy, family assets, transport means, per capita income and recreational facilities; QOL score = 1).

Eq. (20.1) is used to assess the quality of life (QOL).

$$\mathrm{QOL} = \left[(\mathrm{fp}(1) \cdot (\mathrm{fp}(2) \cdot \mathrm{fp}(3) \cdot \mathrm{Wp}^{n}) \left(\sum_{n=1}^{10} \mathrm{fsi} \cdot \mathrm{Wsi} \right) \right] \tag{20.1}$$

where

fp (1–3) = Value of primary parameters as determined from their respective value function curves.

Wp = Score (weightage) of primary parameters (normally 2).

n = Number of primary parameters (1–3).

fsi = Value of secondary parameters as determined from their respective value function curves.

Wsi = Score (weightage) of secondary parameters, taken as 1.0.

• word ‘p’ refers to the primary parameters (1–3) and ’s’ refers to the secondary parameters

• 1, 2, 3 = Housing, water, food and nutrition (calorie intake by an individual)

• n = 1–10 = Sanitation, health and safety, education, medical facilities, public transport and communication, fuel and energy, family assets, own transport means, per capita income and recreational facilities.

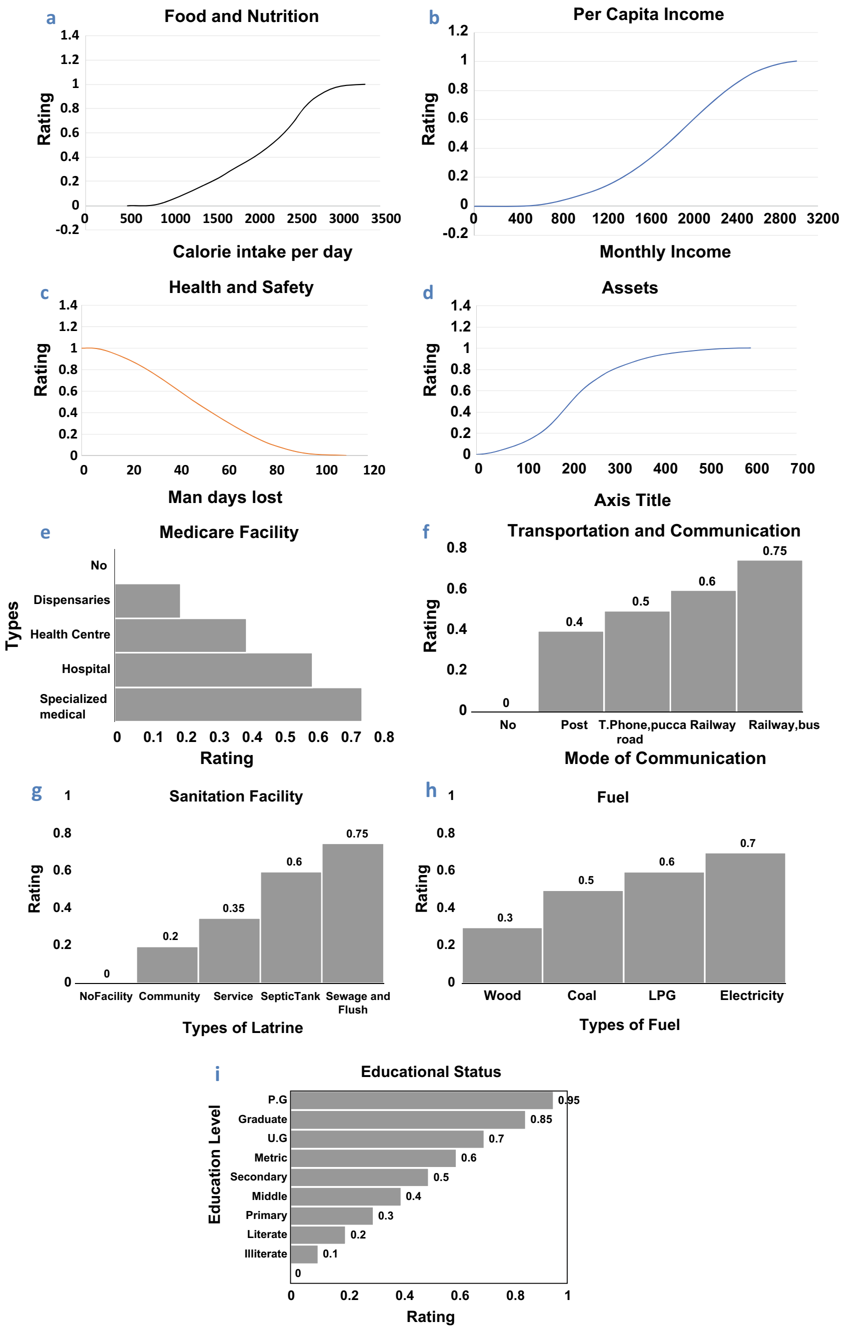


Fig. 20.2 Value function curves. **a** Food and nutrition; **b** per capita income; **c** health and safety; **d** assets; **e** medicare facility; **f** transportation and communication; **g** sanitation facility; **h** fuel; **i** educational status

Table 20.3 QOL ratings

S. No.	For individual/families		For mining complexes	
	QOL score	QOL rating	% of families having poor QOL	Rating/gradation
1	< 6	Poor	> 10%	Poor
2	6–20	Fair	5–10%	Fair
3	20–40	Good	< 5	Good
4	40–80	Very good		

To make an assessment, the QOL rating for the individual/families and complexes has been scaled and defined (Table 20.3). By performing site-specific socioe-conomic study, the overall QOL can be designated as poor/fair/ good or very good and scientific interpretation can be explained.

20.4.1 QOL Determinants

Quality of life instrument presents the best and most satisfying means to assess the social and economical progress and well-being of all the major stakeholders of the mining region, i.e. the government, company and community. QOL determinants are a measure to capture what mining is doing for the region and the local communities, e.g. (a) How social characteristics (basic amenities, literacy levels) are changed with time? (b) How sociopolitical and economic characteristics (income and asset, satisfaction level of an individual and community, perception of health and well-being, freedom, security and safety and activity) are altered or impacted?

Along with the QOL determinants, the core environmental parameters, i.e. air environment, water environment, land use and land cover changes due to externalities including the ecosystem health, i.e. changes in the ecosystem are equally necessary to understand the environment scenario and a person's well-being. If these tools are used regularly, and progress is recorded over time; the QOL tool is quite effective for the assessment of the living conditions in real society. Regional or local indicators may be needed depending on the choices and problems faced. QOL draws focus on community action and ways to improve their milieu, health, security and safety.

It is evident that the periodical changes in society are bound to happen, and therefore, it is monitoring through action plans is important for the assessment. Concerning the societal losses/gains, the agencies or the groups carrying out the planned action shall be made responsible and mitigation measures are taken accordingly. Criteria for mitigation and measurement have been listed in Table 20.2. Feedbacks from the affected population should be aimed at as the result of the progressive improvement of socio-economic status (Saxena 2002).

Table 20.2 Criteria for mitigation of social impacts

Criteria	Definition, measurement
A. Reversibility	How long will it take to mitigate the impact by natural or man-induced means? Is it reversible if so, can it is reversed in the short term or the long term?
B. Economic costs	How much will it cost to mitigate this impact? How soon will finances be needed to address this impact?
C. Institutional capacity	What is the current institutional capacity for addressing the impact? Is there an existing legal, regulatory, or service structure? Is there excess capacity, or is the capacity already overloaded? Can the primary level of government (e.g. local government) deal with the impact or does it require other levels or the private sector?

20.5 Implementation of Socio-economic Development Measures

A comprehensive picture of the living condition in an area, either a mining area or another general area could be described by SEI, QOLI (local or regional) and SDGI (regional/national). In the previous section, a short description of QOL has been covered, whereas in this section, the SDG index (SDGI) is a key evaluation component for national/state/region context along with the implementation components (i.e. CSR) that have been described. Encompassing major domains of the environment and economics, including sociopolitical conditions, implementation of the development measures through a mechanism shall be ensured for the sustainability promotion as well as for the advantage of industry and society.

Sustainable development goal index (*SDG index*) is a helpful tool for implementing social, economic and environmental measures. This is an internationally acceptable index that defines most of the parameters required for positive societal growth. Based on 100 national indicators, the SDG India Index (2019–2020) is prepared to track the progress and ranking of various socio-economic parameters. In India, it is prepared for the existing Indian States and Union Territories (UTs) for the seventeen developmental targets listed internationally by the United Nations (Fig. 20.3). SDGs assessment is derived from the national data (according to a developed framework) collected by the Ministry of Statistics and Programme Implementation (MOSPI). NITI Aayog, India's premier think tank, launches these SDGs as they are increasingly more relevant worldwide. From this index, sustainability in the mining area (region) can be derived comprehensively, e.g. Jharkhand, a mineral-rich state of India has mining, waste, water, environment and rural development are the key developmental factors (Fig. 20.4b) and are an integral part of the developmental agenda. The state has an overall SDG score of 53 (Fig. 20.4a) out of 100 meaning that the overall social, and economic development is of the medium level and scope exists for further improvement.

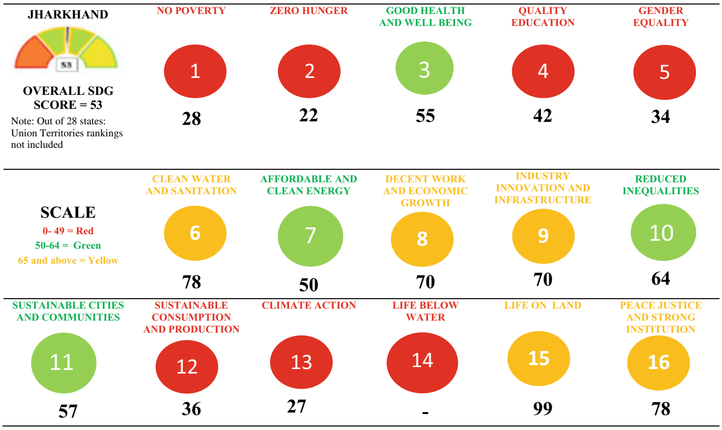
Besides the *SDG index,* one of the latest and the most modern implementation tool available to the industry is *Corporate Social Responsibility (CSR).* Responsible

Fig. 20.3 Sustainable development goals as framed by United Nations

mining business conduct and action plan always consider the CSR as one of the most strong socio-economic instruments or helpful tools (https://pib.gov.in/Pressreleaseshare.aspx?PRID=1568750). Depending on the stakeholder, requirement, either industry or beneficiary, the implementation strategy has been framed for CSR.

Corporate social responsibility (CSR) is a business approach that contributes to sustainable development by delivering economic, social and environmental benefits to all stakeholders. The purpose of CSR is to drive change towards sustainability and examine the social responsibilities of ongoing industrial activity on society. In India, the CSR clause comes under the Companies Act, 2013 and the Ministry of Corporate Affairs (MCA), Government of India is the nodal watchdog agency. For Indian companies, CSR Rules-2014 have been notified by MCA and Section 135 and Schedule VII of Companies Act, 2013 is promulgated.

In brief, CSR is the responsibility of the company towards the society that includes—poverty alleviations, (providing food to the hungry), malnutrition, health care, promoting education, promoting gender equality, setting up of homes for orphans, women, and senior citizens, animal welfare, the welfare of SC/ST/OBC's, protection of national heritage, rural development work, etc. The CSR-related activities have been undertaken by a company to fulfil its CSR obligations and guide towards environmental sustainability. In the literature, CSR topic is well-described (Masoud 2017; Dahlsrud 2008; Moir 2001) giving ideas behind CSR, its definition(s), theories of CSR (social contract's theory and legitimacy theory), stakeholder, indicators of CSR, ways of assessing and reporting CSR performance by the industry, etc. Our purpose here is not to describe all these different aspects of CSR but to make our point that CSR is an inescapable priority for business houses/leaders in every country including India. The CSR associated concepts are for the benefit of the environment, company, activists, stakeholders, local villagers and the whole community/society. The only thing that is needed is its enforcement and concrete actions that should be considered by the industrial organization.



(a) SDG score, Jharkhand state, 2020

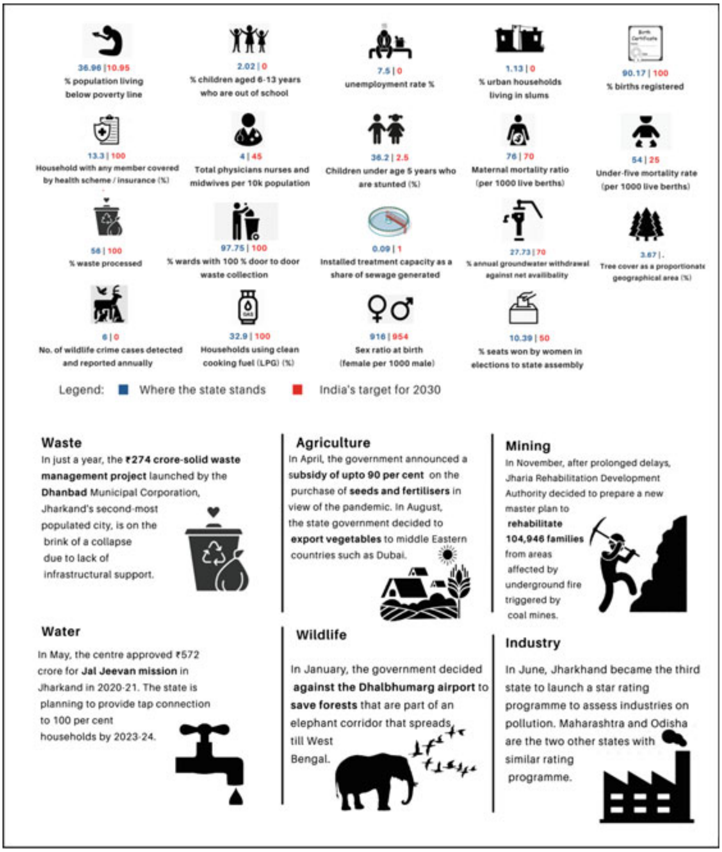


Fig. 20.4 Key development indicators for India and mineral-rich state of Jharkhand in 2020. *Source* CSE, 2021

Concerning the Indian mining sector, India's corporate laws and Companies Act, 2013, which came into effect in April 2014 describe various details about CSR and related matters and its intent is meant to improve accountability and responsibility of companies when it comes to business conduct. This Act makes CSR a matter of corporate governance from planning, monitoring and reporting perspectives and mandates that 2% of company spending be consumed in CSR activities. All over India, Indian companies of the corporate mining sector came forward to make use of a part of their profits to support social and economic changes and give back to the people of the region they are working with. Coal India Limited (CIL), the most vibrant and prominent coal mining organization of the country, had spent 2733.12 lakh rupees as *CSR* expenditure in the financial year 2018–2019 at its Kolkata HQ alone (Annexure III). MOIL Limited, another mining company, as part of its CSR activities created 'Self-Help Groups' at the mines which comprise women hailing from the remote villages. They are trained to make candles, washing powder, washing soaps, bamboo baskets, tailoring and various other vocational activities to make them self-reliant. This programme in MOIL has got a very good response and a huge success (Annexure II).

In this way, corporate, industry, NGO and PAP's together address the sustainability challenges for the mineral sector that forms a part of the raw material constituents.

In India, a state-wise comparison of CSR shows that a major portion of CSR expenditure is concentrated in few states while some are severely neglected. An analysis of cumulative CSR expenditure into various development sectors over the past five years (2014–2019) shows that the education sector has received the most CSR funds (30.1%) followed by health care (17.2%) and the least being rural development (10.9%). To improve the efficacy of CSR, NITI Aayog in collaboration with the state government launched a national programme called as '*Aspirational Districts Programme'* (*ADP*) in 2018. In this, 49 key performance indicators (81 data points) have been identified across various themes—health and nutrition, education, agriculture, and water resources, financial inclusion, skill development and basic infrastructure. These themes, mostly socio-economic parameters, have been considered crucial to maintaining the QOL and economic productivity of citizens (Chawla 2021).

20.6 Discussion and Analysis

A socio-economic profile is an outline characteristic feature of the region and its development. It gives a representative sketch of the social and economical condition of the people and the infrastructure build-up of the discussed locality. Quality of life (QOL) criteria have been used here for the evaluation of social and economic well-being. An interrelationship of impacts and QOL has been explained in Fig. 20.5 which obviously differs on a case-to-case basis. QOL, being a subjective concept has no standard or fixed yardstick for measurement. In a geographic domain, it varies

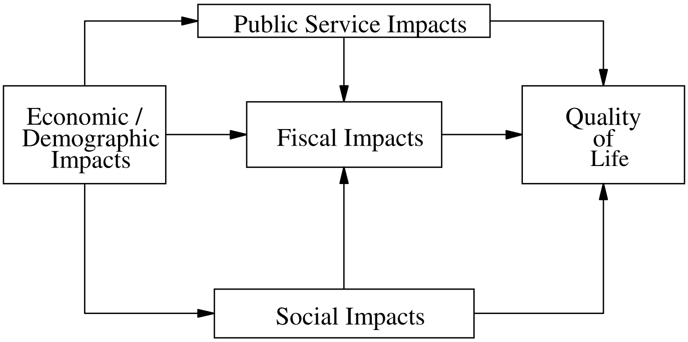


Fig. 20.5 Socio-economic impact and quality of life

with the place, time, availability of resources, educational status and aspiration of the society.

In developing the socio-economic-based index, i.e. QOLI, the biggest difficulty experienced is the variety of scales by which environmental variables can be measured; e.g. temperature is measured in Centigrade/Fahrenheit/Kelvin, whereas mass (weight) can be expressed in kilograms or pounds. Similarly, income pattern and occupation; assets; recreation; fuel and energy consumption; sanitation status; water availability and consumption, safety, etc., all have different units as their description criteria. In each case, the respective scale has no similarity at all. Thus, one has to take into account the ambiguity of scales, i.e. to make sure a sensible change does not affect the impact or reversal of the impact order.

Based on the subjective criteria, a comparison of the socio-economic status at the national level has been done with the mining areas of the Indian mining industry (Table 20.4). In this table, selected parameters are defined using relative terms, i.e. low, medium and high, average, present, dense, etc., the reason being the wide variance in their units of description. The status defined in Table 20.4 has been derived from multiple sources and records. My own experience and judgement have been utilized for the relative explanation; consequently, it is an approximation only for wider coverage.

Case study: Socio-economic studies are survey-based (site-specific) even then here, I am not describing any specific case study as an illustration for one particular site to assess the quality of life (QOL) in a mining region. As of 2020, in nearly all the mining regions of India, the social priorities are drastically different than it was earlier (Dhar and Saxena 1994); hence, rapid changes are inevitable. In Goa, iron ore mining is banned with court orders, and in coal mines, private participation for mining of coal has started. Infrastructure development in remote regions got acceleration in the later part of 2010. All these factors, together with the impact of the COVID-19 Pandemic on industry (Soni 2021), have changed the socio-economic status entirely. The most important of these are the facts that if mining is to happen, enabling conditions needs to be created and put in place to ensure local communities get benefited from the

Table 20.4 A comparison of the socio-economic status: national versus mining areas

S. No.	Parameter name	National status	Status in mining areas	Remarks
1	Demography/population Population density/km^2	High/dense 382 person per km^2	At par with the national average	Dense population in mining localities and industrial setup
2	Sex ratio (male:female)			Mining areas are mostly located in rural areas
	- Total - Rural - Urban	= 1000:933 = 1000:946 = 1000:900	At par with the rural average	
3	Literacy rate (%)	Total = 73% Male = 80.9% Female = 64.6%	Total = 67.8% Male = 77.1% Female = 57.9%	Less than the national average and at par with the rural average
4	Education facilities	Adequate Medium	Not adequate Low/less	Leading to migration from rural to urban areas
5	Housing/shelter	Low to average	Medium	Mining areas are planned areas
6	Food and nutrition	Low to medium	Low	--do--
7	Medical facility and health-related amenities	Low to medium	Medium	--do--
8	- Birth rate (BR) - Death rate (DR) - Male:female ratio	BR = 17.9% DR = 7.2% M:F = 52:48%	At par with the national average	–
9	Income [per capita income/monthly **i**ncome per household**)**	2018–19 = Rs 10,534 /- 2019–20 = Rs 11,254 /- (rise of 6.8%)	Less than average Progressive income pattern noticed in mining areas	* Data as per Ministry of Statistics and Programme Implementation, Govt of India
10	Occupation pattern	Mixed occupation of all types	Mainly mining	Agriculture and mining are the dominating occupation pattern of mining areas
11	Assets (land holdings)	Widely varying; average being medium	Low to medium	Industrial workers have better asset
12	Expenditure capabilities (as a percentage of income)	Widely varying; average being medium	Low to medium	Better standard of living in mining areas hence good expenditure capabilities
13	Recreation	Medium	Less to medium	Dependent on individual

(continued)

Table 20.4 (continued)

S. No.	Parameter name	National status	Status in mining areas	Remarks
14	Fuel and energy consumption (per capita)	22,351 MJ (2016–17) (In the year 2016–17 the energy consumption was 30% of world average; less than the world average) Elect. Consumption—1181 kWh	Medium and at par with the national average	Differs widely from area to area More energy consumption in coal mining areas
15	Sanitation status	Medium	Medium	At par with the national average and as per rural areas
16	Water availability and water consumption	Medium Average: 135 L per person/day (Nat)	Medium 110–120 L/person/day) less than the national average	World average water consumption is 300–375 L per person/day
17	Safety awareness	Medium to Low	High	Better awareness in mines and industrial establishments
18	Infrastructure facilities (transport and communication)	Medium	Medium to low (overall)	'Low' means lack of infrastructure facilities. 'Medium' means inadequate needs improvement. Some mining areas have adequate facilities
19	Migration pattern	Present (interstate and inter-country)	Present (from urban to rural areas)	Mostly for job opportunities

Note Data/statistics shown in the table above are drawn from multiple authentic sources such as Census, 2011 records and Govt of India ministries official websites commercial projects all through the entire life cycle, i.e. from the concept (start) to the decommissioning phase of the project.

As explained earlier, empirical criteria are the approach for socio-economic indexing to define and describe societal status. Since fast changes have been witnessed in mining society, therefore, let me search and explore the answer to the questions: (1) Does mining influence the QOL of the local people? (2) Can we compare the 2021 status with the 2010 or earlier status? The answers to these questions for this case study description are—in all those regions where mining is prominent, e.g. Goa, iron ore mining belt the mining influence the economics of the region significantly. Overall QOL for the Goa mining region was 6 in 2010, and it is 5.6 in the year 2021. This comparison between the past and present status shows a slightly declined status probably due to the mining ban and difficult social liveability conditions. In short, a comparison between two periods is feasible and helpful in defining life quality.

Mining activity and the results of the mining projects have to ensure that there is an improved quality of life in the region. QOL index between 07 and 10 for a majority of population be aimed at, of course, progressively. For locals, infrastructure development must take place, and more attention shall be given to better social and environmental health. The rights of people should be protected and the implications of degradation for mining or society be addressed properly and appropriately. The net result is fewer (or nullified) negative impacts of the mining as far as possible.

QOL has many and widely varying dynamic parameters, limits or constants. *Ligia and Subramaniya* assessed the QOL in the Goa mining region in 2005. Their results suggest that while there is a difference in objective conditions between mining and non-mining regions, there is no statistically significant difference in satisfaction levels between the two, except for the environmental domain. This is especially important in the case of women, who report higher satisfaction levels but overall have lower access to resources (Ligia and Subramanya 2005). Similarly, the quality of life index (QOLI) as determined in the Bhowra Coal mining area of Jharia Coalfield (1998) depicts that a total of 59.8% of families has QOLI $= < 5$, indicating that majority of the families are below the desired minimum quality of life. Nearly, 35.8% of families fair QOLI and only 5.2% of families had good QOLI, between 07 and 10 (Prushty 1998). Scrutinizing these two studies critically reveals that there seems no similarity in between.

20.6.1 Mining and Community Relation

In the context of socio-economic impacts and evaluation, the relationship between mining and community has the most important role because it is none other than a community that faces rungs of mining impacts. The dynamics of the industry are well known and the emerging paradigm put a focus on the ‘Social License to Operate’ (SLO), which is similar to the ‘public hearing clause’ of EIA (environmental impact assessment). SLO identifies a set of concepts, values, tools and practices that represent a way of viewing reality for industry and stakeholders within the context of corporate responsibility, competitive advantage and growth (Nelson 2006).

As regards the Indian mining industry, it is quite clear that for the smooth operation of a mine, all or nearly all, stakeholders must feel satisfied and kept balanced. At each operational phase of the mine, i.e. exploration, development, site remediation, from grassroots to the legacy, project sustainability is a must along with the industry and community relation. Undoubtedly, both industry and stakeholders, development and sustainability will remain at the forefront now and also in future.

20.6.2 Degradation, Population and Policy

Most people feel that environmental degradation is proportional to the number of people, as they are an effective means of environmental destruction. In the simplest possible terms, the total impact of a group of people on its environmental resources is the environmental impact per person multiplied by the number of people. It is expected that a population increase is bound to occur in developing countries contrary to the developed world. Although fertility rates in developing countries are mostly high to very high, many countries have started to decline in recent years. To some extent, this is a reflection of rising incomes, a part of socio-economic development. Increasing income, better standard of living and literacy are almost always associated with lowered fertility rates. Other important causal factors responsible for higher QOL are—reduction in infant mortality increased availability of family planning services and increase in educational opportunities especially for women, etc. Continued emphasis on these factors is in the best interest of people for socio-economic progress in the developing world, not solely for environmental reasons, but also to reduce poverty directly and to make it easier for the institutional developmental changes (Field and Field 2017). Hence, it is clear that the reduction in population growth rates certainly helps to reduce the overall impacts on its environmental resources and thereby reducing degradation. Also, one thing is apparent that sound socio-economic-based environmental policies have no substitute for their people's rights. It should be clubbed with the population either mining or agricultural to facilitate reduced environmental damages (Field and Field 2017). For the improved work performance, environmental degradation, population and policy have many conflicts of interest, as the case may be, either for the area or for the industrial enterprise.

To achieve the UN Sustainable development goals (SDGs) in the Indian mineral industry, there is very little regard to social responsibility and sustainable development implications. Of the 17 agreed SDGs, many aspects related to mining and geosciences including climate change, pollution and contamination, water, waste, minerals and energy. In the industry, issues such as corporate social responsibility (CSR), social license (SL), consent to operate (CTO), artisanal/small-scale mining

(ASM/SSM) have attracted great attention of the indigenous people and the government and becoming more vital for civil society, NGOs and other stakeholders. Especially, environmental concerns and people's rights for the local and regional development, of course, related to the industry come across many examples of responsibility and sustainability either at the policy level or the local subject discussion level. Hence, a more practical way to apply this social responsibility and sustainability awareness is through the social—SDG content. This should be introduced in the industry that includes community relations, human rights, gender issues, poverty alleviation, literacy, climate change, clean energy, e-governance, sanitation/health (occupational and general) and hazards, disaster and safety. The industry and its staff must utilize some of their time to reach out to the local community and engage them to be stakeholders in the project of socio-economic environmental sustainability.

20.7 Addressing Social Issues

Indeed, growing awareness about the environment has pressed the need to look at the socio-economic issues of industrial projects and affected persons (PAPs) from a fresh angle. To address these issues helps of the following can be taken

- Action plan
- Community development programme
- R&R Policy (Rehabilitation & Resettlement Policy).

Owing to the large land area, required for opencast mining, land acquisition becomes a stupendous task and the issue of resettlement and rehabilitation of affected people assumes immense significance. Thus, R&R is one major and difficult social issue for the community living within or in close vicinity of the mining projects. At some places, the population is sparse but at some places, population density is high, thereby creating problems beyond control. To create enabling conditions for the mining companies, effective social handling and management are necessary. Some of the aspects that need to be paid greater attention for the R&R issues are—monetary compensation; fixed recurring monthly allowance to the titleholder or the landholder for a designated period; income generation schemes (training/skill) for the PAPs, new employment alternative; compensatory land for resettlement of PAP's (land for land). All these issues are the responsible social issues, required to achieve the growth path. Their handling will be dependent on the defined plan, policy and programme of the company attending it.

According to the yearbook of the Indian Bureau of Mines published in 2018, the Indian mining sector had employed around 4.77 lakh people in the financial year 2018 (IBM 2018). The mining industry segment in the Indian state of Goa alone used to support about 300,000 people before being shut down by an order of the Supreme Court of India. With the dwindling industrial situation, social issues at the individual level and also at the community level, i.e. infrastructures (transportation by ships, rail, road, water, air, etc.), are considerably brushed up. Persons from the mining regions, including mineworkers who got affected can get better household income provided the improved QOLI is restored by removing the ban on mining, thereby obtaining better health care and nutrition for their families. Thus, it is evident that an enhanced/higher overall standard of living is possible with mining advancements. Fast-changing social scenarios and a vivid variety of different mining regions call for a site-specific in-depth study on socio-economic parameters. To address the social issues of the industry, mining and community relation (Sect. 20.6.1) must be understood.

Similar to the Quality of Life Index (QOLI) criteria for mining areas, as described here and methodology explained to address the social issues, the 'Social Progress Index' (SPI) is yet another method. The SPI provides evidence for social performance based on the basic human needs/dimension. Parameters, namely shelter, nutrition, basic medical care, water, sanitation and personal safety, form the basis for their evaluation and assessment. According to the US-based non-profit group—'Social Progress Imperative', India ranks 102nd among the 132 countries on the SPI index (ET 2014). The SPI is a measure of human well-being that goes beyond traditional economic measures such as GDP or per capita income.

As an end note to this chapter, it is added that the QOL cannot be raised unless we raise the texture of our thoughts and the depth of our understanding because the assessed QOL is only for the physical well-being, and we have to enhance both our mental and physical well-beings.

20.8 Conclusions

The given analysis concludes that a socio-economic-based environmental assessment mechanism is apt and best for the ongoing projects because it covers the overall regional development and economic progress and justifies the sitting of the industry in a better way. Since the basic objective of opening up of mine in any region is the social upliftment and economical gain, apart from the routine mineral production, hence socio-economic performance is a good indicator of governance competence to attain sustainable developmental goals. With this approach, industrial unrests (political and social issues) are minimized and the negative environmental impacts of mining activity are not accelerated further as they are being noticed regularly.

Mining is a long-term business, with hazards, risks and capitalistic costs. Many times, it becomes difficult to run the industry smoothly because of resistance from society. Hence, pre-assessed and evaluated, socio-economic status is helpful to address the general public concern directly and quite effectively. For decision-makers and policy formulators, at different levels, the socioeconomic-based sustainability development indicators meet the short-falls and potential gains criteria of present and future planning too. It is easy to implement it into practice for the individual mines and mining complexes as the industry is labour-centric.

Adequate *quality of life* in a mining region (>7) is therefore desirable to ensure societal development, which could be gauged in terms of employment, infrastructure and literacy enhancement of the local population or the region. Long-term benefits can be linked and expected with higher QOL. To reduce environmental degradation, protect society from the ill effects, preserve the ecology and improve the local economy, socio-economic environmental sustainability is the key and should be promoted.

20.9 Recommendations

Framing recommendations for the socio-economic dimensions of the environment is a stupendous task because it is difficult to reach a consensus. The analysis of the environmental sustainability framework, concerning the Indian mining industry indicates that to handle the environmental degradation menace the QOL should be at par with the national average and not below. Both, society and economic scene are fast-changing; therefore, periodical assessment and evaluation are recommended.

Acknowledgements I am grateful to the Director, CSIR-CIMFR, Dhanbad, for according permission and for extending his support for this technical contribution. As the author, I would like to duly acknowledge all my colleagues and friends for their direct and indirect help.

Disclaimer Socio-economic-related study and analysis, as described in this chapter, will be of help and interest to all in general and for the mining community, in particular, who are involved in planning and designing of mines and mining operations. Personnel involved in the decision-making for implementation and control of environmental mitigation measures, i.e. the management authorities including academicians, researchers and students will be benefitted directly. Conclusively, this can be stated that mineral excavation operation and impact on society be clubbed in such a way that economic gains are harnessed and well-beings of PAP's be ensured.

Annexure I: Socio-economic Survey Questionnaire (to be done on household basis)

Date of Survey: Name of person (who performed survey):

Part 1 of 3: Area/Region and its details

A. Name of State and District
B. Name of Block/Division
C. Name of Village
D. Name of Coalfield /Mining area
E. Name of nearest urban locality and its distance from the village

Part 2 of 3: General Social/Societal details

A. Name of head of household
B. Religion and Mother Tongue

C. SC/ST/OBC Category
D. Demographic Aspects

- Family details and its composition, age, sex, relationship, marital status, Handicap if any.
- Occupation of various members in the house (self-employed, farmer, shopkeeper etc.)

E. Housing and related aspects

- No of houses, ownership status, area of the dwelling, number of rooms, latrine/bathroom facility, livestock shed and open space if any
- Fuel used and its consumption details (Wood, kerosene, LPG, charcoal, electricity)
- Livestock details and type of animals (milching/non-milching). Are they owned for the owner's subsistence?

[Ask Question—How do you rate the general characteristic of the house you live in and are you satisfied with it the existing infrastructure facilities. If not why state reason?]

F. Infrastructural Provisions and its details

- Road and public utilities/facilities
- Water and sanitation facilities (Quality, type, access and availability for use)
- Electricity and its availability for use
- School, college and other educational facilities
- Medical facilities (Doctors, Hospitals, primary health centre/sub-centre, dispensary, family planning centre or other specify here)
- Market (daily/weekly hat) and shopping facilities (Daily needs, clothes, books & stationary, milk, vegetables, grocery, seeds, fertilizers, festive purchases. others)
- Religious places of your worship
- Recreational facilities (playground etc.)
- Gram Panchayat for civic support

[Ask Question—Are you satisfied with the existing infrastructure facilities. If not state the reason for it?]

G. Habits of the family (Smoking, drinking, tobacco consumption and others)
H. Major and chronic disease in the family

- Health status in the last 05 years including handicap, physically challenged and mentally disabled person if any; death, if any occurred in past five years.

I. Migration

- Are you or your family originally from this place?
- Have you migrated from another part of state or country, if so state details?

- Has anyone in your family migrated out if so state details including reasons if any?

J. Forward and Backward Linkages

- *Under this section please specify the frequency of visiting other places, no of the person of family who visited, transportation mode used and purpose of the visit shall be described*

Part 3 of 3: Economy of the people and its details

A. History of employment/Jobs performed

- Parental history; own job details, contribution to the job, if still being performed and its salient details such as the name of the organisation where a job is performed, salary obtained, place of work, previous employment etc.

B. Occupation of various other members in the house
C. Self Employed

- Type of work /job performed, regular or seasonal, income, place and earning.

D. Land Holding

- Type of land and its area (Cultivable /uncultivable, Irrigated, fallow, double-cropped, grazing, forestry, barren or other types such as land damaged or occupied by industry, subsided land etc.)

E. Cropping Pattern for agriculturists and income
1—Irrigated 2—Un-irrigated

- Rabi—Crop, Production,Area,income
- Kharif—Crop, Production,Area,income
- Other (For those, who are seasonally employed)—Employer, Income from job, No of days engaged, place of work and its nature

F. Any assistance from government schemes
G. Animal Husbandry and its Details, whether for self or common for all village
H. Expenditure Pattern
I. Banking and Other Financial Systems of the area—Salient details about surveyed household.

[Ask Questions—(a) What is your monthly take-home income? (b) Is it sufficient for you and your family? (c) How do you consume the income whether it is for self-consumption or family use (d) Are you satisfied with the set-up you have for your daily life? If not, state the reason for it?]
(Signature of Surveyor)

Annexure II: Corporate Social Responsibility (CSR) and Sustainability at MOIL Limited

Source: Annual Report, MOIL Ltd, 2019–20

Tricycle distribution Under CSR

Corporate social responsibility (CSR) in MOIL limited is a continuous process. MOIL has been carrying out CSR activities in a resolute manner for the past several years. The Company has framed a CSR policy, duly approved by the Board of Directors. Several schemes have been taken up and being implemented under CSR which broadly include the following:

- In the education and skill development initiative, MOIL is supporting various schools near its mines in the Balaghat district of Madhya Pradesh and the Bhandara district of Maharashtra.
- In a major step towards providing quality education to rural children, MOIL in association with DAV Group of Schools has constructed a large school at Village Sitasaongi, in Bhandara district with the overwhelming response for DAV-MOIL school of Sitasaongi. The company is in the process to open one more branch of this school at Munsar, Dist. Nagpur, which will cater to the need for quality education of rural children.
- Skill development program: Training on logistic skills, mine mate and blasters has been imparted to 217 youths including contractors' workers. As per NSDC's (National Skill Development Council) guidelines, MOIL has been engaging around 460 trainees each month for Apprentice Training.
- MOIL has also initiated the "Saksham Balika Programme" in which 15 girls belonging to Below Poverty Line families (BPL) have been selected for a Nursing course, in association with Apollo College of Nursing, Hyderabad.
- The company has tied up with Lata Mangeshkar Hospital, etc., for carrying out free cataract surgeries for needy people.

- Ten Organic Waste Converter Machines are being installed under CSR in various Gardens of Nagpur Municipal Corporation, which are used for converting organic garden waste to manure.
- The company has associated with a professional agency BAIF and Maharashtra Institute of Technology Transfer for Rural Areas (MITTRA), an associate organization of BAIF, Pune having vast experience in rural development programmes. MOIL has entered into MoU with MITTRA who has prepared a detailed project report for the project. Initially, 21 villages have been identified in Nagpur, (5 villages) Bhandara (11 villages) districts in Maharashtra and Balaghat (5 villages) district in Madhya Pradesh.
- MOIL is having 797 women employees, 13.32% of its total workforce of 5982 as of 31.03.2020. *Welfare Schemes and Facilities for Women Empowerment* has been taken e.g. *Mahila Mandals* are working effectively at all the mines of the company. Various cultural, social, educative and community activities such as adult education, blood donation camps, eye camps, family planning, etc., are being organized regularly, mostly for the benefit of women residing in the remote mine areas.
- MOIL is a labour intensive organization with 5982 employees on its rolls as of 31.03.2020. More than 80% of the total strength belongs to SC/ST/OBC (SC 19.91% ST 25.33% OBC 35.49%). The company is taking a keen interest in the development of the tribal population living in the vicinity of the mines situated in remote areas by adopting various measures e.g. adopting villages near the mines, providing financial aid, organizing training classes for self-employment schemes, providing training to the physically challenged persons and the person with Disabilities.

Briefly, MOIL has taken up various infrastructural development works like the construction of village roads, personal toilets, community halls, etc., in the vicinity of the operational area of MOIL's mines. Other major areas of developmental activities are—Livelihood; Education; Women Empowerment; Anganwadi based intervention; Water Resources Management; Community Resources Development; Agricultural Training; Infrastructure Development; Livestock Development; Training, Health, Hygiene, Cleanliness, Sanitation & Quality of Life improvement in the mining areas of MOIL.

Annexure III: Statement of CSR Expenditure for FY 2018–2019 of CIL (HQ)

(Source: Official website of CIL HQ, Kolkata)

CSR expenditure for FY 2018–2019

1	2	3	4			5	6	7	8
S. No.	CSR project or activity identified	Sector in which the project is covered	Projects or programs			Amount outlay (Rs. lakhs)	Amount spent on project or program	Cumulative exp. up to the end of FY 18–19 (Rs. lakhs)	Amount spent—directly or through implementing agency
			(1) Local area or other	(2) State	(3) District				
1	Cure and better management of Thalassemia by providing financial assistance for bone marrow transplants (BMTs)	Healthcare	Other	PAN India	NA	2000.00	1080.75	1680.75	6 hospitals across India
2	Eye surgery camps in 3 districts—East Midnapore, West Midnapore and Purulia (West Bengal)	Healthcare	Other	West Bengal	Midnapore, West Midnapore, Purulia	25.00	12.50	25.00	Help age India
3	Installation of 44 nos. of handpumps in villages of Sundarbans	Water supply	Other	West Bengal	South 24 parganas	97.83	47.55	97.55	South Sundarban Janakalyan Sangha
4	Construction of 400 nos. of Individual household toilets in villages of Sundarbans	Sanitation	Other	West Bengal	South 24 parganas	97.10	46.83	96.83	South Sundarban Janakaly anSangha

(continued)

(continued)

CSR expenditure for FY 2018–2019

1	2	3	4			5	6	7	8
S. No.	CSR project or activity identified	Sector in which the project is covered	Projects or programs			Amount outlay (Rs. lakhs)	Amount spent on project or program	Cumulative exp. up to the end of FY 18–19 (Rs. lakhs)	Amount spent—directly or through implementing agency
			(1) Local area or other	(2) State	(3) District				
5	Payment for the year-round cleaning and sweeping of 20 schools in Bidhan Nagar Municipality	Sanitation	Local Area	West Bengal	North 24 Parganas	10.91	5.63	5.63	M/s Service Master Clean Ltd
6	Development of charitable dispensary by way of installation of medical equipment	Health care	Local area	West Bengal	North 24 Parganas	10.92	1086	10.86	Ramakrishna Math Barasat
7	Cure and better management of Thalassemia by providing financial assistance for Bone Marrow Transplants (BMTs)	Healthcare	Other	PAN India	NA	16.80	2.61	10.12	Thalassemic s India
8	Construction of Blood Bank with component separation	Healthcare	Other	Uttar Pradesh	Kanpur	300.00	17.62	29,437	Indian Medical Association, Kanpur
9	Providing aids and appliances to differently-abled people	Welfare of the differently-abled	Local area	West Bengal	Kolkata	4.37	2.18	4.37	NRS Hospital, Kolkata

(continued)

(continued)

CSR expenditure for FY 2018–2019

1	2	3	4			5	6	7	8
S. No.	CSR project or activity identified	Sector in which the project is covered	Projects or programs			Amount outlay (Rs. lakhs)	Amount spent on project or program	Cumulative exp. up to the end of FY 18–19 (Rs. lakhs)	Amount spent—directly or through implementing agency
			(1) Local area or other	(2) State	(3) District				
10	Construction/Renovation of Prarthana Bhawan at Hooghly district	Women empowerment	Local area	West Bengal	Hoogly	4.89	2.44	4.89	Garalgaccha Vivekananda Samaj Seva Kendra
11	Kitchen cum dining hall complex at Ramakrishna Math Premises	Eradicating hunger and malnutrition	Local area	West Bengal	Howrah	10.00	10.00	10.00	Ramakrishna Math Belur
12	Financial Support to Center for Child Development for children with severe disabilities	Welfare of the differently-abled	Other	Uttarakhand	Dehradun	68.00	34.00	34.00	Latika Roy Foundation
13	Different development works in Purulia district of West Bengal	Rural development	Other	West Bengal	Purulia	3291.89	649.53	2610.70	The Energy and Resources Institute (TERI)
14	Road safety awareness campaign in K Kolkata	Others	Local area	West Bengal	Kolkata	69.85	15.82	68.42	Traffic Dept., Kolkata Police
15	Menstrual hygiene management project in Purulia district	Women empowerment	Other	West Bengal	Purulia	85.94	20.47	85.94	Nirmaan Foundation

(continued)

(continued)

CSR expenditure for FY 2018–2019

1	2	3	4			5	6	7	8
S. No.	CSR project or activity identified	Sector in which the project is covered	Projects or programs			Amount outlay (Rs. lakhs)	Amount spent on project or program	Cumulative exp. up to the end of FY 18–19 (Rs. lakhs)	Amount spent—directly or through implementing agency
			(1) Local area or other	(2) State	(3) District				
16	Construction of building to facilitate medical research and medical care for underprivileged people	Healthcare	Local Area	West Bengal	North 24 parganas	92.76	62.17	92.17	Institute of Pulmocare and Research
17	Training of 2000 persons at different centres of CIPET	Skill Development	Other	PAN India	NA	1290.00	353.46	353.46	Central Institute Engineering & Technology (CIPET)
18	Promotion of preventive healthcare in Assam	Health care	Other	Assam	Kamrup	31.45	5.25	31 0.45	NILA
19	Construction of student community hall	Education	Local area	West Bengal	North 24 parganas	31.22	20.14	31.22	RK Math Baranagar
20	Construction of road in Ghazipur	Rural development	Other	Uttar Pradesh	Ghazipur	99.13	25.45	48.23	PWD Ghazipur
21	Construction of 200 nos. of individual toilets under Swac hh Bharat Mission in Kathua, J&K	Sanitation	Other	Jammu & Kashmir	Kathua	74.00	24.00	48.66	District Administration, Kathua

(continued)

(continued)

CSR expenditure for FY 2018–2019

1	2	3	4			5	6	7	8
S. No.	CSR project or activity identified	Sector in which the project is covered	Projects or programs			Amount outlay (Rs. lakhs)	Amount spent on project or program	Cumulative exp. up to the end of FY 18–19 (Rs. lakhs)	Amount spent—directly or through implementing agency
			(1) Local area or other	(2) State	(3) District				
22	Installation of 100 hand pumps in Ghazipur Uttar Pradesh	Water supply	Other	Uttar Pradesh	Ghazipur	43.59	14.53	29.06	UP Jal Nigam, Ghazipur
23	Distribution of 120 nos. of blankets at SOS Children Village	Others	Local area	est Bengal	North 24 Parganas	0.93	0.93	0.93	SOS Children Village
24	Construction of 100 bedded hospital at Muzaffarpur	Health care	Other	Bihar	Muzaffarpur	493.00	118.89	487.89	Ramakrishna Mission Sevashrama
25	Conducting health camps	Healthcare	Local area	West Beng al	Kolkata	6.00	0.02	0.02	Medical Dept CIL
26	Installation of 275 nos. of hand pumps in Shravasti water supply	Water supply	Other	Uttar Pradesh	Shravasti	99.20	18.68	68.68	UPSICL Allahabad
27	Providing menstrual cups in flood-hit areas of Kerala	Women empowerment	Other	Kerala	Multiple	7.50	7.50	7.50	HLL Lifecare Ltd

(continued)

(continued)

CSR expenditure for FY 2018–2019

1	2	3	4			5	6	7	8
S. No.	CSR project or activity identified	Sector in which the project is covered	Projects or programs			Amount outlay (Rs. lakhs)	Amount spent on project or program	Cumulative exp. up to the end of FY 18–19 (Rs. lakhs)	Amount spent—directly or through implementing agency
			(1) Local area or other	(2) State	(3) District				
28	Financial support for solar power station for supply of solar power to education and health centre	Environment Sustainability	Other	Andhra Pradesh	Chittoor	26.75	26.75	26.75	Rishi Valley Education Centre
29	Setting up of Community Drinking-Water Project	Water Supply	Other	West Beng al	Bankura	96.00	18.00	96.00	Bishnupur Municipality
30	Construction of soak pits, drains, platforms etc. for spot sources including training and IEC activities	Sanitation	Other	West Beng al	Purulia	99. 91	22.90	72.90	WSSO PHED West Bengal
31	Construction of pre-university college block building	Education	Other	Karnataka	Udupi	99.75	24. 94	49.88	Anandtirtha Trust
32	Renovation of juvenile home and purchase of the vehicle for mentally retarded children	Education	Local area	West Bengal	North 24 Parganas	26.59	6.00	6.00	Bodhana Kolkata
33	CSR expenditure of North Eastern Coalfields (NEC)	Rural development	Local area	Assam	Tinsukia	30.05	30.05	30.05	NEC

(continued)

(continued)

CSR expenditure for FY 2018–2019

1	2	3	4			5	6	7	8
S. No.	CSR project or activity identified	Sector in which the project is covered	Projects or programs			Amount outlay (Rs. lakhs)	Amount spent on project or program	Cumulative exp. up to the end of FY 18–19 (Rs. lakhs)	Amount spent—directly or through implementing agency
			(1) Local area or other	(2) State	(3) District				
34	Adjustment of the advance amount released in favour of TERI	Rural development	Other	West Bengal	Purulia		4.32		TERI
35	Amount spent on miscellaneous activities through Imprest	Administrative Expenditure					0.05		
	Gross CSR EXP						2742.82		
36	Refund of unutilized CSR fund	Women empowerment	Local area	West Bengal	Kolkata		1.00		Ankur Kala
37	Refund of unutilized CSR fund	Others	Local area	West Bengal	Kolkata		7.33		Traffic Dept., Kolkata Police
38	Reversal of old liabilities						1.37		
	Total of refunds/reversals						9.70		
	Net CSR EXP						2733.12		

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Chapter 21
Trade and Gas Emission in Mauritius: Impact on Socioeconomic Health and Environmental Degradation

Sheereen Fauzel and Verena Tandrayen-Ragoobur

Abstract The chapter analyses the short-run and long-run effects of international trade on the environment. For this purpose, the bounds testing method to cointegration is applied to a small island country setting of Mauritius and over the period 1980–2018. The result shows that that trade has adversely impacted on the environment. In addition to that, higher economic growth is as well observed to generate higher CO_2 emission. Furthermore, the CUSUM and CUSUM square confirm the stability of the model for Mauritius.

Keywords Trade · CO_2 emissions · ARDL · Mauritius

21.1 Introduction

The increased trend in global trade and investment has stimulated greater interest amongst both policy makers and researchers on the prospective trade consequences on the environment. The literature on the trade liberalisation-environment nexus is rather extensive (for instance, Tisdell 2001; Beghin and Potier 1997; Ferrantino 1997). The findings of this literature remain, however, mixed. Given the controversy in the debate on the correlation between trade and environmental quality, this paper attempts to add to the existing empirical works by analysing the trade and environment link for a small island economy.

Mauritius is an interesting case study as the island faces inherent environmental vulnerabilities related to the characteristics of small island developing states (SIDSs). Despite having a low greenhouse gases (GHGs) emission of the order of 0.01%, Mauritius is very much prone to natural hazards and disasters, inadequate natural

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resources and sensitive ecosystems amongst others.[1] Further, Mauritius is highly dependent on international trade and more than 70% of its imports comprise of food products. Being a geographically remote and small island, high freight costs associated with trading with the main traditional European and US markets remain a major challenge. The country also faces low economies of scale owing to limited productive capacity and difficulties to supply the demands of existing markets or diversify into new markets. Further, the gradual erosion of the island's competitiveness against low-cost and high-volume economies like Brazil, Thailand and Scandinavian economies poses important threats to Mauritius situation on global markets.

Further, to our knowledge, the existing work analysing the trade and environment linkage in small islands and in particular for the African continent is very scant. Most studies probing into the trade-environment nexus, undertake cross country or panel analysis where different countries are grouped together. For instance, Baliamoune-Lutz (2012) examines the marked impacts of trade and political institutions on the quality of the environment in Africa and further probes into the effects of political institutions on the trade-environment link. The study uses panel data for a group of African countries, covering the period from 1990 to 2008.The results reveal that, in the case of CO_2 emissions, political institutions affect the trade and environmental quality nexus. The findings are also unanimous with an environmental Kuznets curve when it concerns pollution (CO_2 emissions). However, this is not applicable when the net forest depletion (deforestation) variable is used. In addition, Tran (2020) investigates into the association between trade openness and environmental pollutants in 66 developing nations from 1971 to 2017. The study focusses on different factors affecting environmental quality in these countries and the findings reveal the negative consequences of trade openness on the environment. In addition, the results further provide support to the environmental Kuznets curve hypothesis.

However, the environmental policies and macroeconomic structures of economies are different, whether they form part of the same continent or they are part of a particular income group. Nations are heterogeneous and differ in a number of ways, so the association between trade and environment needs to be studied at the country level. The chapter thus builds on existing work to assess the trade-environment link for Mauritius from 1980 to 2018. The study adopts an autoregressive distribution lag model given the differing stationary nature of the variable, to probe into the relationship between trade and the environment. The chapter is structured as follows: Sect. 21.2 probes into the existing literature analysing the effects of trade on the environment. Section 21.3 analyses the Mauritian situation with respect to foreign trade and CO_2 whilst Sect. 21.4 sets out the methodology adopted. Section 21.5 highlights the findings, and Sect. 21.6 discusses the results. Finally, Sect. 21.7 conclude with relevant recommendations.

[1] https://www.unep.org/news-and-stories/story/reducing-climate-change-and-disaster-risk-mauritius.

21.2 Literature Survey

Since the expansion of international trade, its effects on the environment are highly debated by scholars and policy makers (Neary 2006; Copeland and Taylor 2005). Globalisation has led to an increase in foreign trade and has contributed to massive increase in the world production of goods and services. Such a situation can have various positive effects on the economy as well as on the welfare of the population but it is also observed that there are negative externalities associated with it. For instance, increased production can lead to an increase in pollution and degradation of the environment. Moreover, environmental economists have been claiming that economic growth as a consequence of an increase in trade is not bad but there is the problem of pollution as well as the fear of an ultimate depletion in the natural resources. Hence, trade can impact adversely on environmental quality of a country mainly with poor environmental regulations (Ali et al. 2015). Countries which are more at a disadvantage when production increases due to trade are those whose export products are mainly linked with creating pollution, like those that involves the use of natural resources to produce them and those whose combustion leads to the emission of greenhouse gases. However, it is also debated that trade can as well lead to better environmental quality. For instance, these are trade that transfer environmental friendly technologies.

Theoretically, the effects of international trade on pollution levels are not straight forward. Using a conventional Heckscher-Ohlin approach, if a country has a relative abundance of ‘environment’ (reflected by emissions), freer trade leads to increased specialisation in ‘environment-intensive’ (pollution-intensive) goods. Conversely, from the Stolper-Samuelson theorem, the price of the environment relative to other inputs will rise, hence causing all industries to use less polluting-intensive techniques. In particular, Grossman and Krueger (1991) assess the linkage between trade and environment in terms of the scale, technique and composition effects. The scale effects refer to the rise in pollution and depletion of natural resources because of increased economic activities and consumption. Higher economic growth generated by greater market access leads to increased pollution (see Grossman and Krueger 1996; Lopez 1994). The second set of effects which are the technical impacts arise from the evolving techniques of production that go hand in hand with the liberalisation of trade. These may result from income-induced demand for stringent environmental regulations and procedures as well as greater access to eco-friendly production techniques and technologies. As trade and wealth expand, there is a tendency towards cleaner production processes and environmental best practices (Grossman and Krueger 1996). Lastly, the composition effect is the changing composition of an economy, namely its economic base where trade may create a high-tech and services-based economy or one based on extractive and polluting industries. This happens as countries specialise in activities where they have a comparative advantage. Overall, the environmental effects of trade thus arise from all three dimensions (Cole 2004).

A growing strand of the literature has also focussed on the environmental Kuznets curve (EKC) to explain a potential inverted U-shaped link between per capita income

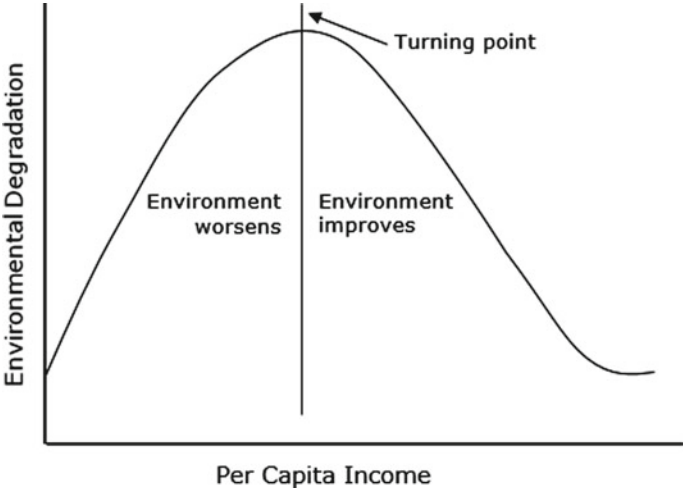

Fig. 21.1 Source authors' computation from different sources

and pollution (see Shafik 1994; Selden and Song 1994; Grossman and Krueger 1995; Arrow et al. 1995; Stern et al. 1996; Ekins 1997; Cole et al. 1997; Stern and Common 2001). The inverted U-link between environment and economic growth through the Kuznets curve postulates that the quality of the environment deteriorates initially as GDP per capita increases, but as it reaches a certain point, environmental conditions improves (Grossman and Krueger 1991). This concept is shown on the diagram (Fig. 21.1).

One major criticism against the EKC is the exemption of trade patterns which may partly explain why pollution is rising in low income economies whilst a declining trend is observed in high-income countries. The pollution haven hypothesis (PHH) may create such trade patterns as there are differences across countries in environmental regulations and standards. With less stringent environmental laws in the South compared to the North, the former has a comparative advantage to pollution-intensive output whereas the North has an inclination to clean production. Hence, the relatively lax environmental standards in least developing economies may attract pollution-intensive trade and FDI which seek weaker regulations to avoid high pollution control compliance expenditure domestically (Copeland and Taylor 2005).

Analysing the empirical studies on the environment-trade nexus, it is found that no consensus can be reached. Analysing the link between national income and environment across both developed and developing countries, Grossman and Krueger (1995) show that in relatively poor, there is an inverse relationship between environment and economic growth, but once income level has increased to some critical level, environmental quality improves. This provides support to the Kuznet curve hypothesis. Further, Antweiler et al. (2001) investigate the consequences of trade liberalisation on pollution. They argue that trade liberalisation affects the environment through the scale effect. Since pollution is the by-product of consumption and production, hence a rise in the scale of these economic activities will impact the environment. Further, the technique effect was discussed whereby the different procedures of production can have varied risks of damaging the environment. More so, there is the composition effect which results from the fact that each good has its own polluting propensity.

Their empirical results reveal that trade enhances the technique and scale effects and as such may lead to a net fall in pollution. Finally, they discuss that free trade is not bad for environment.

It is also noted in the literature that the environment-trade nexus is different for developing countries as compared to developed countries. For instance, Azhar et al. (2007) find that across developing countries, the impact of international trade on environment operates via the agricultural sector and the exploitation of natural resources. This is explained by the fact that these countries want to keep a balance of payment surplus. For instance, the study concentrates on Pakistan where it was observed that its high trade volume leads to an overexploitation of natural resources, impacting negatively the environment in both the short and longer term. In addition to that, Ali et al. (2015) examine the effect of trade openness on environment for Pakistan where a causal relationship between FDI and CO_2 emissions was observed.

Another strand of literature pointed out that FDI can as well result in environmental degradation. This happens mainly when foreign investment is concentrated essentially in the resource base industries like oil extraction and mining of minerals. International trade has also been found to result in high rate of tropical deforestation. For instance, trade with developed countries has compelled Latin American and Southeast Asian countries to increase deforestation. For the African case, trade liberalisation has resulted in the extermination of valuable animal and plant (Rudel 1998). Hence, it is observed that though extensive research has been conducted, no consensus has been reached on the environment-trade linkage.

21.3 Situational Analysis of Trade and GHG Emissions in Mauritius

21.3.1 Foreign Trade in Figures

Located in the middle of the Indian Ocean, near Madagascar, Mauritius has 1.3 million inhabitants and a total land area of 2040 km^2. It has recently moved into the high-income league with a GNI per capita of US $ 12,740 in 2019, a 3.5% increase over the 2018 figure (World Bank 2020). The island's economy has gone through major structural changes in the last five decades. Starting from a mono crop sugarcane economy, Mauritius has diversified to manufacturing, financial services, tourism and information and communication technology (ICT). Today, the island's landscape has changed to a service-oriented economy where the services sector contributes to around 76% of GDP (Statistics Mauritius 2019).

The island has achieved a welfare paradigm that is consistently progressive. As such, Mauritius' Human Development Index (HDI) for 2019 stood at 0.804, which placed the country in the very high human development group. This places Mauritius at 66 out of 189 countries and territories studied. Between 1990 and 2019, Mauritius' HDI value rose from 0.624 to 0.804, which represents a rise of 28.8%.

Although, Mauritius is viewed as an economic success in the African continent, the country still faces a number of challenges in terms of increased income inequality, growing trade and budget deficits and high competition on the world market. In essence, income inequality has been rising with a gini coefficient rising from 0.388 in 2006/07 to 0.413 in 2012 and then slightly falling to 0.400 in 2017 whilst poverty rate shot to 9.4% in 2017 and 2012 relative to 7.9% in 2006/07. Mauritius has a very liberal economic and trade policy. Mauritius trade to GDP ratio for 2019 was 92.81%, a 2.3% decline from 2018 (Statistics Mauritius 2020a, b). Mauritius is a member of the World Trade Organisation since 1995 and has joined different regional economic communities like the Southern African Development Community (SADC), the Common Market for Eastern and Southern Africa (COMESA) and the Indian Ocean Commission (IOC).

The principal goal is to move the country towards an open and globally competitive economy and facilitate its integration into the world market. In 2017, the main exports were prepared or preserved fish, cane or beet sugar and clothing (mostly t-shirts, shirts and suits). Mauritius is a heavy importer of petroleum products, frozen fish, cars, medicaments and radio transmission equipment. It mainly trades with France (15.8%), the United Kingdom (11.9%), the US (11.2%), South Africa (8.9%) and Italy (6.9%); whilst China (16.4%), India (16.4%), South Africa (8.5%) and France (8.0%) were the leading import countries. The island economy is highly dependent on imports which is the cause of a significant trade deficit. In 2017, exports were USD 2.3 billion whilst imports were USD 5.2 billion. The following table shows foreign trade figures for Mauritius (Table 21.1).

21.3.2 Greenhouse Gas (GHG) Emissions

In recent years, there has been special focus from the government to integrate green economy principles and initiatives into mid- and long-term development plans. There has been a number of policy reforms to build knowledge and create awareness about green economy opportunities in the public and private sectors.

From 2018 to 2019, GHG emissions rose by 2.9%. In 2019, carbon dioxide (CO_2) was the main GHG representing 73.9% of total GHG emissions. Methane (CH4) contributed 23.3%, nitrous oxide2.6% and hydrofluorocarbons 0.2% (Statistics Mauritius 2020a, b). Figure 21.2 shows a rising trend in average CO_2 concentration as well as methane concentration over the period 2010–2019.

In addition, in 2019, the energy sector makes up for the largest share of emissions (74.2%) (see Fig. 21.3), followed by the waste sector (23.0%) (Statistics Mauritius

Table 21.1 Foreign trade indicators from 2013 to 2017

Foreign trade indicators	2013	2014	2015	2016	2017
USD million					
Goods					
Imports	5397	5610	4792	4654	5253
Exports	2869	2650	2457	2361	2363
Services					
Imports	2143	2426	2176	2068	2231
Exports	2734	3119	2654	2867	2981
Trade balance	−2270	−2260	−1862	−2031	−2629
Goods and services					
Yearly percentage change (%)					
Imports	−1	8	6	−0	n/a
Exports	−6	11	−0	−5	n/a
As a percentage of GDP (%)					
Total foreign trade	110	113	108	98	97
Imports	62	62	59	54	55
Exports	48	51	49	45	42

Source WTO—World Trade Organisation, World Bank—Latest available data

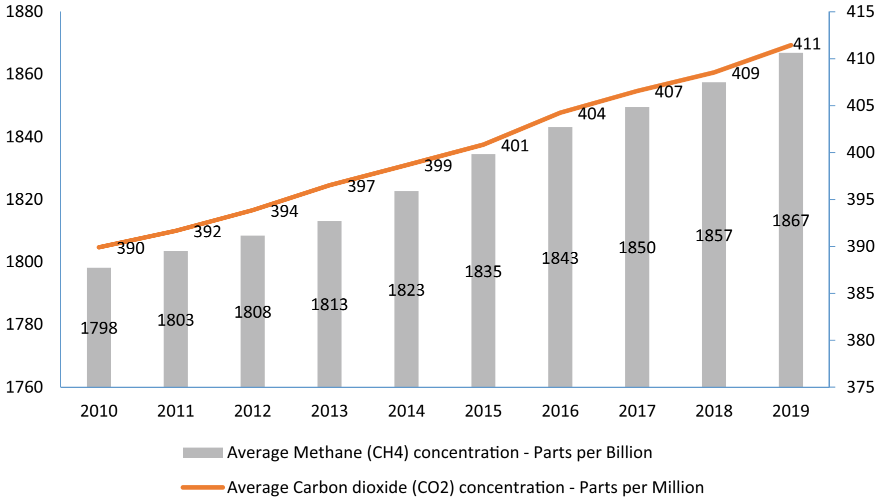

Fig. 21.2 Average carbon dioxide (CO_2) and methane (CH_4) concentration from 2010 to 2019. *Source* Authors' Computation from Digest of Environment Statistics 2019, Statistics Mauritius 2020a, b

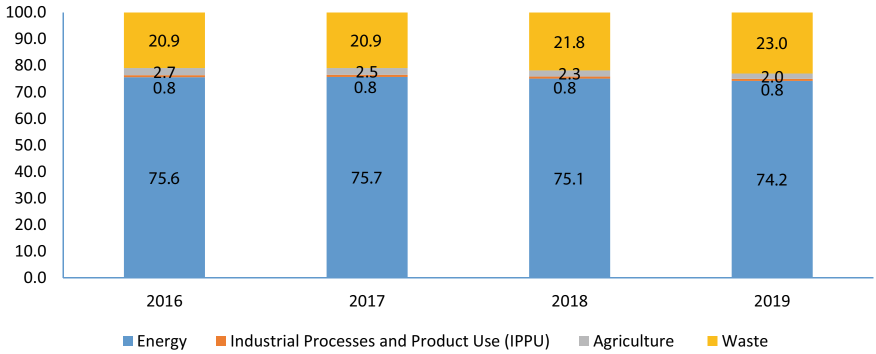

Fig. 21.3 National inventory of greenhouse gas emissions by sector as a % of total GHG emissions, from 2016 to 2019. *Source* Authors' Computation from Digest of Environment Statistics 2019, Statistics Mauritius 2020a, b

2020a, b). In 2019, GHG emission from the energy sector rose by 1.8% relative to 2018.

In fact, the energy industries mainly electricity generation contributed to 57.1% of GHG emission followed by the transport sector (26.4%), the manufacturing sector and construction (8.3%) and the remaining 8.2% are from other sectors.

21.4 Econometric Model

The chapter analyses the link between trade and the environment for Mauritius over the period 1980 to 2018. For this purpose, annual data have been used. The econometric model has been adopted from Ali et al. (2015), Cederborg and Snöbohm (2016), Fauzel et al. (2017) and Fauzel (2017).

$$\text{ENV} = f(\text{OPEN}, \text{GDP}, \text{EDU}, \text{POP}) \tag{21.1}$$

To deal with the issue of heteroskedascity, the variables are converted in logarithm form as follows;

$$\ln \text{ENV}t = \beta_0 + \beta_1 \ln \text{OPEN}t + \beta_2 \ln \text{GDP}t + \beta_3 \ln \text{EDU} + \beta_4 \ln \text{POP}\varepsilon t \tag{21.2}$$

where t signifies time; ε is the random error term and $\beta_1 \ldots \beta_4$ characterise the parameter estimates (Table 21.2).

Estimation Issues

Prior to estimating the model, the univariate properties of all the individual data series have to be explored. First and foremost, the unit roots of all variables are investigated.

Table 21.2 Sources and definitions of variables used

Variables	Definition	Literature	Sources
ENV	CO_2 emission per capita	Tiwari (2011) and Han et al. (2013)	World development indicators (WDI)
TRADE	Exports as a % of GDP	Akin (2014)	WDI
GDP	GDP per capita	Tiwari (2011) and Han et al. (2013)	WDI
EDU	Secondary enrolment ratio	Cooray (2009)	Statistics Mauritius
POP	Population size	Fauzel (2017)	WDI

Source Authors' Compilation, 2020

This is followed by an investigation of possible long-run relationship amongst the variables.

Unit root test

Adding trends in time series data cause it to be non-stationary. Performing a regression analysis on such data can lead to spurious outcomes (Granger and Newbold, 1974). Phillips (1986) argues that the results will be misleading unless cointegration exists. Hence, the findings from the ordinary least square regression will only be credible provided that the variables are stationary. In fact, for cointegration to exist, it is important to ensure the stationarity of variables. There are different statistical tests, as suggested in the literature that can be used to check the stationarity of data. For the actual study, the augmented Dickey-Fuller (ADF) (1979) unit roots tests are used. The stationarity tests reveal that the variables are integrated of order 1 and are therefore stationary in first difference.

The chapter thus adopts the autoregressive distributed lag (ARDL) method to cointegration in line with Pesaran et al. (2001). The ARDL bounds cointegration method is selected, based on several deliberations, to ascertain the long-run and short-run linkages. As per Pesaran et al. (2001), ARDL models generate consistent estimates of the long-run coefficients that are asymptotically normal regardless of whether the macroeconomic time series are I(1) or I(0). Further, ARDL models produce unbiased long-run estimates and valid *t*-statistics despite endogenous regressors (Harris 2002). The endogeneity bias may well be corrected by the inclusion of the dynamics as shown by Inder (1993) and Pesaran et al. (1997).The bound approach is better than the Johansen cointegration method whilst taking into account the sample size and the number of estimated parameters. However, the bound approach estimates a system of equations which can cause a substantial loss in degree of freedom. Hence, the ARDL cointegration method estimates the long and short-run coefficients. The bounds *F* test is used to establish whether a long-run relationship prevails across the macroeconomic time series. Hence, Eq. (21.1) below is estimated as a conditional ARDL error correction model (ECM):

$$\Delta \ln \mathrm{CO}_{2t} = \propto_0 + \sum_{i=1}^{n} \propto_i \Delta \ln X_{t-1} + \sum_{i=1}^{n} \partial_i \Delta \ln \mathrm{GDP}_{t-1} + \sum_{i=1}^{n} \delta_i \Delta \ln \mathrm{EDU}_{t-1} + \sum_{i=1}^{n} \beta_i \Delta \ln \mathrm{POP}_{t-1} + \Delta_1 \ln \mathrm{CO}_{2t-1} + \Delta_2 \ln X_{t-1} + \Delta_3 \ln \mathrm{GDP}_{t-1} + \Delta_4 \ln \mathrm{EDU}_{t-1} + \Delta_5 \ln \mathrm{POP}_{t-1} + \Delta_8 \ln \mathrm{TO}_{t-1} + \varepsilon_t \quad (21.3)$$

where the drift component is represented by α_0 and the white noise error term is ε_t. In Eq. 21.3, the lagged level variables are in fact the long-run multipliers. The symbols α_i, δ_i, β_i, σ_i and γ_i characterise the short-run influences on CO_2 emission. The ordinary least squares method is utilised in estimating the equation. Furthermore, it is important to test whether there is cointegration in the model. Hence, the null hypothesis of no cointegration; ($H_0 : \eta_1 = \eta_2 = \eta_3 = \eta_4 = 0$) is set against the alternative hypothesis ($H_0 : \eta_1 \neq 0, \eta_2 \neq 0, \eta_3 \neq 0, \eta_4 \neq 0$). This is done by using the F test alongside an asymptotic non-standard distribution. Two asymptotic critical value bounds deliver a test for cointegration when the independent variables are $I(d)$ with $0 \leq d \leq 1$. For instance, the lower bound posits that the variables are integrated of order 0 that is $I(0)$, and the upper bound posits that they are integrated of order 1 that is, $I(1)$. Therefore, as per Pesaran and Pesaran (1997), if the computed F-statistic is above the upper level of the band, it indicates that there is cointegration, and the null hypothesis is thus rejected. In contrast, if it is below the lower level band, then it can be concluded that there is no cointegration. Hence, when the long-run link is being obtained, the final step of the ARDL is to estimate the long-run coefficients (see Pesaran and Pesaran, 1997). There are two additional steps which are involved at this stage. The first step is to select the orders of the lags based on Schwarz Bayesian Information Criteria (SBIC) or the Akaike Information Criteria (AIC). Second, the ARDL model restricted to the selected lag structure is predicted by incorporating both the short-run dimensions and the error correction model.

An error correction term in lagged form is then included to replace the set of lagged variables. Hence, the short-run coefficients as an error correcting model is estimated as well as the long-run coefficients as follows:

$$\Delta \ln \mathrm{CO}_{2t} = \propto_0 + \propto_0 + \sum_{i=1}^{n} \propto_i \Delta \ln X_{t-1} + \sum_{i=1}^{n} \partial_i \Delta \ln \mathrm{GDP}_{t-1} + \sum_{i=1}^{n} \delta_i \Delta \ln \mathrm{EDU}_{t-1} + \sum_{i=1}^{n} \beta_i \Delta \ln \mathrm{POP}_{t-1} + \Psi_t \mathrm{ECM}_{t-1} + \gamma_t \quad (21.4)$$

In the above equation, the error correction term is signified by the ECM_{t-1} and the term ψ_t is the speed of adjustment.

Table 21.3 Cointegration test

Dependent variable	*F* statistics		Lower bound	Upper bound
		1% critical *F* values	3.29	4.37
$LnCO_2$	4.7429	2.5% critical *F* values	2.88	3.87
		5% critical *F* values	2.56	3.49
		10% critical *F* values	2.20	3.09

Source: Authors' Computation, 2020

21.5 Findings

21.5.1 Results for Unit Root Test

The stationarity test was carried out and it was noted that there is a combination of both $I(0)$ and $I(1)$ variables.

21.5.2 Results for Bounds F Test

The bounds F test is as per Table 21.3 which relates the computed F-statistic with the bounds. It is observed that the computed F-statistic is larger than the upper bound critical values at 1, 2.5, 5 and 10% significance levels. The null hypothesis of no cointegration is, therefore, rejected. Hence, the results confirm stable long-term cointegration link between trade and CO_2 emission.

Once, cointegration relationship was identified, the coefficients of the long-run and short-run ECM were determined using Eq. 21.4. Results show a statistically significant coefficient of the lagged error correction term, ecm(–1), of value −0.55. In addition, diagnostic test in terms of the Breusch-Godfrey serial correlation LM test is applied. The findings reveal no problem of serial correlation.

21.6 Discussions

The estimated coefficient of the long-run relationship between CO_2 emission and export is positive and significant. It, therefore, implies that a rise in exports leads to an increase in CO_2 emissions in Mauritius. More precisely, a 1% increase in exports increases CO_2 emission by 0.608%. The technique used to produce the goods as a result of trade liberalisation can affect the environment. For instance, if the techniques of producing goods for trade are harmful to the environment and increase pollution levels in an economy, this implies negative effects on environmental quality (Ali et al. 2015). Relating this result to the case of Mauritius, it is noted that whilst trade has been increasing, the level of pollution is also on the rise. A 3% rise in green gas emissions has been observed from 2016 to 2017, with an increase in gross emissions from 5403 to 5572 thousand tonnes of CO_2 equivalent and an increase from 5040 to 5207 thousand tonnes CO_2 equivalent in net emissions, after absorption by forest and land use practices (Statistics Mauritius 2018).

The findings indicate that a rise in GDP is likely to raise CO_2 emission in the country. In fact, in the long run, a 1% rise in GDP contributes to a 0.92% rise in CO_2 emission. Similar results were obtained by Seetanah and Sannassee (2011). Other studies revealing results alike to the present study are Ferda (2008) and Coondoo and Dinda (2002) for the case of Africa and Asia. These results support the 'scale effect' of international trade specifying that trade tends to expand economic activities, which ceteris paribus worsen the environment.

Moreover, it is noted that the population coefficient is positive but insignificant. Further, the result for education as well insignificantly influence carbon emission as per the present study. Moreover, as a follow up to the ARDL findings, the short-run estimates are next reported. As the variables are cointegrated, the ECM representation is applied to analyse the short-run dynamics. The findings are depicted in Table 21.4 whereby a positive and significant short-run impact of exports on CO_2 emissions is noted. In addition, the signs of the short-run dynamics are preserved to the long run.

Overall, there is support for the view that international trade has increased pollution in both the long run and short run for the small island of Mauritius. Further, economic growth has contributed towards a degradation in the environment.

Table 21.4 Long-run and short-run results

Regressor		Ln CO_2	
		Coefficient	
Long run	LX	0.608**	
	LGDP	0.924***	
	LEDU	−0.574	
	LPOP	2.224	
	Constant	−8.094**	
Short run	D(LX)		0.336***
	D(LGDP)		0.511***
	D(LEDU)		−0.317
	D(LPOP)		1.229
	constant		−4.472**
	ecm(-1)		−0.553***
MODELSUMMARY $R^2 = 0.99$		DIAGNOSTIC TEST	
		Serial correlation: 0.531	

* significant at 10%, ** significant at 5%, *** significant at 1%
Source Authors' Computation, 2020

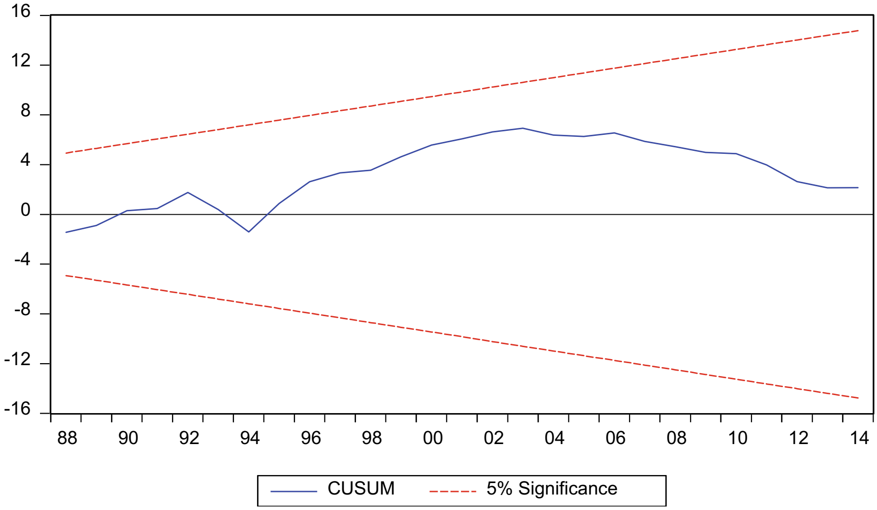

Fig. 21.4 Structural stability. *Source* Authors' Computation, 2020

Stability of the Model

The last step probes into the stability of the long-run coefficients and the short-run dynamics. The CUSUM (Brown et al. 1975) tests were adopted in line with Pesaran and Pesaran (1997). In fact, the tests are carried out on the remnants of the model. Precisely, the CUSUM test evaluates the cumulative sum of recursive residuals based on the first set of n observations and is updated recursively and plotted against break points. We do not reject the null hypothesis that the estimated coefficients in the ECM are stable as the plot of CUSUM statistics is within the critical bounds of 5% significance level. The results are shown below and it can be depicted that there is no evidence of any significant structural instability (Fig. 21.4).

21.7 Conclusions

By using an ADRL approach, this chapter investigates the potential association between international trade and environment in the small island economy of Mauritius from 1980 to 2018. There is evidence that international trade has eventually led to an increase in pollution as measured by CO_2 emissions in both the short run and long run. Moreover, an increase in economic activity also leads to environmental degradation. The results support the 'scale effect' of international trade specifying that trade expands economic activities, which ceteris paribus tend to worsen the environment. Moreover, the CUSUM test proves that the model is stable.

The findings indicate that the construction and planning of strategies of any country is highly dependent on the identification of the consequences of international trade on the environment, especially for small island economies where a significant rise in trade openness has been recorded. Nonetheless, further investigation on the negative consequences of trade openness on the environment has not been prioritised.

21.8 Policy Recommendations

Though trade objectives are achieved in terms of foreign exchange revenue, creation of employment and new industries and activities as well as higher economic growth, the environmental perspective needs to be considered in policy making. From the results, there are serious negative environmental effects of trade on the environment. These can in turn have important social effects on communities and the vulnerable segments of the population. Hence, the need to reduce environmental damage should be addressed in the early phases of the design of trade policies. This necessitates the development of integrated trade-environment policies to ensure sustainable trade without causing harm to the environment. Moreover, more focus should be laid on environmental friendly technologies and production techniques which will stimulate green technological innovation that will help Mauritius moves towards sustainable and inclusive development. There is a need to unlock the green economy potential of the island so much that policies are centred on SDG linkages, and where business and industries across varied sectors as well as the financial markets support such transition.

There should be a process designed by policy makers to develop sustainable development policy packages to embrace a proactive environmental policy stance. There is a need for greater commitment to environmental protection in Mauritius and as such develop an overall environmental regulation policy to minimise the environmental impact of international trade. However, the implementation of such policy should not be too restrictive as it may lead to a contraction in production and affect economic growth negatively.

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Chapter 22
Plastic Waste Management: Current Overview and Future Prospects

Neha Parashar and Subrata Hait

Abstract The consistent usage of plastic products has resulted in a proportionate rise of global plastic waste generation predominantly from domestic and industrial sectors. Effective management of plastic waste has become crucial to deal with complex environmental challenges imposing damage to our natural resources. This is an attempt to assess different existing collection, disposal, and treatment technologies for plastic waste management. With the challenges and limitations imposed by factors influencing the inadequate handling of plastic waste, this is an attempt to highlight recent advancements that emerged out lately to tackle the issue along with their environmental implications. Widely adopted treatment and disposal methods like material recycling with and without plastic waste separation, thermo-chemical recycling, pyrolysis, heat recovery incineration, and landfilling are compared, and problems associated with their efficacy are proffered to identify research and investment opportunities. The key drivers leading to plastic waste mismanagement in nature and its impact on the social, economic, and environmental dimensions from developed and developing economies are explored. Future scopes and technological outlook on an effective plastic waste management system in an environmental and resource compatible perspective have been discussed.

Keywords Plastic waste · Single-use plastic · Plastic waste management · Treatment and disposal techniques · Microplastic pollution · Environmental sustainability

22.1 Introduction

Since the starting of commercial manufacturing of plastic in the 1950s, it has become one of the dominant sectors in the consumer market place which is now a ubiquitous part of our day-to-day lives. Around 8 million plastic waste discharges into

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the marine environment every year, and presently our oceans are contaminated with 150 mn tonnes of plastic debris, and it has been anticipated that by 2050 there could be the presence of more plastics than fishes in the oceans (Jambeck et al. 2015). The origin of plastic waste ending up in the seawaters started from the land-based sources involving inefficient management and inappropriate discard of plastics. Around 80% of waste plastic polluting the oceans every year originates from land-based sources while less than 20% of them released from ocean-based sources like fisheries, ships and fishing nets (GESAMP 2015). The intensified leakage of solid plastic waste has resulted from the increased usage of plastic products in the fast-growing nations with poor management of solid waste systems. According to Jambeck et al. (2015), of the 192 studies coastal regions in the world, 275 mn tonnes of plastic waste were released from that channel which eventually contributes around 4.8–12.7 mn tonnes of plastics discharge into the oceanic segments. One of the main disadvantages of plastics is their non-biodegradability which ultimately leads to the fragmentation of plastic particles into tiny sizes with variable shapes and is commonly called microplastics (MPs) (Barnes et al. 2009). Some important data due to the enormous plastic production and associated pollution in the environment has been presented in Fig. 22.1. Such tiny plastic particles have detrimental consequences in the aquatic and terrestrial environments along with human health hazards and irrespective of their availability in larger or smaller plastic pieces. For instance, many studies have revealed the detection of ingested plastic pieces in the guts and stomach of birds, fishes, turtles, dolphins, whales, plants, earthworms and even in human bodies (Catarino et al. 2018; Choi et al. 2020). Aquatic species ingest such plastic debris which further paves their way into the different food webs and ultimately reaches the human body via seafood. Smaller plastic particles exhibit hydrophobicity and larger surface-area-to-volume

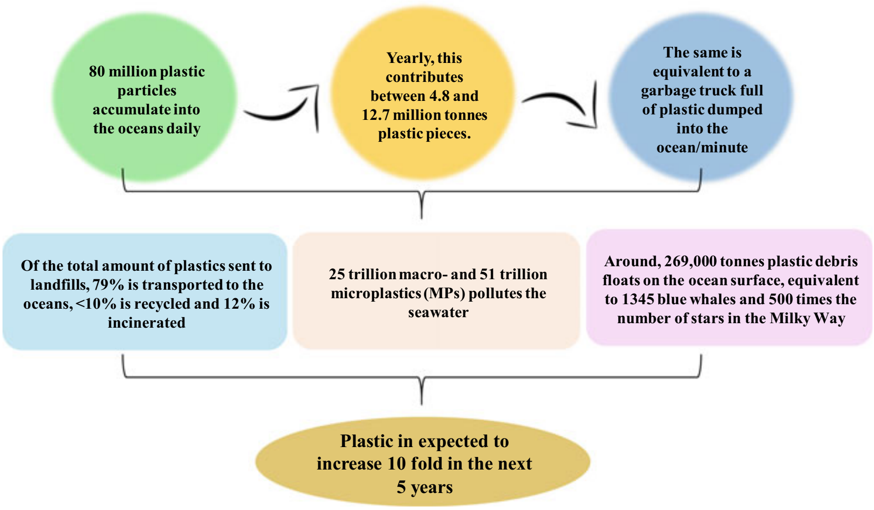


Fig. 22.1 Some important facts on plastic pollution

ratios causing the adsorption of other micropollutants present in the water and act either as source or sink of the contaminants in the organisms (Cole et al. 2011). The variety of chemicals used in the manufacturing of the plastic particles to improve their characteristic properties are found to leach into the ecological systems resulting in the bioaccumulation of toxic substances in the organisms incorporating a new route of exposure to plastic contamination (Barletta et al. 2019). A variety of rules and legislative tools exists in different countries worldwide aimed at handling or reducing the increasing use of plastic products especially single-use plastics (SUPs). However, most of these regulatory policies have little or no impact considering the large-scale production and consumption of plastic-based products involving significant applications at different levels. Moreover, different conventional and advanced methods have emerged with the perspective to efficiently treat the bulk of plastic waste involving recycling, incineration, pyrolysis, gasification, etc. (Al-Salem and Khan 2014; Parashar and Hait 2021). Besides, the majority of these treatment methods are not much feasible and remain challenging due to the inherent risks associated with plastic waste collection and segregation as a part of the waste management system (Jambeck et al. 2018). Essentially, most of the treatment methods are specifically designed to treat the plastic waste at its end-stage, therefore, reprocessing and reuse of the discarded plastic waste face various technical challenges and operational barriers. Many countries are already facing the challenges associated with plastic mismanagement and to add to this exists different technical issues prevalence within the plastic waste management systems. The foremost requirement prevails regarding the implementation of a strong regulatory framework controlling the manufacturing, usage, plastic recycling and their waste in order to save the environment.

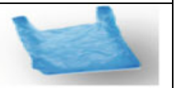
Presently, no effective legislative policies or tools exist to collect and clean up the accumulation of plastics and MPs once they have contaminated the environmental compartments. Improvement of traditional and conventional treatment methods, therefore, seems to be the viable option for managing plastic waste. Lack of knowledge and accurate information undermine the important understanding of the biological, toxicological and ecological effects of plastics. Within this context, this chapter is an attempt to assess different existing collection, disposal and treatment technologies for plastic waste management. With the challenges and limitations imposed by factors influencing the inadequate handling of plastic waste, this is an attempt to highlight recent advancements that emerged out lately to tackle the issue along with their environmental implications. Widely adopted treatment and disposal methods like material recycling with and without plastic waste separation, thermo-chemical recycling, pyrolysis, heat recovery incineration, and landfilling are compared, and problems associated with their efficacy are proffered to identify research and investment opportunities. The key drivers leading to plastic waste mismanagement in nature and its impact on the social, economic and environmental dimensions from developed and developing economies are explored. Future scopes and technological outlook on an effective plastic waste management system in an environmental and resource compatible perspective have been discussed.

22.2 Plastic Production, Consumption and Waste Generation

With the production of the first synthetic plastic 'Bakelite' in the year 1907, plastic industries marked their beginning across the globe. Though until the 1950s, no significant growth in global plastic production was observed; however, rapid plastic generation escalated over the next 68 years leading to the total accumulation of 360 million metric tonnes in the year 2018 (Geyer et al. 2017). Plastics have gained its popularity over many other materials due to its cheap availability, durability, versatility, resistant, and the ability to be transformed into required shape and sizes. Plastic exists in different shapes and sizes contributing to a particular category of polymer depending on their constituent materials. Various types of plastics along with their characteristics and common application have been provided in Table 22.1. Different sources contribute to the production of plastic materials, and their constituent units may have the origin from fossil fuels such as natural gases and crude oil, renewable and mineral sources like vegetables, starch, sugarcane and salts. Regardless of their origin, plastics are a significant resource that we can utilize either as new material or as a substitute source for vitality recuperation purposes (Plastics Europe 2019). Today the total global plastic production has reached up to 400 million metric tonnes (approx.) with an average growth rate of 3.6% annually, and the score has been projected to further reach up to 460 million metric tonnes by the year 2025. Interestingly, Europe was the world's largest plastics producer till 2002, after which Asia the USA (18%), Europe (17%), Middle East Africa (7%), Latin America (4%) and Commonwealth Independent States (CIS) contributing to 3% (Geyer et al. 2017; Jambeck et al. 2015; Plastics Europe 2019). Besides, Asia's strength in the plastics business didn't prompt a decrease in interests in plastic manufacturing infrastructure in Europe which keeps on growing (In 2018, the European industry reached a positive trade balance of more than 15 billion euros and the USA became the first trade partner with Europe). To date, around 400 million metric tonnes of plastic are produced annually posing a risk of simultaneous plastic waste generation. In 2010, China was the leading nation in producing plastic waste across the globe (59.08 mn tonnes) followed by the USA (37.83 mn tonnes), Germany (14.48 mn tonnes), Egypt (5.46 mn tonnes) and India (4.49 mn tonnes). In 2015, primary plastics produced accounted for around 407 mn tonnes of which around 75% (302 mn tonnes) wound up as plastic waste. In the same year, higher plastic waste generation within industrial sectors was reported by packaging industries (141 mn tonnes) followed by textiles (42 mn tonnes), consumer and industrial products (37 mn tonnes), transportation sector (17 mn tonnes), electronics (13 mn tonnes), construction sector (13 mn tonnes) and least production was from the machinery (1 mn tonnes). The reason for such a huge generation of plastic waste from the packaging sector is stated to be the short lifetime of packaging plastic (around 6 months) relative to the plastic materials used in building and construction that comparatively has a higher lifetime up to 35 years (Geyer et al. 2017).

Poorly managed plastic debris can be classified as the sum of plastic waste which is either littered inappropriately or disposed of inadequately likewise: open waste

Table 22.1 Types of plastic, their applications and characteristic properties

Symbols	Plastic types	Applications	Properties	Examples
1 PETE	Polyethylene terephthalates (PETE)	Transparent bottles, recording tapes, beverages bottles, Salad trays	Hard and clear, difficult to mould, provide resistance to solvents, gas and moisture	
2 HDPE	High-density polyethylene (HDPE)	Insulation and cable wires, grocery bags, juice bottles, detergent and shampoo bottles. coldrink crates, toys	Tough to little stretchable, barrier to chemical and moisture interference, clear and have waxy surface, reprocessing is easy with softening at 75 °C	
3 PVC	Polyvinyl Chloride (PVC)	Pipe, conduit, home siding, window frames, cosmetic boxes, blood bags	Hard and clear, have strong handling properties and allow the softening of products at 80	
4 LDPE	Low-density polyethylene (LDPE)	Polyethylene carry bags, agriculture tubes, packaging films, dustbin bags, cellophane, squeeze bottles.	Light weight, flexible, transparent to translucent, Soft flexible, easily scratched at 70 °C	
5 PP	Polypropylene (PP)	Tiffin boxes. Microwave containers, ice cream containers and crates, chips packets, straws, kettles	Tough, versatile, resistance to solvents and moisture, transparent to translucent in color and soften 140 °C,	
6 PS	Polystyrene (PS)	Compact disks, cutleries, brittle toys, packaging, imitation glassware, insulating materials in building and construction, egg cartons	Rigid with glassy edges, transparent, properties easily influenced when comes in contact with fatty acids and solvents but provide resistance to salt and alkaline solutions	
7 OTHER	Other	Materials used in glazing, automobiles, thermo-flask bottles, computers and electronic devices	Consisted of resins and are multi-layered, basic properties are affected by combination of different polymers	

dumping, landfills and littered waste (Jambeck et al. 2015). Mismanaged pieces of plastic end up ultimately into the oceans via passing and contaminating different waterways channels and threatening the survival of aquatic species. Common plastic waste treatment methods include recycling, incineration and waste discard. In 2015, plastic waste treatment through discard was accumulated to higher weightage (55%) contrasting to recycling (19.5%) and incineration (25.5%) where the former method widely comprises open disposal, landfills or littered plastic waste. Accounting for more than 60%, the East Asia and Pacific regions dominated the worldwide generation of mismanaged plastic alone in the year 2010, while the global distribution of the same is projected to show only slight changes in the year 2025 with the overall waste generation seems to be constant. China is the largest producer of mismanaged plastic waste in 2010 (27%) estimated to fall by a couple of percentages in the year 2025 (25.79%), whereas South Asia's share increases to some extent (highest contribution from India) as compared to Sub-Saharan Africa. In the next five years (2025), it is accordingly anticipated that the relative contribution will have a slight change in the plastic waste generation from the Americas, Europe and North Africa towards Sub-Saharan Africa and South Asia (Geyer et al. 2017; Jambeck et al. 2015).

22.2.1 Plastic Littered Waste with a Focus on Single-Use Plastics (SUPs)

Polyethylene (PE) and polypropylene (PP) are the commonly utilized polymeric materials especially in disposable products like bottled water, plastic packaging, coffee cups and straws and are used at a single time only is called single-use plastics (SUPs). According to the United Nations Environment Programme (UNEP), the majority of plastic production has shifted from conventional plastic products to SUPs due to their advantageous properties where the packaging sector dominates the contribution of SUPs discharge in the ecosystem (Giacovelli et al. 2018; Ksenia et al. 2019). Reportedly, SUPs have contributed around 50% in the global plastic production (~360 million Mt) in the year 2018 corresponding to its increasing demand, and alone in India, of the total manufactured plastics, 43% are utilized for the packaging purpose further contributing in the SUPs littered waste due to their sheer mismanagement (Plastics Europe 2019; Plastic Oceans 2020). Plastics are produced using oil, and it has been anticipated that the production of 380 billion plastic products (mostly SUPs) yearly by the U.S. burns-through 1.6 billion litres of oil (Marcia 2016). Notwithstanding, in the wake of being utilized once, most SUPs are discarded in the landfills or are burned to cause the loss of natural resources and contaminating the oceans, rivers and soils due to the accumulation of littered waste (Boucher et al. 2019; Law et al. 2010; Wang et al. 2018a, b). Littered SUPs waste throughout the urban and rural areas block storm channels and sewage lines leading to potential flooding and have prompted various instances of death and injuries to aquatic as well as terrestrial species brought about by the ingestion of plastics both ashore and in water (Cartraud et al. 2019; Markic et al. 2018). In horticultural zones, plastic waste, including mulching film build-up, disrupted the movement of water and air through soils have answered to diminish farmland profitability, keeping plants from retaining nutrients (Yan et al. 2014) with lakes, streams and seas have been significantly contaminated with SUPs littered waste (Boucher et al. 2019; Law et al. 2010). Littered and landfilled SUPs often undergo the process of fragmentation passing through different environmental factors and release harmful chemicals that are used in the processes of plastic manufacturing (e.g. dimethyl phthalate (DMP), diethyl phthalate (DEP), benzyl butyl phthalate (BBP), diethylhexyl phthalate (DEHP) and bisphenol A (BPA)), which ultimately make their way into our food chain or drinking water systems (Al-Salem et al. 2015). Studies have shown that leaching of such toxic chemicals over a prolonged period of time span led to exaggerated severe health issues and diseases in humans such as male reproductive dysfunction, breast growth, testicular cancers, premature birth, intrauterine growth retardation and stillbirth (Chen et al. 2013; Huo et al. 2017; Zhang et al. 2012). The various adverse environmental impacts posed due to the bioavailability of plastics (SUPs and MPs) in a range of organisms have been briefly depicted in Fig. 22.2.

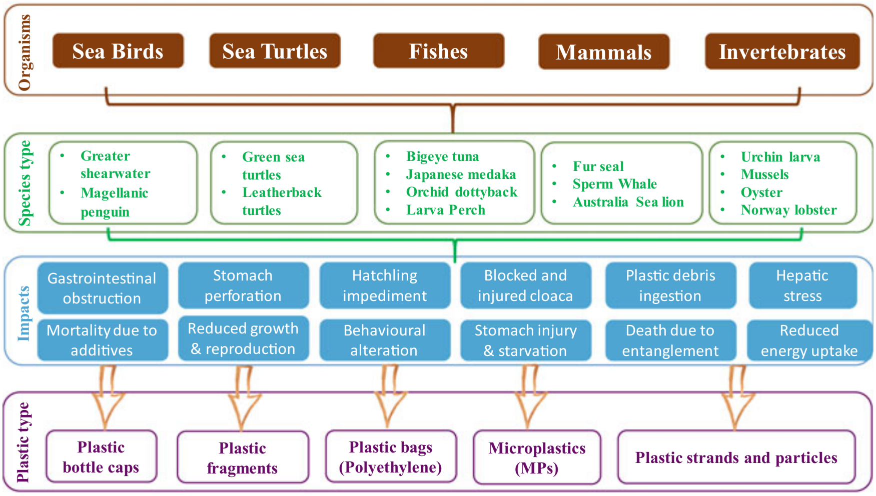


Fig. 22.2 Adverse impacts of plastic waste (including SUPs) on human and animal health

22.2.2 Microplastics Pollution: As an Emerging Micro-pollutant Threat

Fragmentation of SUPs due to high temperature, UV irradiation or mechanical mixing into tiny sizes with diameters less than 5 mm falls under the category of microplastics (MPs) (Connors et al. 2017). The continuous growth in MPs pollution has been reported recently as they are easily dispersed in the environment and are tedious to filter as compared to the larger plastic debris (Thompson et al. 2004). Based on the sources, MPs are categorized as (1) primary MPs, which are deliberately manufactured of the microscopic size range, and (2) at times, fragmentation of larger plastic pieces into the smaller debris results in the formation of secondary MPs (Geyer et al. 2017). Profound studies have been done in recent years investigating the prevalence of MPs in the environment with lesser evidence available on MPs toxicity in the terrestrial system compared to the aerial and aquatic ones. However, the terrestrial system is highly exposed to MPs contamination, the reason being excessive human activities and several transporting pathways, allowing easy accessibility to MPs movement in the surrounding compartments (Horton et al. 2017). MPs pollution in the terrestrial environments is 4–23 folds higher than the marine environments with major contamination reported from the agricultural fields. The average mass of MPs in the farmlands applied every year surpasses 0.4 million tonnes which are higher as compared to the plastic waste (by mass) currently present on the surface of oceans (Horton et al. 2017; Nizzetto et al. 2016). The elevated presence of MPs is troublesome as they can adsorb toxic chemicals/pollutants onto their surfaces due to the leaching of harmful particles (Gasperi et al. 2018). Per day, exposure of atmospheric MPs is around 97–132 particles and worldwide this accounts for approximately 35–62,000 MPs particles/person annually with microfibres being the prevalent type (Cox et al. 2019; Dris et al. 2017). Ingestion of MPs by the aquatic species due to their increased accumulation in the surrounding habitats poses a serious environmental concern, as they are difficult to be removed from the aquatic system (Hidalgo-ruz et al. 2012). The bioavailability of MPs and their inadvertent ingestion by the aquatic species are highly influenced by the characteristics properties of different plastics like size, shape, colour and abundance in the medium (Wright et al. 2013). MPs have been known to contaminate the food chain reaching the top consumers and have the tendency to interfere with the blood–brain barriers inducing psychological and behavioural changes within the human body (Mattsson et al. 2017). The prevalent pathways for the entry of MPs in the human body are via air, seafood consumption and MPs contaminated vegetables/fruits, dermal exposure through personal care products, and by drinking bottled water/beverages (Conti et al. 2020; Pivokonsky et al. 2018). Once inside the human body, MPs disposed of through the human excreta, for instance, MPs in the size range of 50–500 μm has been detected in the human faeces with the dominant polymer being polypropylene and polyethylene terephthalate (PET) (Schwabl et al. 2019). Limited research has been conducted to date exploring the adverse MPs toxicity impact and more experimental research, and data is required completely understand the toxicity at the molecular level of such emerging micro-pollutant (Rubio et al. 2020).

22.3 Plastic Waste Management (PWM): Assessment of Waste Disposal and Treatment Techniques

Plastics constitute around 10–15% of the total municipal solid waste (MSW) generated by weight based on the regional variations; besides, it contributes a significant fraction of up to 40% by volume in waste composition which further makes it difficult to collect and handle plastic waste (Banerjee and Shelver 2021). Socio-economic profile and urbanization/industrialization along with the degree of climatic conditions greatly affect the plastic waste generation dynamics in any sector. Plastic waste management rules and regulations created by regional municipalities and waste management authorities focused mainly on reducing the amount of plastic waste that may undergo landfilling through the selective collection, reuse, recycling and recovery of large chunks of plastic waste. Advanced waste management systems in some developed and developing nations aimed to dispose of the plastic-littered waste by prominent treatment methods, viz. plastic waste recycling, incineration, pyrolysis and landfills (Al-Salem 2009; Al-Salem et al. 2017).

22.3.1 Recycling: Types and Technical Complications

Plastic waste recycling involves a combination of additional technologies so as to produce secondary raw materials for the manufacturing of an entirely new product. Despite having several long-lasting advantages, recycling activities have recently gained enormous environmental and waste management concerns due to the gradual increase of awareness among communities at large. The different types of plastic recycling measures along with their associated advantages and limitations have been depicted in Fig. 22.3. In a typical solid waste system, nearly all the types of plastic waste are quite compatible to undergo recycling with certain degreed of efficiency. In any case, the measures need to be environmentally effective, monetarily productive without any technical constraints. In any solid waste management, hierarchy, recycling of waste after the waste source reduction and reuse and composting, is given the top priority corresponding to its high recovery rate (Antelava et al. 2019). The activity of recycling the plastic waste undoubtedly needs the cooperation from the citizens as they play an important role in segregating the released plastic waste at the source of generation itself. Due to varying degree of characteristics properties, the recycling of plastic waste has some specialized difficulties too; however, effective collection and separation of waste plastics at the initial stages could help enhance the efficiencies of the recycling activities.

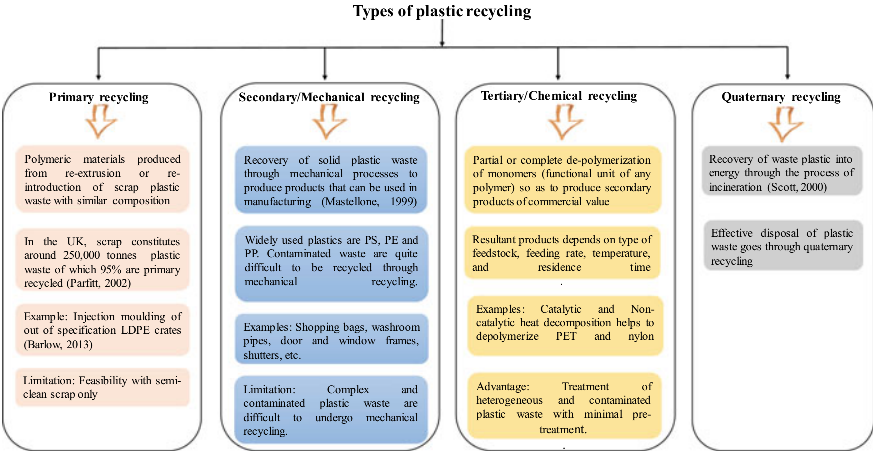


Fig. 22.3 Different plastic waste recycling methods with associated properties

22.3.1.1 Technical Complications of Recycling the Plastic Waste

Recycling plastic waste alone cannot solve the environmental damages caused due to plastic littering mainly due to the continuous and intensified usage of plastic products, its mismanagement in nature and the technical complexities that arise during the waste collection and their subsequent separation. One of the major barriers encountered during plastic waste recycling is the incompatibility between the different groups of polymeric materials that interferes with the rate of recycling (Al-Salem et al. 2017). Besides, different plastic waste exhibits variations in melting point, which at times led to the complete degradation of the plastic components affecting the mechanical properties as well as having the potential to damage the equipment. Moreover, the release of harmful gases during the recycling processes significantly affects the quality of life and health of terrestrial species. The expense brought about by recycling the plastic waste might be successfully diminished if expenses of waste collection and segregation are performed in a scientific manner. In some countries, recycled plastic products have a good market value yet the awareness of the associated health hazard of recycling activities is lacking. Recycling only reprocesses the used plastic products or the generated waste into the low-quality plastic materials, and thereby it has limited cycles to undergo recycling (generally 3–4 times) and they become unsuitable for additional reprocessing. Plastic recycling measures are additionally scrambled by the chances of possible contamination with the pollutants they once consisted (Brachet et al. 2008). Further, with the restricted accessibility of the knowledge and resources worldwide, waste reduction and recovery should be the fundamental principle to environmental sustainability. Moreover, active participation from the public in adopting various approaches towards sustainable waste management may contribute to increase the efficiency of the complete plastic waste management system to a great extent. Public support can build the effectiveness of the entire waste management framework involving the recovery and reduction of plastic waste which otherwise led to poor performances within the different stages of a typical plastic waste management frameworks.

22.3.2 *Energy Conversion from the Plastic Waste: Incineration*

The best method to decrease the plastic waste is via burning them in an appropriately planned and designed working atmosphere involving the use of high-heat temperature, and the method is commonly known as incineration (Yang et al. 2021). In an ideal burning cycle, the hydrocarbon chemically mixed with oxygen to produce water with CO_2, and as a by-product releases metal or minerals oxides. The fundamental favourable circumstances of a typical incinerator include less land requirement and furthermore be viably utilized for the generation of energy (Chang and Wey 2006). Besides, the number of advantages emerges with the burning of the plastic waste such as decreased volume, quick removal without hanging tight delayed biodegradation, reduction of toxic substances and comparable quality enhancement of the waste through energy recuperation or by creating electricity system.

22.3.2.1 Incineration: Comparison of Technologies

Several technological advancements have been made in the last decade for incineration of municipal solid waste including plastics such as adopting strategies for the conversion of incinerators or the required inclusion of additional pre-treatment structures in the plant itself. For the purpose of waste to energy conversion, incineration is performed by two methods: (1) the direct burning of the bulk plastic waste or (2) preprocessing of the waste to produce the more homogenous materials, which is further called 'refuse-derived fuel (RDF)'. The later product is generated via plastic waste shredding and simultaneous sorting into a relatively uniform portion of combustible MSW (USEPA 2018). Incineration of plastic waste through RDF is considered to be effective from the point of view of energy recovery; however, the same poses major environmental challenges as well in terms of emitting hazardous gases in the surrounding medium. To promote environmental health and sustainability, a specifically designed incineration plant with inbuilt control devices to monitor the harmful gaseous may provide the optimum results, and therefore, selecting appropriate technology is crucial during the incineration of the plastic waste considering the size of the infrastructure (Mrkajić et al. 2018). Several studies have compared the selected strategies adopted for plastic waste to energy conversion for effective waste management options. For instance, Klein (2002) revealed that gasification results in the best electrical conversion rate but it requires high maintenance costs. In the same alignment, Murphy and McKeogh (2004) investigated the higher suitability rate of incineration as compared to the other traditional combustion methods together with producing maximum electricity and lesser generation of CO_2 gas coupled with lower cost consumption. Dong et al. (2018) compared and evaluated traditional incineration specifically design grate heating chamber with temperature selective gasification methods associated with the plasma system of high-heat pyrolysis. The result provided insights about the increased efficiency of the system due to the combined technologies (gasification and pyrolysis) leading to the minimum release of gases than any other conventional method. Besides, the processing of nitrogen and mercury oxides and conventional combustion approaches have a higher gas emission factor as compared to the gasification process. Moreover, thermal pyrolysis methods have a range of advantageous properties like less expensive, lesser gas or pollutants emission, energy recovery efficiencies, etc., as compared with the gasification process for the degradation of the waste plastic (Acevedo et al. 2015).

22.3.3 Pyrolysis for Treating the Plastic Waste

High-heat decomposition of organic materials under anaerobic conditions to produce carbonized solid char, liquid fuel, or gas of high calorific value as the resultant products, and the process is known as pyrolysis (Sheth and Babu 2009; Wang et al. 2015). The characteristics of the resultant products obtained after pyrolysis are prominently dependent on the properties and composition of the feedstock used as well as the operating conditions (Benavides et al. 2017). In the treatment of solid waste, pyrolysis has been found to offer several advantages including the thermal degradation of constituent polymers of the plastic debris by burning them under non-reactive inert atmosphere and between the temperature ranges of 350–900 °C. Reducing the environmental pollution load by cutting down the carbon footprint emission of the plastic products and thereby minimizing the release of harmful gases in the environment such as carbon dioxide and carbon monoxide are some of the advantages of using pyrolysis over gasification or combustion for the degradation of plastic waste (Cunliffe et al. 2003). The flexible operational or working conditions involved during the process of pyrolysis like optimization of residence time, temperature and pressure immensely contribute to get the desired product composition. Though the role of pressure during pyrolysis is not well-studied for the plastic waste relative to the other factors like time and temperature; however, the effect of pressure is noted to have significance at a relatively lower temperature (Abbas-Abadi et al. 2014). Al-Salem et al. (2017) have evaluated the two different types of pyrolysis process for treating the solid plastic waste, namely via thermal pyrolysis and catalytic pyrolysis. Production of combustible fluids with lower octane and higher residue contents in the absence of any external catalysts at moderate temperatures results in thermal pyrolysis (Seth and Sarkar 2004) while catalytic pyrolysis is performed at low temperature and smaller time duration in the presence of an external catalyst to produce hydrocarbons with high calorific value (Almeida and Marques 2016). Some of the major advantages of catalytic pyrolysis over thermal pyrolysis include improved efficiency due to the decreased residence time of the process affecting the selectivity of the final products. Further, the use of external catalysts such as zeolites during catalytic pyrolysis yields high-quality fuels to be used in automobiles so that the upgrade downstream of the pyrolytic actives could be reduced. Moreover, depending on the geographical locations, thermal pyrolysis has been suggested to be employed near the areas with existing oil refineries as its resultant product may require further up-gradation in quality (Abnisa and Daud 2014). Solid plastic waste predominantly consists of poly-vinyl chloride (PVC) as one of the dominant plastic waste and decomposition of the same led to the production of hydrochloric acid in the environment posing risks to the wildlife. In order to combat such environmental health issues, studies have suggested an efficient pre-treatment stage or inclusion of an effective absorber into the system. It can likewise be reasoned that pyrolysis will be an ideal treatment technique because of intermixed waste plastic or MSW if the raw materials exhibit similar properties to meet the acceptance standards at the stage of processing (Chen et al. 2014; Kanniche et al. 2010).

22.3.4 Landfilling of Plastic Waste

Disposal of waste plastic through landfilling is considered an effective treatment method to reduce the overwhelmed burden of plastic pollution in the environment. Despite the increased recycling rate, some fraction of the solid plastic waste requires its appropriate disposal, and considering landfilling as an easy method to tackle the bulk of littered plastic debris makes it one of the most common disposal methods (Eriksson et al. 2005). Conversely, plastics due to their inherent properties are resistant to microbial degradation and, hence, remain unaffected for a longer time duration in the environment posing another source of plastic pollution. During the landfilling process, plastics degradation involves the cycle of physical or synthetic modifications in the polymeric composition of plastics because of a few natural variables, viz. daylight, dampness, temperature, microbial attack and so on (Iribarren et al. 2012). The hydrophobicity of polymers with higher molecular masses has been continuously improved via biodegradation process employing enzymatic actions or hydrolysis that produces certain new functional groups within the main polymeric system. Formation of these functional groups allows resins more inclined to decompose into their monomeric units (de-polymerization) through the enzymatic activities of different microbial communities (Bovea et al. 2010). Moreover, de-polymerization of the long polymeric chain gives monomers of low molecular weight depending on different environmental factors such as availability of oxygen, light, humidity, etc. For example, in the presence of oxygen, along with the microbial biomass, carbon dioxide and water are released as the final products, and under anoxic conditions, methane is produced as one of the primary products. In any case, total breakdown of any polymer can scarcely be accomplished as the bit of plastic debris will commonly be consolidated into bacterial population or in other characteristic items (Urbanek et al. 2018). Polyethylene degradation in landfills has been accounted for by various scientists through different mechanisms, for example, chemical degradation, thermal degradation, photo-degradation and biodegradation. Generally, polyethylene is easily degraded by photo-degradation and/or chemicals, which is fundamentally accomplished through two major mechanisms: hydro-biodegradation and oxo-biodegradation. Nonetheless, a few studies likewise revealed that polyethylene sheets hatched in sodden soil for a very long time give no indications of decay and just half degradation could be accomplished following 32 years (Barlaz et al. 1989). Similarly, for another prominent plastic waste made up of polystyrene and PVC, partial biodegradation by selective groups of microbes has been extensively reported under different operational conditions. Nevertheless, conventional plastics are not biodegradable and, hence, just fragmentation into smaller plastic particles ultimately exhibits certain toxic substances in nature, which may have the potential to pollute the groundwater, if not appropriately managed (El-Fadel et al. 1997). Additionally, adopting landfilling of the waste plastics is not an appropriate sustainable approach, as it can reduce any opportunity for the recuperation of secondary crude materials or energy for additional utilization.

Conventional plastic production requires the utilization of natural resources basically non-sustainable petroleum products, both as a crude material and to give energy to the manufacturing activities. Generally, 10% of the world's yearly petrol creation is used for the production of virgin plastics; 4% is utilized as a crude material; and an extra 6% is burned to give fuel or energy during manufacturing (Burlakovs et al. 2019). Ultimately, on-the-off chance that the waste plastics are landfilled, at that point, it lessens any prospects to recuperate the secondary crude materials from such waste products. Waste plastic mismanagement further adds to the existing environmental damage and has huge ecological effects by creating extra load on the limited natural resources available on the earth. Hence, the plastic waste management solutions should be tied inseparably to monitor natural resources and their use. Additionally, landfilling the plastic waste hinders the entrance of gas and moisture into sand or gravels which will eventually have detrimental effects on the life of plant and soil species due to the reduced water-retaining ability of the soil components thereby severely affecting the level of groundwater table.

22.4 Plastic Waste Management: Recent Approach and Technological Advancements

Productive utilization of plastic waste materials helps in alleviating major challenges of any waste management hierarchy. Plastic waste disposal in landfills has a few destructive impacts on the environment; in this manner, the significant reduction of such harmful impacts can be achieved by reusing/reprocessing the waste plastic to be used in some other enterprises. One of the effective manner for plastic waste reduction includes their application as fuel in cement kilns where the effect of high temperature decreases the emission of any toxic gas. Usage of waste plastic in the form of fuel is best suited and effective corresponding to its high calorific value over any conventional fuel; moreover, chlorinated polymers like PVC generates hydrochloric acid and chlorine gas, which can be neutralized at the later processing stages (Breyer et al. 2017). Also, a cement kiln has the potential to consume around 10–30,000 metric tonnes of waste plastic attributing to their average annual capacity of 1 metric tonne revealing the potential of such technology for effective plastic waste disposal approaches. Further, using waste plastic as a source of fuel adds to environmental benefits like reduced gaseous emission compared to other fossil fuels and a decrease in the production of solid or ash residues. Plastic waste plays a huge role in the substitution of non-renewable energy sources, for example, coal or petrol. In a few developed and developing nations, there is now developing rivalry between the cement companies and MSW incinerators generating energy, both seeking the utilization of plastic waste as an alternative fuel (Shekdar 2009). However, the utilization of processed plastic as fuel for cement kilns is usually considered in terms of energy recuperation.

Using waste plastic as an alternative fuel in muffle furnaces has the potential of recycling or reuse; for example, a significant pulverized coal portion for the production of pig iron from iron ores has been recently replaced by a substantial fraction of waste plastic. Also, the application of high temperature (over 1500 °C) in any blast furnace leads to reduced generation of harmful gases like dioxins, carbon monoxide, and hydrochloride gas. Even the minute release of dioxin or hydrochloride gas during the process of incineration can be neutralized by the use of limestone (Sarker et al. 2012). One of the needful and promising remedial solutions to cope with this high plastic waste accumulation is its utilization in asphalt pavement construction. The road construction sector suits well for this challenging issue as it can utilize a huge proportion of generated plastic waste, and the inclusion of plastic in asphalt enhances the strength and durability of asphalt mix; thus, sustainability and improvement in pavement performance can be achieved in a single attempt (Angelone et al. 2016). Further, reinforcement of different polymers to produce filter materials for the enhancement of physical and chemical properties is gaining importance in recent times. So far, sand, fibre, debris, rice husk and wood husk have been utilized for this purpose along with the plastic waste. Further, many areas have to be explored in the field of sustainable plastic waste management by the use of emerging technologies as well as allowing suitable modifications in the existing techniques.

22.4.1 Key Drivers for Sustainable Plastic Waste Management

The major drivers for sustainable plastic waste management for any region depend on economic, environmental and social drivers identified at local and regional levels (Mwanza and Mbohwa 2017) (Fig. 22.4). Besides, for the effective reprocessing and reuse of post-consumer plastic waste, the identified drivers would be beneficial at each

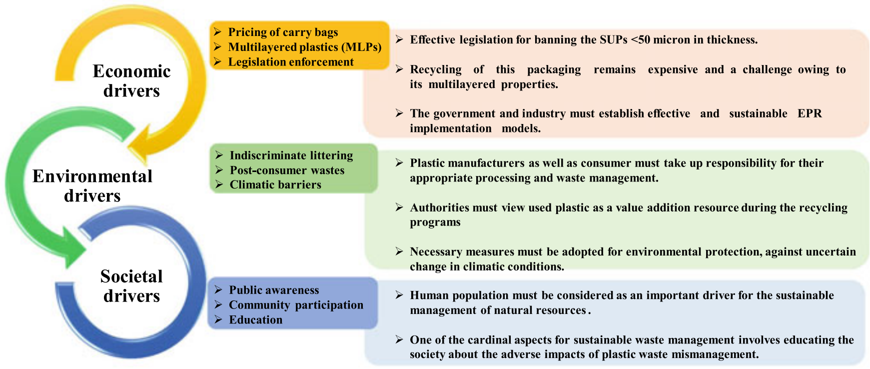


Fig. 22.4 Identified economic, environmental and social drivers for effective management of solid plastic waste

level of the municipal solid waste system. However, there persists a continuous need for rigorous empirical studies to conduct the statistical analysis on the associated impacts and influences caused by each driver on the sustainable development of plastic treatment methods like recycling, incineration and landfilling. Recent studies have suggested that the significant improvement in practices to achieve efficient plastic waste handling of plastic depends on the use of such drivers in both developed and developing nations in different contexts of sustainability. The major approach is to identify the means to fill the gaps utilizing the distinguished variables to make post-consumer plastic waste an economically viable, eco-friendly, and socially acceptable resource among the communities.

22.5 Strategies and Scopes for Sustainable Management Plastic Solid Waste

(a) Social strategies

To strengthen the reverse logistic chain, robust interventions are required to promote the circular economy chain by mainstreaming informal recycling with formal recycling programmes. It can be accomplished through different organizations supported by associations to incentivize the collection of low-value plastic waste by the informal sector to work in collaboration with the existing recycling activities in order to manufacture the second life plastic products with comparable economic value in the market (Simon et al. 2016). The local authorities together with the government need to establish strong infrastructure facilities providing the continuous supply of raw materials required to effectively run the recycling programmes as well as to establish recycling centres in close proximity to cities/towns so as to reduce the loss of energy during transportation. The governmental organizations can play a vital role in incorporating better ideas and strategies that can be beneficial in mechanism identification for the integration of informal and formal sectors to implement a better plastic waste management system. Implementation of extended producer responsibility (EPR) through different social and organizational channels may prove productive in highlighting the need of processing back the used plastic products to the recyclers or recycling chains. Regulating bodies across different countries will have the financial advantages in mechanisms/approaches, which will promote segregation and collection of segregated plastic waste through the implementation of strong EPR policies in consensus with the local governing bodies. Enhancing the reprocessed plastic products sustainability can pave the way for enormous opportunities leading several platforms for employment, energy conservation, boosting the global economy as well as fulfilling the other environmental objectives for sustainable development (Thompson et al. 2009).

(b) **Market and economic strategies**

A complete ban on the use of SUPs might not be effective in eliminating the overwhelming burden of plastic pollution from the environment. Strengthened solid waste management practices involving concrete action plans for waste collection, waste segregation and appropriate treatment methods may act as an important key in putting back the plastic waste to the circular economy chain (Mudgal et al. 2013). Mandating plastic manufacturing companies to invest in their plastic recycling targets by issuing feasible EPR policies may help them in achieving recycling credits to trade-off in the future. Such approaches can be helpful in the adequate collection of low-value or multi-layered plastics waste which is often difficult to recycle otherwise. Companies must comply with the standards issued by the regulating agencies (e.g. Bureau of Indian standards in India) for the appropriate packaging of other specific products that will ease the process of their recycling and reprocessing (Mwanza et al. 2018). In addition, reinforcing public awareness programmes in collaboration with various stakeholders like manufacturing industries, waste recyclers, waste collectors as well as consumers for the recycling or upgrading the viability of the recycled products could be one of the effective solutions for managing the waste plastic.

(c) **Environmental strategies**

Focusing on the implementation of policies with alternative sustainable choices relying on the principle of 4Rs (reduce, reuse, recycle, and recover) may act as a key driver in reducing the waste plastic accumulation (Bhattacharya et al. 2018). Policies involving robust action plans like reduction in plastic packaging, choosing reusable packaging, buyback schemes to integrate the used plastic back into the market, opting for agricultural residue as an alternative to plastic packaging, cloth grocery bags, and decreasing the stubble burning may turn out to be one significant solution to tackle the prevailing health risks in nature due to indiscriminate plastic littering. Innovative research and experiments are the need of the hour to develop products with similar properties as plastics with the advantages of being biodegradable and reducing water and carbon footprint in the environment with a life-cycle assessment approach. The development of bioplastics by the use of organic materials like starch, cellulose, hemicellulose and polylactic acids (PLAs) as raw materials could be considered as a feasible alternative to plastics (Emadian et al. 2017). Biodegradable plastic products resulting from extended manufacturing can produce green packaging options and disposable cutlery that can likewise be utilized as eco-friendly alternatives for the expulsion of harmful colours and heavy metal pollutants from the aquatic and terrestrial mediums.

22.6 Recommendations

In today's society, the need of plastic waste recycling, recovery and management is critical. Some of the proposed recommendations for reducing plastic loss in the environment and its subsequent management include:

- In the first instance, actions to prevent the accumulation of plastic waste must be considered. Wherever possible, initiatives to limit wasteful use could be taken advantage of. This is technically possible, for example, where plastic cannot be avoided, it can be engineered to be reused and recycling, reducing the quantity of waste produced.
- Minimizing the plastics consumption via removing needless packaging, proper labelling, awareness through education, as well as giving environmentally appropriate alternative to plastics without negative repercussions.
- Plastic waste management often begins at the household and individual level, and effective strategies to educate and motivate citizens can drastically change behaviour. Communities across the country can participate to raise awareness about waste management and keep the environment clean and healthy.
- In many countries, informal waste collectors constitute the backbone of recycling operations, and increasing their capacity can boost plastic recycling. Thereof, authorities from different regions may use the informal sector to decrease plastic pollution while also empowering socially vulnerable communities.
- Implementation of life-cycle assessment (LCA) for each product and process to improve environmental-friendly design, taking into account the expected end of life of the product.

22.7 Conclusions

Production and consumption of plastic have been tremendously increased since the 1950s owing to its growing demand across the globe. Though businesses and economies have been flourished continuously with the rising plastic rates, however, the unscientific management of the same has led to adverse environmental impacts on a range of aerial, aquatic and terrestrial species. The major challenge lies within the poor implementation of rules and legislation at different levels of solid waste management hierarchy along with the limitations of different conventional treatment methods adopted for plastic waste. Recycling is considered the best opted with the growing plastic waste but the existing heterogeneity in the properties of littered and unsegregated plastic particles contributes to its ineffective operation. Lack of alternatives (bioplastics and recycled plastic with equal market value) and constraints related to the acceptability of value-added products manufactured from the waste plastic remains challenging issues within communities and households, although of the different recycling types (primary, secondary, tertiary, quaternary), tertiary or mechanical recycling is preferred for the treatment of multi-layered plastics where the separation of individual layers is tedious with the rest of the recycling types. Nevertheless, the inclusion of modified techniques and improvised operating conditions (temperature, residence time, feedstock availability, infrastructure, etc.) could be beneficial in case of incineration, landfilling, pyrolysis and gasification so as to tackle the problem of waste plastic accumulation. The conversion of waste plastic into fuel as the source of energy has been accomplished by some advanced pyrolysis methods such as thermal or catalytic pyrolysis. Implementation of sustainable options such as plastic co-processing in cement kilns, incentivize recycling, integrating informal sectors for waste collection and separation within the municipality structure as well as reprocessing and reuse of used plastic products may help to promote the circular economy within the plastic waste management networks. Besides, collective efforts from the regulatory bodies, local agencies and different stakeholders in detailed mapping of plastic waste sources, waste volume and associated toxicity could be vital for the implementation of effective management of plastic waste.

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Chapter 23
Transboundary River Management of the Ganges–Brahmaputra–Meghna (GBM) Delta: Environmental Challenges and Strategies

Haniyum Maria Khan and Mohammad Moshiur Rahman

Abstract The Ganges, Brahmaputra and Meghna rivers are the three main rivers contributing to the formation the GBM (Ganges–Brahmaputra–Meghna) delta system. The delta system undergoes several environmental challenges both natural and manmade. A significant portion of population from different nations is directly and indirectly dependent on these three rivers for their sustenance. As transboundary rivers, they suffer a lack of transnational cooperation in terms of river protection and sustainable management. This review article analyses the environmental challenges in the GBM delta system to better understand the critical issues related to sustainable delta management. It also focuses on the transboundary issues and their solutions through cooperation, knowledge sharing and other joint activities between nations. The Ganges, Brahmaputra and Meghna rivers suffer from different forms of pollution. Significant sources include domestic, industrial and agricultural affluents along with direct defecation, bathing, washing, solid waste dumping and throwing of ritualistic burnt dead bodies into river water. The level of pollution creates havoc in aquatic ecosystem and leaves the water unusable for humans as well. The significant growth of population in these regions has modified the land cover of the GBM delta system. The rise in agricultural land, dams and other hydraulic structures has modified the erosion and sedimentation dynamics of the Ganges, Brahmaputra and Meghna rivers. As a result, the cases of riverbank erosion, riverbed siltation and river course shifting are also rising. The rivers also struggle with the various types of natural disasters like cyclones, storm surges, floods, droughts, salinity intrusions, coastal erosions and tidal bores. There is also a lack of understanding and cooperation between countries when it comes to sustainable delta management. To top it off, other issues like extreme poverty, lack of education, dependency on nature-based agricultural practices have also clouded the long-term development of the delta system and its people. The above-mentioned challenges require holistic and integrated action plans

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among respective nations. This can be achieved through effective policy dialogues, transnational protection and conservation plans, information sharing, co-learning, joint research programs, transstate accountability and technological advancements which can be ensured by each of the participating nations. The Ganges–Brahmaputra–Meghna (GBM) delta system extends for more than hundreds of kilometres along the Bay of Bengal coastline. The Ganges and Brahmaputra River drains roughly around 75% of the Himalayan mountain range. These two rivers carry around 1.1 GT/yr of sediment and dump on the Bengal Basin. This amount is equal to around 6–8% of the total sediment input dumped on the oceans globally. These rivers are extensively affected by different types of pollutions, erratic flood intensities and altering tidal characteristics. They also suffer from river stage fluctuations in the downstream riparian regions due to the construction and operation of hydraulic structures in the upstream regions. This study provides a critical analysis of the present issues and challenges regarding the active rivers of the GBM delta system and recommends a holistic and sustainable management plan for the protection and conservation of the rivers by analysing previously published research works and secondary datasets. The Ganges, Brahmaputra and Meghna river basins experience various point and non-point pollutions. The downstream regions face a higher rate of pollution than the upstream ones. As the rivers approach the delta mouth, land use patterns and land covers change due to increased rate of urbanization, industrialization, agricultural practices and climate change effects. Their flow is also being controlled by several upstream hydraulic structures like dams, barrages and reservoirs. Consequently, the river basins face many natural and anthropogenic disasters. The combined effect of these issues elevates the vulnerability of the downstream delta mouth population and destabilizes their socio-economic conditions. These crises can be solved through transnational cooperation, regional capacity building and sharing of information between upstream and downstream riparian countries. Inclusive and flexible strategies with appropriate policy dialogue may lead to amendments of current agreements which may eventually create a sustainable platform to overcome the environmental challenges of the Ganges–Brahmaputra–Meghna delta system.

Keywords GBM delta · Ganges River · Brahmaputra River · Meghna River · Pollution · Land use · Disaster · Climate change · Transboundary river · Cooperation · Management

23.1 Introduction

The Bengal Basin covers a large area within India and Bangladesh. It is drained by the Ganges, Brahmaputra and Meghna rivers and their tributaries. The Bengal Basin is bounded by the Indian Shield to the northwest, Indo-Burman Ranges to the east and the Bay of Bengal to the south. It covers Bangladesh, some parts of the West Bengal and also stretches to the Tripura states of India, and parts of the Bay of Bengal (Alam et al. 2003). The delta that formed in the Bengal Basin was from the combined sediment inputs of these three rivers. This delta system is known as the Ganges–Brahmaputra–Meghna (GBM) delta system (Mukherjee et al. 2009). The GBM delta is among one of the largest deltas dominated by the fluvial system in the world and covers an area of approximately 1,712,700 km^2 (JRCB). According to the water encyclopedia (www.waterencyclopedia.com), the Brahmaputra and the Ganges are the fourth and fifth largest rivers that have by very high amount of discharge with an average discharge of 700 and 660 thousand $feet^3/s$ of water at the mouth, respectively. According to the United Nations Environmental Pogram (2008), the highest flow in the GBM river system near the estuary is about 141,000 m^3/s, which is equal to about 1,150 billion cubic metre of water that is going into the Bay of Bengal (Babel and Wahif 2008). The average discharge of the Ganges river close to Farakka Barrage was about 12,037 m^3 of water per second from 1949 to 1973. Near the northern boundary of Bangladesh, the average discharge of the Brahmaputra river was about 19,673 cubic metres per second from 1969 to 1975 (www.sage.wisc.edu, September 2006). The GBM river system stands four on the world ranking of cumulative riverine discharge to the ocean through a basin (Millman and Meade, 1983). In terms of sediment dispersal, the GBM delta is the largest system to be contributing to the world's largest amount of sediment dispersal (Kuehl et al. 1989; Milliman et al. 1995; Goodbred et al. 2003). About 1060 million tons of sediments are carried and emptied into the Bay of Bengal each year through a delta front that is approximately 380 km long (Allison 1998). The GBM delta has active interactions between fluvial and wave processes. Along with sediment discharge, it is subjected to subsidence as well (Becker et al. 2020). The mean rate of subsidence of the GBM delta is about 3.9 mm/year (Brown and Nicholls 2015).

23.1.1 Background

The Ganges river approaches the delta plain from the northwest direction (Fig. 23.1). Before entering the main delta plain, it branches out into two distributaries. One of them flowed towards Bangladesh and took the name the Padma. The other flowed towards West Bengal in India and was named Bhagirathi-Hoogly. After entering Bangladesh, it joined the Brahmaputra river which entered the Bengal delta from the northeastern side. The Ganges river has a meandering course and an avulsion direction towards the eastern part of the delta plain (Brammer 1996). Unlike the Ganges, the Brahmaputra shows an overall braided pattern and was originated in the elevated regions of Tibet. The braided river course has mid-channel bars and islands that contain vegetation. The Brahmaputra river also exhibits a lateral migration (Allison 1998). The Brahmaputra river met the Meghna river near the east side of the Madhupur Tract and then flowed towards the Bay of Bengal. The Meghna river entered the GBM delta from the eastern side and drained the Sylhet basin and part of Tripura hills.

The livelihood of the people of the GBM delta is primarily traditional rice cultivation; however, other livelihood options like artisanal fishing, culture fisheries, shrimp

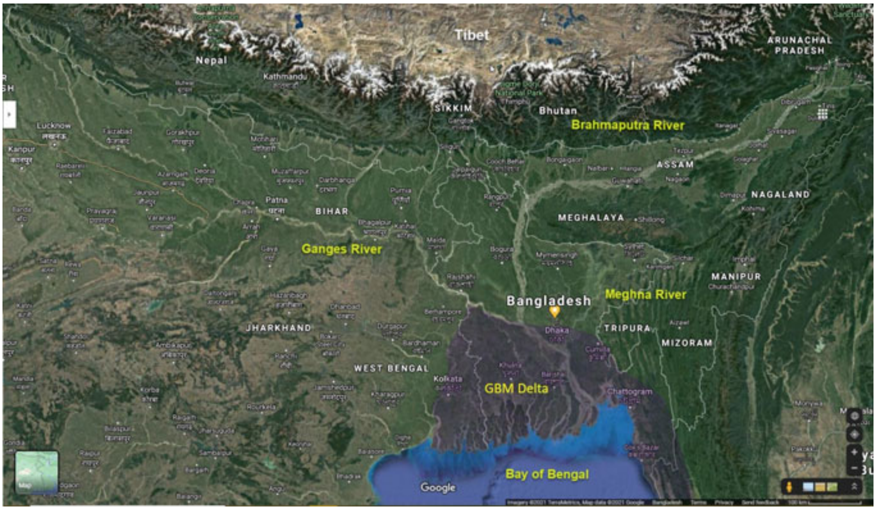

Fig. 23.1 The location map showing the Ganges–Brahmaputra–Meghna delta. The shaded part shows the extent of delta plain over Bangladesh and some parts of southeastern India. The Ganges–Brahmaputra–Meghna rivers confluence inside the border of Bangladesh and finally approached the Bay of Bengal towards south (image modified from Google Earth)

cultivation, honey collection, etc. are also seen throughout the delta plains. During monsoon periods, the plains benefit from floodwater as it increases groundwater recharge and soil fertility which in turn enhances agricultural productions. At the same time, the flood havoc causes loss of life, property and creates economic uncertainty for thousands of families residing on or near the floodplains. The southwestern part of the delta is covered with dense mangrove forest which is also rich in many ecosystem services. A considerable number of populations depend on this mangrove forest for their livelihoods (Gopal and Chauhan 2006).

The southernmost part of the delta faces some natural hazards like recurring destructive cyclones, storm surges, tidal and fluvial floods which are accentuated by riverbank erosion, salinity intrusion, tidal bores and other challenges related to sea-level fluctuations in that area.

Moreover, transboundary waters can be consumed in several natural and anthropogenic ways. Any interference with the flow of water for whatever purpose may change water quality, quantity, flow and river dynamics. The transboundary Ganges, Brahmaputra and Meghna rivers cross borders and are shared by upstream and downstream riparian regions. A myriad of issues like natural and anthropogenic pollution, changing of land cover due to excessive urbanization and agricultural practices, water quality degradation as a result of saline water intrusion and other climate change effects, catastrophic floods and droughts, excessive river bed siltation, changing river courses due to upstream structural interventions etc. are being faced by the vast amount of population residing on the banks of these rivers and their tributaries and distributaries. Pollution, land use, hydraulic structures, natural disasters and other related issues require careful resolution and co-management as they stretch over borders of different countries. All the neighbouring countries need to cooperate and resolve any transboundary issue to ensure sustainable use of water in the GBM delta.

Previously, considerable amounts of research works have been done focusing on a number of different challenges that are associated with these three rivers and the GBM delta. However, those were all individual studies on the rivers and their watershed areas separately. This review article is probably the first one to compile research findings for the entire GBM delta and the associated major rivers that drain through it.

23.1.2 Objective

This chapter emphasizes on identifying the environmental challenges associated with the Ganges, Brahmaputra and Meghna rivers and the effects that they have on the GBM delta. It also analyses ways to improve the transboundary river management of this particular region to overcome the anthropogenic and natural environmental challenges that are posed on the delta system.

23.2 General Overview of the GBM Delta

23.2.1 Morphology of the GBM Delta

Both the Ganges and the Brahmaputra rivers originated from the actively rising Himalayan mountain range and drain through the Bengal Basin. Unlike other major rivers which generally approach the ocean along passive margins, they flow through the tectonically active basin to approach the Bay of Bengal. The GBM delta on the Bengal Basin is situated on the southward side of the Himalayan foreland hinge. To the north and northwest, it is bounded by Precambrian Shillong Massif and Indian Shield. The eastward side is bordered by Neogene Tripura Folded Belt and to the south; it is bounded by Rajmahal Hills (Fig. 23.2).

The rivers that carry and distribute sediments to all parts of the basin are greatly influenced by regional tectonic activities. According to Alam et al. (2003), the Indian continent along with its adjacent oceanic crust is being overridden by the Burmese Plate. This collision between these above-mentioned plates is responsible for the subsidence of the Bengal Basin. This particular tectonic activity has been going on since the Eocene Epoch (Alam et al. 2003). Seismic sections and borehole data can trace the Eocene Carbonate Platform. It has been observed that the Eocene Carbonate Platform can be found on the Indian side at about a few hundred metres depth. This

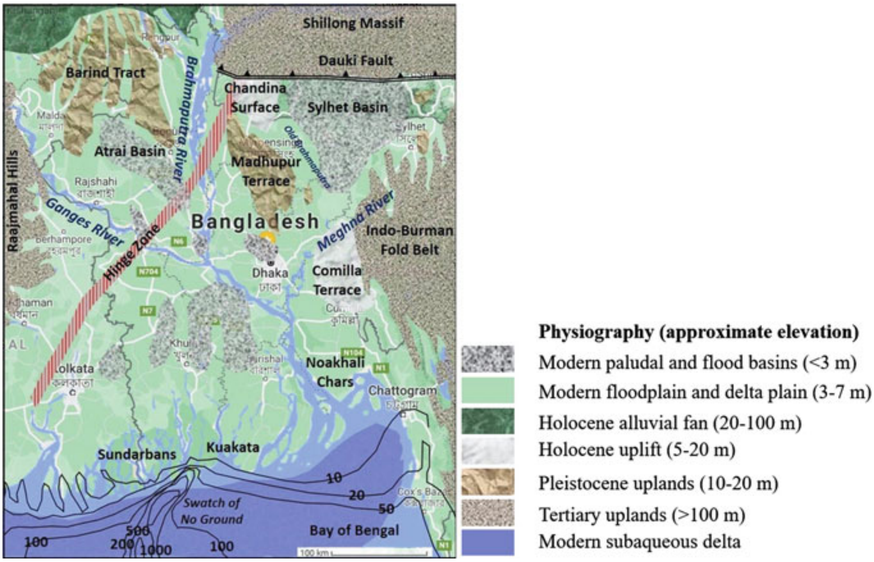

Fig. 23.2 The tectonic and physiographic map of the GBM delta. The ages and distribution of landforms are shown in the figure. The delta is bordered by Tertiary elevated lands. Inside the delta plain, Pleistocene and Holocene uplands like Madhupur, Barind Tracts and Comilla Terraces can also be observed. (modified after (Kuehl et al. 2005))

Platform dips southeastward to a depth of about 6 km under the deltaic sediments (Reimann and Hiller 1993).

In the central and eastern parts of the basin, the deltaic sediments can go as deep as 20 km (Johnson et al. 1976; Curray et al. 2002). The hinge line which shows the transition of the Indian ocean can be marked by anomalies in gravity and magnetic survey datasets (Supriya 1966; Imam and Shaw 1985). Erosion of the Himalayan landforms is the source of sediment supply for this delta plain. This sediment supply creates a balance for the tectonic subsidence of the eastern and southern basin (Alam et al. 1996). The basin generally shows a flat surface with low relief. This flat surface gently dips southward towards the Bay of Bengal. However, two elevated faulted terraces composed of Holocene sediments (Madhupur and Barind) can be observed in the delta plain. The broad front of the delta shows progradation bounded by Hoogly river (west) and Tripura folded Belt (east) (Kuehl et al. 2005).

The Ganges and the Brahmaputra rivers along with their numerous tributaries, drain through different geologic formations (Fig. 23.3).

The basic geology of the drainage basins of the Ganges–Brahmaputra–Meghna rivers are shown in Table 23.1.

The specific rock types drained by these rivers give rise to diagnostically different mineralogy of the sediments carried by the rivers (Heroy et al. 2003; Khan et al. 2019). The Ganges sediments have a higher amount of smectite clays, whereas the Brahmaputra sediments exhibit relatively higher percentages of illite, kaolinite and

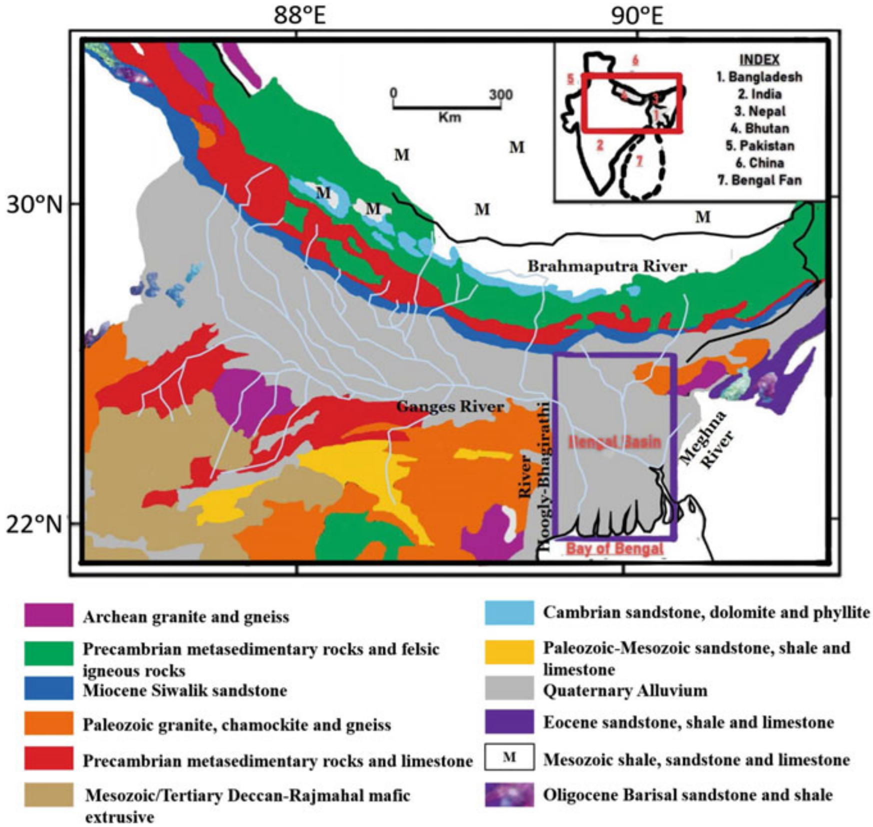

Fig. 23.3 Map showing geological formations drained by the Ganges–Brahmaputra–Meghna rivers (modified after (Heroy et al. 2003))

Table 23.1 The various rock types drained by the GBM rivers

River		Types of rocks
Ganges[a]	Upper part	Precambrian Metamorphic rocks, sedimentary rock sequences of the Paleozoic-Mesozoicage, and Pleistocene alluvium
	Lower part	Flood basalts of the Mesozoic-Tertiary age, Precambrian metamorphic rocks, and granites and gneisses of the Archean age
Brahmaputra[a]		Sandstone, shale and limestone of the Mesozoic age with Precambrian intrusive rocksthat are basically acidic and Cambrian sedimentary rocks
Meghna[a]		Pleistocene Indo-Burman fold belt sequences and Pleistocene to recent alluvium

[a] Kuehl et al. 2005)

chlorite clays. The Ganges and Brahmaputra rivers combinedly carry about 3% of the global total dissolved ions to the oceans. By weight, which are about 0.13×10^{12} kg per year (Kuehl et al. 2005). The Ganges river has the maximum discharge from June to November during monsoon, whereas the Brahmaputra river has the highest discharge from May to November (Coleman 1969).

Catchment Characteristics of the GBM Delta

The headwaters of the Ganges and Brahmaputra rivers originate up in the high mountains of the Himalayan Mountain Range. However, they both took completely different routes and entered the basin from different directions. After the confluence, they jointly flow southwards towards the Bay of Bengal. The Gangotri glaciers of the southern Himalayas sourced the Ganges river. The Ganges river drained the southern and lesser Himalayas after originating and took a turn to the east towards the Bengal Basin. By the time she reached the delta plains, she already had numerous large and small tributaries. On the other hand, The Brahmaputra river was born from the Chemayungdung glaciers situated in the Kailas range in the northern Himalayan Mountain Range. He then traveled through the Tibetan Plateau and the Nanga Parbat before approaching the Bengal Basin. (Coleman 1969)estimated that the Ganges and Brahmaputra rivers drain 1,087,300 and 543,400 km^2 area, respectively, and have a combined drainage area of about 2×10^6 km^2. The Brahmaputra splits into two branches after entering Bangladesh, the larger one meets with the Ganges river and the smaller one proceeds southeast and joins the Meghna river. The Meghna river drains about 82,000 km^2 area of the GBM delta plain. Before discharging to the Bay of Bengal, the combined flow of the Ganges and Brahmaputra river confluences with the Meghna Estuary (Bajracharya et al. 2015).

The GBM catchment experiences a monsoon climate. The combined seasonal flow that is contributed by the rivers along with their tributaries and distributaries varies considerably and causes the most severe flood events and droughts in the region. Different parts of the GBM rivers receive different amounts of precipitation. For instance, the western part of the Ganges river receives about 760–1020 mm, the middle part receives about 1020–1520 mm and the eastern part receives about 1520–2540 mm of precipitation (FAO 2021). The upper part of the Brahmaputra river receives around 300 mm of annual precipitation, east of the middle part receives 1200 mm and south of the lower part receives about 6000 mm of precipitation (Bajracharya et al. 2015; IWM 2013). For the Meghna basin, the amount of precipitation received in the northeast region of Bangladesh is about 2150 mm, and towards the southern foothills of Meghalaya, it rises to 6000 mm. The Upper Meghna River (also called Barak) receives annual precipitation of about 1700 mm to 3000 mm from east to west (Palash et al. 2018). In Table 23.2, the physical and hydrological features of the Ganges–Brahmaputra–Meghna river basins are presented. The seasonal variations in the river hydrology for the Ganges, Brahmaputra and Meghna rivers can be observed from Fig. 23.4. For the Ganges river, maximum rainfall occurs during July and highest discharge has been recorded in August. For the Brahmaputra river, the maximum rainfall and highest river discharge both are recorded in the month of July. However, the Meghna River shows similar lag time as the Ganges River where

Table 23.2 The physical and hydrological features of the Ganges–Brahmaputra–Meghna river basins (Data reference: Public Works Datum (PWD) 0.46 m below the mean sea level (MSL)

Parameter		Ganges (discharge and WL at HB)	Jamuna (discharge and WL at Bahadurabad)	Meghna (discharge and WL at Bhairab Bazar)	Barak (UM: discharge and WL at Amalshid)[a]
Basin area (km^2)[b]		1 087 300	543 400	82,000	24 600
As % of total *area* of the basin (as % of total area of the country)[b]	India	79 (26)	36 (6)	57 (1)	100 (0.03)
	China	3 (0.3)	50 (3)	—	—
	Nepal	14 (100)	—	—	—
	Bangladesh	4 (32)	7 (27)	43 (24)	—
	Bhutan	—	7 (100)	—	—
Average annual rainfall within the basin (mm)[c]		1200	1900	4900	2350
Average annual discharge ($m^3\ s^{-1}$)[c]		11 300	20 200	4.600	1075
Discharge ($m^3\ s^{-1}$)[c]	Average flood	52 000	70 000	13 700	4000
	Average low flow	600	4250	—	230
Water level (rn. PWD)[c]	Average max	13.70	19.10	6.00	17.00
	Average min	5.40	13.60	1.50	6.20
Flood danger level (m, PWD)[d]		14/5	19.5	6.25	15.85

[a] Palash et al. (2018), [b] FAO (2021), [c] Sarker et al. (2003), [d] FFWC (2021)

maximum rainfall is occurring in June and maximum discharge is occurring in Aug (Fig. 23.4).

23.2.1.1 The Ganges River Basin

Being the holy river for millions of Hindu devotees, the Ganges River flows through the fertile and densely populated plains of the Indian subcontinent. The five headwaters of the Ganges river—the Bhagirathi, the Alakananda, the Mandakini, the Dhauli Ganga and the Pindar—all originated in the state of Uttar Pradesh (UP). The Bhagirathi and the Alakananda confluence at Dev Prayag and flowed through the middle ranges of the Himalayas. Taking a south/southeasterly course, the Ganges flowed past Varanasi. Near UP, the Ganges was fed by several tributaries on either side, among

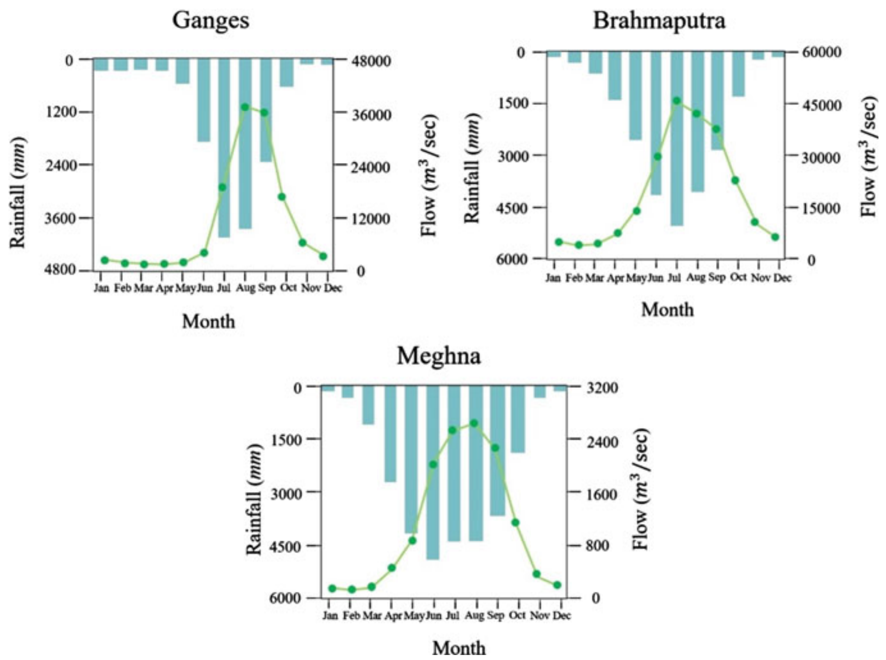

Fig. 23.4 The relationship between rainfall and discharge has been shown where rainfall is plotted on the primary *y* axis. For better understanding, the values are presented in reverse order (Modified after Palash et al. 2018)

which the Ramaganga and the Gomti are the most important. The river flowed eastward towards Bihar from UP and joined with several tributaries like the Gandak, the Bagmati, the Kosi and the Burhi Gandak. Gradually, it approached the West Bengal by swinging almost southwards. The Ganges river joined the boundary of the GBM delta near Farakka where it gets divided into the Padma (left arm) flowing eastward into Bangladesh and Bhagirathi (right arm) flowing southward into West Bengal. The Ganges in the Bangladesh part joins the Brahmaputra at Goalundo and moves southeastward until they confluence with the Meghna River near Chandpur. From that point on, the combined streams proceed downwards where the lower Meghna river becomes an estuary (Chaturvedi 1985).

23.2.1.2 The Brahmaputra River

Surrounded by the solitude of the great KonggyuTsho Lake, the Brahmaputra river originates from the Kailash range glaciers in the northern Himalayas. In Tibet, the river is called Tsangpo. From its place of origin, it flows southeastward until it takes a course that runs roughly parallel to the great Himalayan range. Throughout the course towards the Arunachal Pradesh in India, the river is fed by many tributaries, among which Luhit and Dihang are noteworthy. After the confluence, the combined stream moves southward towards Bangladesh and is named the Brahmaputra. In Sanskrit, Brahmaputra means "The son of Brahma, the creator". The Brahmaputra crosses the upper Assam valley for about 720 km as a mighty meandering river. Even during the dry seasons, the river has a considerable discharge amount. Throughout the lower Assam valley, several Himalayan streams—the Subansiri, the Kaneng, the Dhansiri, the Manas, the Champamati, the Saralbhanga, the Sankosh—joins the Brahmaputra River. As it reaches further south, some more tributaries, like the Noa Dihing, the Disang, the Dikhu and the Kopoli confluences with the river. In North Bengal, the important tributaries of the Brahmaputra are the Tista, the Jaldhaka, the Torsa, the Kajlani and the Raidok. The river enters the delta plains of Bangladesh near Goalpara. From there, it flows further southwards until it confluences with the Ganges near Goalundo. From the convergence with Tista and till Goalundo, the river is called Jamuna (Chaturvedi 1985).

23.2.1.3 The Meghna/Barak River

The headwater of the Meghna River is the Barak River. The Barak River originated in the hilly regions of the Manipur district in India. From the high elevation of the Manipur Hills, it flows about 250 km towards the southwest direction. Then, it takes an abrupt opposite bend to the north. It changes its course direction again to the west and enters Bangladesh with a meandering course. Right after crossing the Bangladesh border, the river bifurcates into two rivers, namely the Surma and the Kushiyara. These two rivers flow downwards and confluence again and are called the Kalii river. The Kalii River meets the Padma (combined flow of the Ganges and the Brahmaputra) near Chandpur. Right before the confluence, it takes the name Meghna. The lower Meghna forms a very large estuary in terms of width and depth. From Chandpur to the Bay of Bengal, it travels around 130 km and splits into four main channels before discharging to the sea. The general course of the river suggests two distinct geomorphological settings—first, the steep slopes of the Manipur Hills in India, and second, the flat and low-lying alluvial basins in Bangladesh. The Meghna river basin near Chandpur acts as very large detention storage. This basin protects the region from greater floods and submergence (Chaturvedi 1985). However, the upper Meghna basin has lowlands (haors) that suffer from severe monsoon and flash floods (Japan International Cooperation Agency 2011).

23.3 Materials and Methods

The study adopted a review methodology where a total of 1532 articles and 54 book chapters have been identified, among which 104 have been selected for the study (Fig. 23.5).

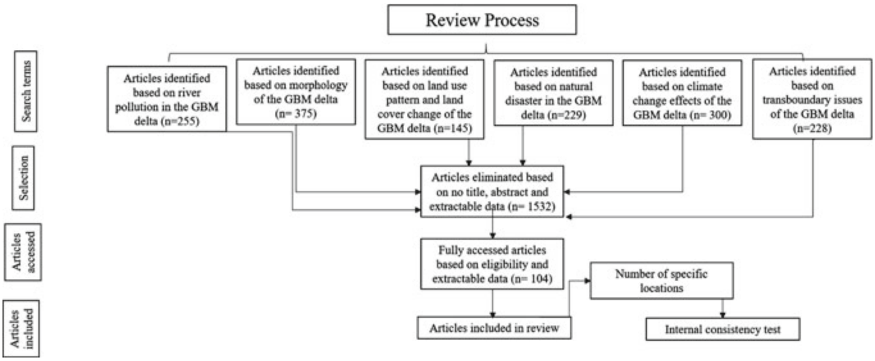

Fig. 23.5 The review methodology that has beenadopted for this study

The data used in this study have been searched and collected using the following terms (Table 23.3):

Table 23.3 The search terms that have been looked for while exploring the database and the related parameters for searching the database

Term classification	Search terms	Articles identified
Ganges river basin	Pollution, land use, climatic stress, urbanization, natural hazard, socio-economic vulnerability, disaster, mitigation, management, transboundary, toxicity, water level, precipitation, land area, geomorphology, geology, age, rock, rivers	475
Brahmaputra river basin	Pollution, land use, climatic stress, urbanization, natural hazard, socio-economic vulnerability, disaster, mitigation, management, transboundary, toxicity, water level, precipitation, land area, geomorphology, geology, age, rock, rivers	413
Meghna river basin	Pollution, land use, climatic stress, urbanization, natural hazard, socio-economic vulnerability, disaster, mitigation, management, transboundary, toxicity, water level, precipitation, land area, geomorphology, geology, age, rock, rivers	358
GBM delta	Pollution, land use, climatic stress, urbanization, natural hazard, socio-economic vulnerability, disaster, mitigation, management, transboundary, toxicity, water level, precipitation, land area, geomorphology, geology, age, rock, rivers	286

23.4 Effects of Pollution on the GBM Delta

The exposed flowing water of the Ganges, Brahmaputra and Meghna rivers is open to anthropogenic modifications and the natural deposition of pollutants and sediments. The surface water quality gets degraded by geochemical contamination, anthropogenic influences, river basin's chemical compositions, rock water interactions and many other factors (Giridharan et al. 2010; Subramani et al. 2010). With the growing population, the amount of industrialized agriculture and expansions of current agricultural activities have increased. Urbanization and industrialization on the banks of the GBM rivers have also had a multifold bloom. These activities have increased water use extensively for agriculture, industry and domestic purposes. Simultaneously, these activities have age-old effects on the water quality of these rivers which are most likely to be intensified in the days to come. Among the many socio-economic factors that potentially affect the water quality in the GBM delta, population dynamics, sewage treatment facility, water quality control measurements, irrigation water demand and supply, atmospheric nitrogen admission, change in land use pattern and water circulation patterns are the most notable ones (Whitehead et al. 2015). Along with the above-mentioned concerns, climate change-induced change in temperature and precipitation pattern has also aggravated the environmental challenges by enhancing salinity intrusion near the coastal part of the GBM delta. This disrupts the balance of ecosystems of the GBM floodplains (Dobrovolski 2007; Wang et al. 2015). The effects of pollution on the rivers of the GBM delta is described below.

23.4.1 The Ganges River

The urban and industrial growth in the Ganges River basin has added a huge amount of nutrients, contaminants, construction debris and other sediments to the river from its origin to the end. The pollution level and the temperature of the river water have increased and are associated with erratic rainfall patterns (Cumming 2011). Global warming associated with sea-level changes and glacial melting will alter the distribution and movement of pollution even more in the coming days (Kumar and Sanghi 2014; Singh et al. 2003; Guhathakurta et al. 2011). The major sources for Ganges water pollution are (Kumar and Sanghi 2014)-

- The discharge of about 1.4×10^6 and 0.26×10^6 m^3 per day of wastewater from domestic and industrial sources, respectively, into the river
- The direct discarding of solid wastes that go straight into the river
- Non-point source of pollution mainly from the agricultural fields
- Burnt and half-burnt human and animal corpses were thrown directly into the Ganges river
- Bathing, defecation and ritualistic use of Ganges water by mass people.

Pollution effects intensify with increased sedimentary load from the upstream regions. Moreover, massive industrialization and agricultural productions on either bank of the Ganges River release a number of pollutants (Table 23.4) into the river water which is degrading the quality of the river water. As a matter of fact, the water pollution in the Ganges River is affecting river ecosystem and causing pollution-induced problems in biota and human beings as well (Tripathi et al. 2017).

In 2007, the Ganges River was listed as one of the world's five most polluted rivers (http://www.greendiary.com/entry/ganga-is-dying-at-kanpur/). Near Varanasi, the presence of faecal coliforms exceeded the permissible limit by hundred times

Table 23.4 The potential river pollutants and their corresponding major biological effects for the Ganges River. Adapted fromTripathi et al. (2017)

S. No.	Pollutants	Climatic interactions	Major biological effects	Ref.
A	Persistent organic pollutants	Photolysis, biodegradation, oxidation and surface exchange properties resulting from increased temperature	Abnormalities in reproductive and congenital behaviour	a
B	Heavy metals	The temperature increases mobilization and distribution of heavy metals in post-monsoon periods	Detrimental to the physiology of all plants and animals, especially toxic for phytoplankton and zooplankton	b, c, d, e
C	Added fluxes of NPK and other nutrients	The mobilization of nitratesand phosphates, along with photo-oxidation and photo-mineralization increases with temperature	The combined effects of eutrophication and algal blooms cause toxicity in the nervous systems, liverdamage and other hazardous effects in fish bodies	f, g
D	Pesticides	Property changes like change in temperature, salinity, pH would also change the action of pesticides, their half-life, biodegradation, etc	Alters the reproductive and cognitive abilities of fishes	h
E	Radionuclides	Climatic patterns govern the amount of weathering, transportation and deposition of sediments carrying radionuclides	Aquatic animals suffer from carcinogenic issues due to radionuclides	i

[a] Timoney and Lee (2011), [b] Singh et al. (2003), [c] Pandey et al. (2009), [d] Wasim Aktar et al. (2010), [e] Duan et al. (2014), [f] Pandey et al. (2014), [g] Ye and Grimm (2013), [h] Bandow et al. (2014), [i] Sarin et al. (1990)

(Kumar and Sanghi 2014). A change in the dynamics and varieties of the fish population can be observed due to climate change-induced sedimentation (Sarkar et al. 2012; Das et al. 2013). A recent study shows that thermal pollution in the Ganges River has a significant effect on the fisheries in the Gangetic plains. Due to the pollution, the reproduction of native fish has decreased. On the other hand, this elevated water temperature favours the increase of non-native invasive fishes (Das et al. 2013).

23.4.2 The Brahmaputra River

Being one of the major rivers in the northern Himalayan ranges, the Brahmaputra River is a vital source of water-based livelihood for the floodplain population of the GBM delta. Various natural and anthropogenic factors cause pollution throughout the river. The recurring landslide incidents in the Tibetan upstream regions cause a massive increase in sediment supply which increases the level of turbidity in the downstream water (Shivashankar and Thomas 2020). Other than increased sediment supply, the river also experiences an abundance of heavy metals in the surface water (Bhuyan et al. 2019). As urbanization increases, anthropogenic discharge of toxic heavy metals also increases (Gao et al. 2010; Nduka and Orisakwe 2011). Direct dumping of solid waste and sewage materials into the river, oil spills, metal leachate from different types of wastes, metal scrapes and metal components from industrial waste disposal, faecal matters of animals and humans are the main sources of heavy metals in the Brahmaputra river water (Förstner et al. 1981). Along its course, the Brahmaputra river gathers contaminants from various industrial sources like cotton and spinning mills, jute mills, dying industries, textile mills, cement factories, brick-fields and other different types of industries. All these sources contribute to elevated concentrations of Al, Pb, Cu, Mn and Ni ions (Bhuyan et al. 2019). Urban runoff plays a key role in the alkalinity, hardness and biological oxygen demand of the river (Girija et al. 2007). Other than the anthropogenic sources, natural physical weathering of the riverbed and surrounding formations can also add higher concentrations of heavy metals (Bhuyan et al. 2019).

River sediments play a vital role in metal pollution. It can either source metal mobilization or, contain metal traces through processes like chelation, precipitation or absorption. Other chemical water quality parameters like pH, TOC and dissolved nutrients also may impact the amount of metal transport in the Brahmaputra river (Gogoi et al. 2020). The distribution and storing of different types of metals in river water causes biomagnification and increases bioconcentration factors. Consequently, river transport processes, river ecosystems and the bio-organisms in these ecosystems are severely affected. These accumulations may have long standing effects on human health as well (Gogoi et al. 2015; Bhat et al. 2013). Another potential effect of this pollution is possible lixiviation of metals from the river beds to underlying groundwater table among which Cd and Cr shows higher potential for leaching into groundwater (Gogoi et al. 2020).

23.4.3 The Meghna River

The Meghna River is one of the major and widest rivers inside Bangladesh. It drains through different landscapes and different geomorphologies. The Meghna estuary is responsible for the combined discharge of sediments and water into the Bay of Bengal. It is a very important course in terms of navigation, transportation, industrial expansion and other important national activities. However, the river faces a huge crisis in terms of water quality degradation. A large number of different types of industries, agrochemical effluents, municipal and domestic wastes are constantly degrading the water quality of the Meghna River (Bhuyan et al. 2019). There is seasonal variability in the pollution pattern of the Meghna River. The dissolved oxygen level, biological oxygen demand and total suspended solid in the river water suggest that pollution is higher during the pre-monsoon period (Bhuyan et al. 2019). The fish resource in the Meghna River basin shows a sharp decline due to heavy pollution. Among the river pollutants, the followings are listed as the major ones (Hasan et al. 2019).

- Trace metals (Cr, Cu, Fe, Mn, Ni)
- Imbalance in major cations and anions (Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, Cl^-, F^-, NO_3^-, HCO_3^-, SO_4^{2-}, PO_4^{3-})
- Bacterial contamination
- Agricultural affluents (pesticides, inorganic fertilizers, preservatives)
- Pathogens from raw sewage, urban solid waste disposal, human and animal excreta)
- Industrial effluents including wastewater from treatment plants
- Elevated temperature from electric power plants
- Sedimentation from construction debris and natural weathering.

As for the drinking water quality, the maximum limit for Fe, Cr, Mn, Ni and Cd exceeds the World Health Organization (WHO) standard. In terms of irrigation water quality, Ni, Mn and Cd exceed the Food and Agriculture Organization (FAO) standard. The Meghna River sediments also show higher amounts of Zn, Pb, Cd, Cr and Ni as per the United States Environmental Protection Agency (US EPA) standard. The lower Meghna basin shows 1.9 to 2 mg/L dissolved oxygen indicating highly polluted water. This reduced amount of dissolved oxygen may cause aquatic ecosystem degradation. The biological oxygen demand (BOD) was higher towards the estuary as that part of the Meghna river is highly polluted. The estimation of total suspended solids (TSS) during the monsoon period can rise as high as 10.8275 mg/L. This elevated amount of BOD and TSS is damaging for the bio-organisms (Sharif et al. 2017). Also, the Meghna river water contains heavy metal pollutants which cause bioaccumulation into fish samples (Table 23.5) as well as bird species that could be fatal for any human consumption (Uddin and Jeong 2021).

Local population and people with river-specific livelihoods suffer from a number of skin diseases due to the metal pollution (Sikder et al. 2016). Heavy metal accumulation in human bodies also cause health issues like functional disruption in kidney,

Table 23.5 The effects of metal accumulation on the biota in the lower Meghna River basin (modified from Siddiquee et al. (2009)

Organism type	Effect of heavy metal pollutants
Fish	Pre-mature hatching, increased mortality, reduced immunity
Coelenterates mollusk	Irregular cell division, malnutrition, increased mortality, lower amount of growth
Crustaceans	Reduced body defence, irregular cell division, high mortality
Sea birds	Slower growth, reduced breeding capacity, eggs with thin egg shells, irregular structure
Benthos	Significantly toxic state at river bottom with slower growth

brain, heart, liver and bone. Abundance of Pb in the river water influences reduction in cognitive development on children, elevated blood pressure and heart diseases in adults (Commission of the European Communities. Commission Regulation (EC) 2002).

23.5 Effects of Land Use on the GBM Delta

The fast population growth throughout the Anthropocene has changed the patterns and characters of delta lands. There is increased pressure on the food supply which resulted in extensive agricultural production. As a consequence, the land use pattern has also been modified. Both in the Indian and Bangladesh portion of the GBM delta, profound land cover change can be observed (Fig. 23.6a, b).

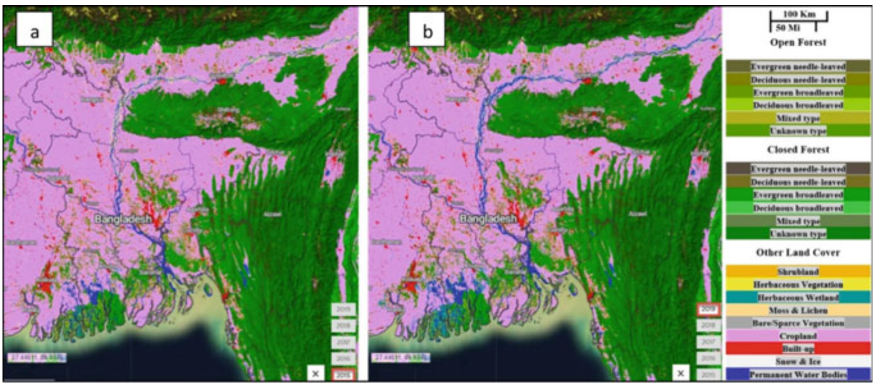

Fig. 23.6 **a** The land use pattern changes in the Bangladesh part of the GBM delta for the years 2015 (left) and 2019 (right). **b** The maps have been constructed using Global Land Cover (https://lcviewer.vito.be/2019)

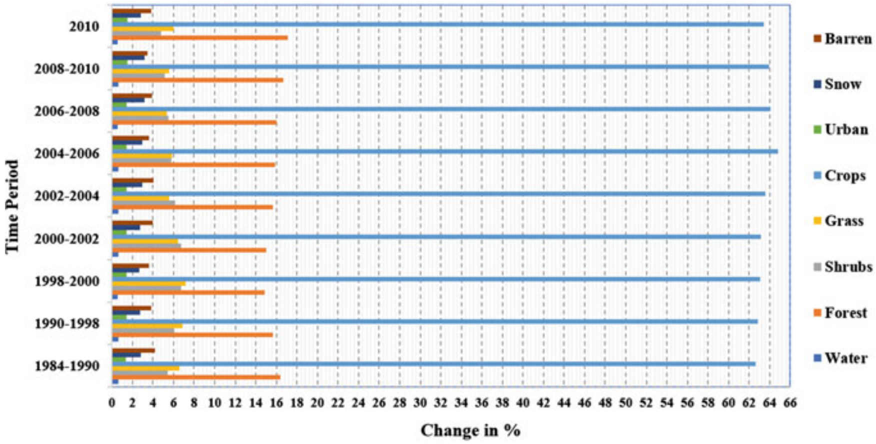

Fig. 23.7 The net change from the Ganges River basin has been illustrated using bar chats for different classes (barren lands, snow cover, urban areas, croplands, grasslands, shrubs, forest areas, water resources) during 1984–2010 (modified after (Tsarouchi et al. 2014))

As the sea level rises, the coastal regions of the GBM delta face many challenges including increased salinity on land and in water bodies. Another reason for downstream salinity increase is the mismanagement of hydrological flow in the upper part of the delta system. The elevated salinity concentration has led to increased shrimp cultivation which is a key driver for the change in land use pattern. There is a gradual change in the land-use practices in the Indian part (Fig. 23.7b) of the delta. First, a large portion of the mangroves changed into agricultural lands and human settlements. Later, some of the agricultural lands were converted to aquaculture and brickfields. In the Bangladesh part (Fig. 23.7a), there was a decrease in the agricultural area and an increase in human settlements and aquaculture. The southwest aquaculture practices increased economic benefits but at the same time caused huge deterioration of the soil quality. Some of the regions in the southwest part of Bangladesh have gained better-quality drainage which resulted in increased agricultural practices. The active delta process governs the rising mudflats near the estuary. There are patches of government-led mangrove afforestation on the mudflats (Rahman et al. 2020).

23.5.1 The Ganges River

The Ganges River basin is affected by the land cover change in various ways. The northern and central parts of the Ganges catchment are governed by dense vegetation, forests with occasional grasslands and some barren lands. The agricultural practices are observed mostly in the southern portion of the catchment. The overall trend in cropping increased by 1.3% from 1984 to 2010. However, there was a decrease in the forest cover. The amount of grass and barren lands kept fluctuating over the years. Shrubs have converted most of the forest areas inside the river basin. In contrast, availability of water, amount of growth of grasslands and snow cover are responsible for the conversion of barren lands (Tsarouchi et al. 2014). The conversion of barren plains, change in water access, amounts of shrubs and grasses influenced the conversion of grasslands. The increased amount of animal grazing, agricultural usage and forest fires are responsible for the decreased amount of forest cover in the basin from 1984 to 2010. The amount of cropping increased with time in southern, central and northern parts of the basin (Tsarouchi et al. 2014). The net change from a land cover over the years can be seen in Fig. 23.7.

23.5.2 The Brahmaputra River

The quality and extent of sediments being carried by the Brahmaputra River are often affected by its land use pattern. Present modifications in the sediment transport and hydrological conditions of the Brahmaputra River directly link to the land use pattern and hydraulic interventions in the river (Sarma 2005; Ray et al. 2015). To increase the living standards of people residing near the upper Brahmaputra basin, many ventures like agricultural and hydropower developments are being carried out. These interventions are most likely to intervene with the hydrology and land use pattern of the region (Dikshit et al. 2014). There is a lack of available data sets for the land cover measurements over the Brahmaputra basin (e.g. Sarma 2005; Goswami 1985; Islam et al. 1999). Previous studies focused on satellite images for land use data (Fischer et al. 2017; Jung et al. 2010; Mersel et al. 2013; Prasch et al. 2015).

23.5.3 The Meghna River

The Meghna River basin is governed by active tidal influences, saline water intrusion, shrimp cultivation and agricultural extensions. Rapid urbanization and infrastructure development affect the land use pattern of the Meghna River basin. The riverbanks and "Char" areas of the Meghna basin are not stable and undergo erosion and accretion over time. Salinity intrusion threatens agricultural activities in the lower Meghna region and conversion of agricultural fields into shrimp aquaculture is becoming more common with time. This degrades the quality of the wetland ecosystem. As soil salinization occurs, lands lose fertility and change the vegetative cover due to reduced biodiversity (Islam 2016).

23.6 Effects of Natural Disaster on the GBM Delta

Being a coastal river delta, the GBM delta faces continued challenges regarding natural disasters. Environmental vulnerability is comparatively higher in the GBM delta compared to the other coastal deltas. River forces and tidal waters are constantly shaping the flat-lying delta morphology. The GBM river, its tributaries and distributaries connect waterways over the GBM delta. These waterways offer several services like, connecting settlements and creating navigation routes within the delta system. The benefits are often overshadowed by a number of natural disasters. The GBM delta system is continuously being affected by

- Different types of flooding and effected population [river flow, flash floods, tidal floods, cyclonic flood (Fig. 23.8)] (Sebesvari, et al. 2016, 2016)
- Elongated periods of drought (Sebesvari, et al. 2016, 2016)
- Bank erosion of rivers (Sebesvari, et al. 2016, 2016)
- Erosion in the coastal areas (Sebesvari, et al. 2016, 2016)
- Recurring cyclones with associated storm surges (Fig. 23.8) (Sebesvari, et al. 2016, 2016)
- Seawater intrusion and tidal bores (Sebesvari, et al. 2016, 2016)
- Tsunamis and earthquake hazards (Sebesvari, et al. 2016, 2016; Steckler et al. 2008)

The effect of natural hazards increases multifold when they are associated with rapid urbanization, social and environmental transformation which enhances hazard vulnerability in various parts of the GBM delta system (Hinkel et al. 2014; IPCC 2014; Syvitski, et al. 2009).

23.6.1 The Ganges River

The Ganges River basin undergoes a number of different types of natural hazards throughout its course. In the upper part of the river, challenges like river bank erosion and flooding causes grave socio-economic situation. The lower and middle part, however, suffers from the effects of severe flooding, cyclone and cyclone-induced inundation, storm surges, dry season droughts, heavy siltation and increased salinity intrusion towards the southernmost part of the delta. As the adaptation and coping mechanisms lack proper support, these regions have become absolutely defenseless and unprotected in the face of these natural hazards (Biswas and Anwaruzzaman 2019).

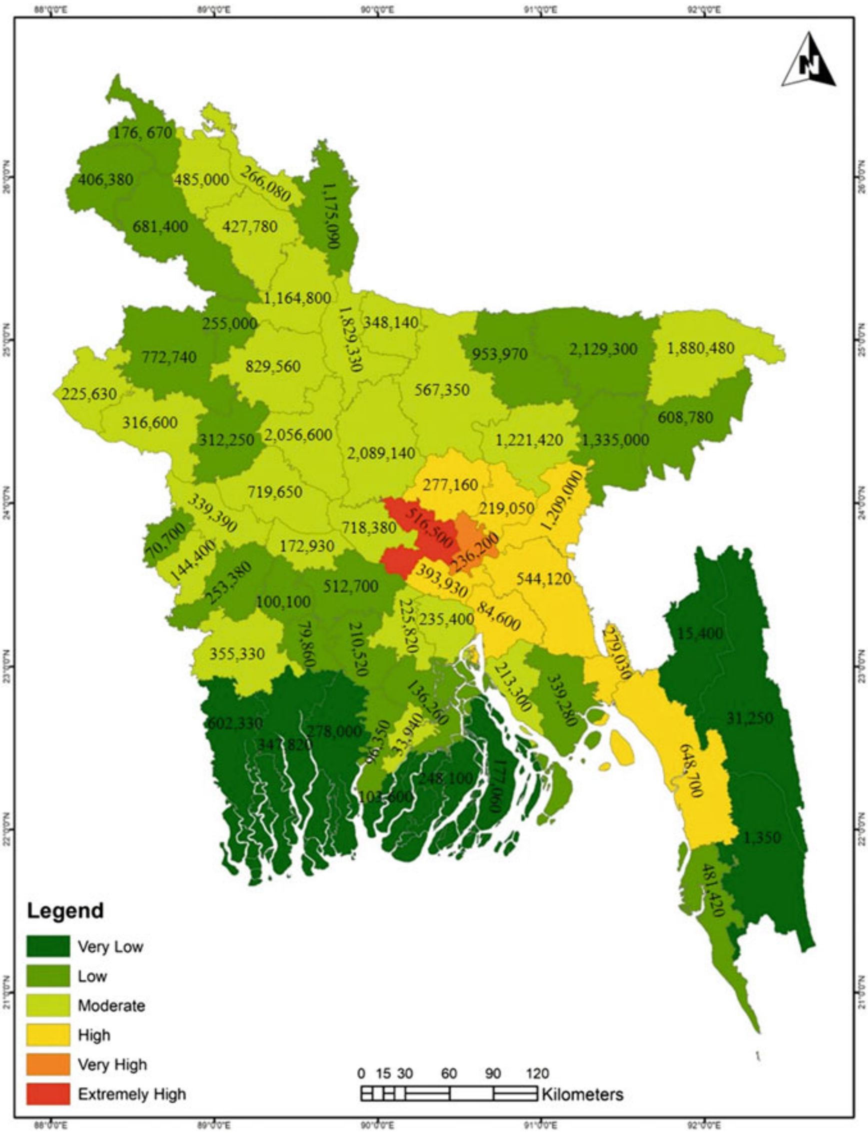

Fig. 23.8 Population density in the Bangladesh part of the GBM delta with numbers of flood effected population in all administrative districts during July 2020 (Flood affected population data collected from www.unitar.org/unosat)

23.6.2 The Brahmaputra River

The Brahmaputra River basin experiences severe flooding throughout its course. As the upper part of this basin contains a high number of headwaters and distributaries, there are chances of frequent heavy flow. The major disasters that the Brahmaputra riverine people face are severe floods, riverbank erosions, riverbed siltation and deposition of coarse materials. As these events are recurring, they leave many agricultural folks landless and propertyless. Moreover, the basin has a huge number of populations who are vulnerable due to a lack of infrastructure. The economic growth in the upper Brahmaputra region, specifically in Assam is very slow. There is also a problem of lack of alternate livelihood options and sustainable disaster management approaches (Hazarika et al. 2018).

23.6.3 The Meghna River

The Meghna River basin and the estuary is affected by several natural disasters due to the location and geomorphologic condition. Among the most devastating natural disasters, flood and water logging, increasing salinity, recurring cyclones and storm surges, coastal erosion are the major ones. The population of the Meghna River basin fights with these catastrophes each year and become vulnerable with passing time. A number of different factors for these vulnerabilities are listed as follows (Shamsuddoha and Chowdhury 2007):

- Human-made factors like sudden demise of bread earner, property loss, conflicting social condition
- Natural disasters like cyclone, surges, erosion, salinity, inundation
- Lack of governance, transparency and accountability.

The causes of vulnerability can be expressed through Fig. 23.9 where the percentages of the possible causes have been shown.

23.7 Effects of Hydraulic Structures on the GBM Delta

The GBM rivers flow through several countries, and each of the countries has its specific water withdrawal as well as hydraulic structures built. For instance, in Nepal, there are two major reservoirs named Kosi and Gandaki with diversion barrages (Biswas et al. 2008). In Bhutan, several large dams like Chhukha dam, Tala-Wankha dam, Kurichhudam, Basochu dam and Punatsangchu dam contribute to the hydropower generation. On the other hand, the entrance of the Ganges into the plains of Bangladesh is being controlled near Farakka by India. By definition,

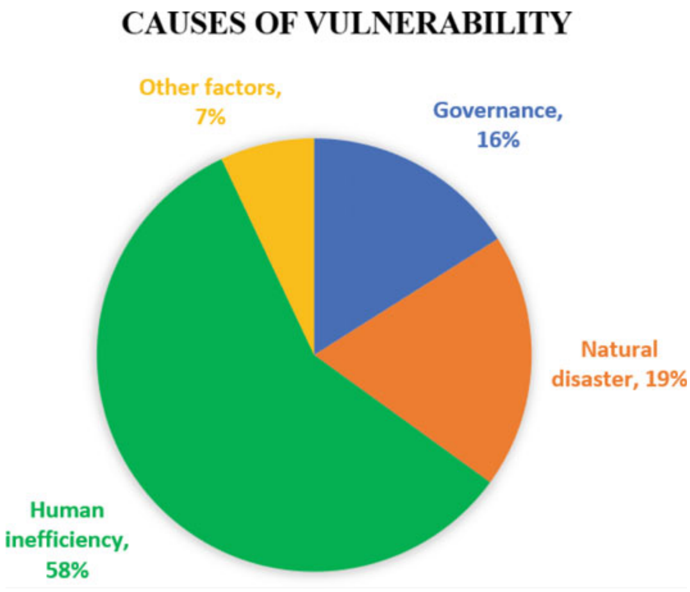

Fig. 23.9 Causes of vulnerabilities in the Meghna river basin (modified after (Bangladesh Bureau of Statistics, 2006))

the Farakka is not a very large diversion hydraulic structure. It is being used to redirect water from the core Ganges course to the Hoogly-Bhagirathi channel through the Hoogly canal. In further upstream near Haridwar, India has another dam called the Bhimgoda dam. This dam was constructed by the British reign in 1854. It was used to redirect snowmelts for irrigation purposes. This diversion caused a reduction in the downstream flow. However, in the Bangladesh territory, there is no such large dam on the GBM river systems. Three small-scale barrages have been made in Bangladesh on the Teesta, Tangon and Manu rivers. These barrages are being used for the deviation of water used for irrigation (FAO 2011). Table 23.6 presents the important hydraulic structures constructed in the GBM river basin:

The transboundary water issues related to the hydraulic interventions upstream:

- The different countries on the GBM delta system have conflicts in interests as they are located on upstream and downstream riparian regions (World Bank 2010)
- India and Bhutan joined in an agreement over the Chhukha Hydroelectric Project in 1905
- Nepal and India had a number of joint commissions over Kosi river (1954, 1966), Gandak river (1959), reformation and lengthening of Chandra Canal, Pumped canal and Western Kosi Canal (1978) (World Bank 2010)
- In 1972, the Indo-Bangladesh Joint River Commission (JRC) started to roll to negotiate on several issues like management operations, development strategies and allocation of downstream riparian water resources (JRCB 2011). The other objectives of this joint commission were (JRCB 2011)

Table 23.6 The important hydraulic structures built in the GBM river basin (Modified after (FAO 2011))

Country	Name	River	Year	Height	Main Use
Bhutan	Chhukha	Ti Chu	1988	40	H
	Tala-Wankha	Wang (Raidak)	2006	91	H
	Kuricchu	Kuri	2002	33	H
	Basochu	Baso Stream	2001	-	H
	Punatsangchu	Puna Tsang	Under construction	141	H
India	Rihand	Rihand	1962	91	H
	Farakka Barrage	–	1974	–	–
	Bhimgoda	–	1854	–	I
Nepal	Gandaki	–	–	–	–
	Kosi	–	–	–	–
Bangladesh	Manu Barrage	Manu			I
	Tangon Barrage	Tangon			I
	Teesta Barrage	Teesta			I

- Cooperation on sharing common waters, hydrologic data sharing, protecting river banks along the rivers having common water bodies and borders
- Monitoring and co-sharing of the Ganges water near Farakka and Hardinge Bridge in India and Bangladesh, respectively
- Mitigating flood hazards and sharing flood-related data with Nepal for common water use
- Cooperating with China to exchange hydrologic data of the Brahmaputra river, mitigate flood hazards, ensure fairness and equitable share of transnational waters, skill development, etc.
- The Farakka dam poses a risk of conflicts as Bangladesh claims that a huge amount of water is being stored back during the dry season and monsoon discharge is too high (FAO 2011).
- Another agreement was signed between India and Bangladesh over the allotment of the Ganges water at Farakka in 1977(World Bank 2010).
- Bangladesh and India proposed other arguments in 1978 where Bangladesh emphasized the construction of dams and reservoirs in Nepal to store monsoon water. Then again, India proposed to construct a canal that will be linked to transfer water from the Brahmaputra river to the Ganges river. None of the proposals took effect afterwards.
- Bangladesh and India signed another agreement called the "Ganges Water Sharing Treaty" intending to ensure an equitable share of Ganges water (Parua 2021).
- Although there had been a primary agreement in 1983 between Bangladesh and India regarding the distribution of Teesta river water (World Bank 2010), no realistic framework for Teesta water management could be formed by either of the countries (Biswas et al. 2008).

23.7.1 The Ganges River

Most of the hydraulic structures on the Ganges basin is national and project by project based. Although a number of countries share the flood plains of the Ganges river, there is a significant lack in regional cooperation and transcountry partnership. As for the Farakka Barrage project, the initial design was focused on better navigation and transportation of sediments and reducing salinity in Kolkata city water supply (Crow et al. 1995; FBP 2015). The monthly maximum, average and minimum discharge over pre- and post-Farakka periods (Fig. 23.9) show that during the dry season, the water availability in the downstream riparian regions of Bangladesh is reduced to a significant extent. On the other hand, as the monsoon period approaches, specially during July to September, the downstream water discharge increases (Rahman and Rahaman 2018) (Fig. 23.10).

Consequently, the southern Bangladesh faces increased amount of salinity during the dry seasons. This puts serious restrictions on freshwater dependant agriculture and fresh surface and ground water availability. The long-standing reduction of river discharge also effects fresh water fish varieties in the region. In some cases, agricultural lands are transformed into brackish water shrimp ponds which in turn increase soil and water salinity. The increased soil salinity affects the mangrove regeneration and growth. Apart from environmental and ecosystem damages, the southern waterways also face decreased navigability due to lack of flow in the main channel.

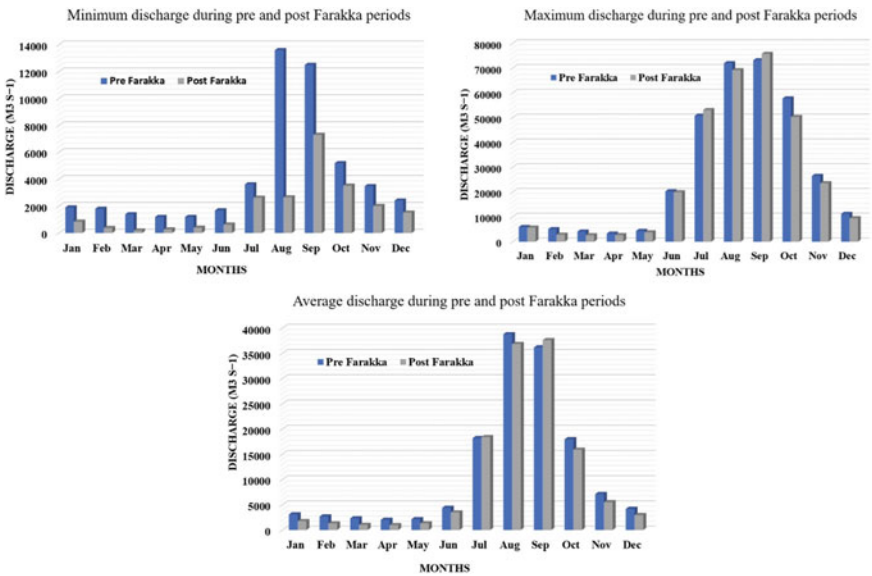

Fig. 23.10 Changes of monthly maximum, average and minimum discharges in the Ganges river at Hardinge Bridge station, Bangladesh during the pre-barrage and post-barrage periods (modified after (Rahman and Rahaman 2018))

As a result, river health gets negatively affected and makes it difficult to maintain socio-economic stability in the region as many of the parameters of socio-economic development and growth are directly linked with river health and related ecosystem services (Rahman and Rahaman 2018).

23.7.2 The Brahmaputra River

The banks of the Brahmaputra River suffer from serious flooding caused by a number of hydraulic structures, i.e. dams, dykes and embankments. The river dykes and embankments are constructed mostly to protect the people from flood. And the dams and barrages aim to produce hydropower as well as used for irrigation purposes. Unfortunately, these structures in most cases could not protect the people residing on either bank of the Brahmaputra river from flood-induced life and property damages. In cases of river dykes, a number of reasons like overtopping, erosion, seepage caused hydraulic failure and reduced their functionalities. The irrigation projects suffer from high amount of backflow. In some cases, the barrages bifurcated main channel causing deviation of original flow. This resulted in heavy siltation in the downstream regions. Although the riparian countries of the Brahmaputa river have greater potential for development, the sustainable utilization of river resources is not sufficiently targeted (Sarma 2004).

23.7.3 The Meghna River

The constructions of flood protecting structures on the Meghna river has influenced the flow towards the estuarine region. Other than flood control structures, a number of bridges have been built on the Meghna river at various points. The flanks of these bridges increased the velocity of river water at different points. This resulted in high amount of bank erosion and river bed scouring (Alam et al. 2009).

23.8 Effects of Other Issues on the GBM Delta

Although the GBM delta system exhibits tremendous opportunities for growth and cooperation, environmental challenges and climate change effects pose a direct threat to the survival of a large number of delta plain population. The direct impacts of climate change, such as saltwater intrusion, coastal inundation, riverbank erosion, recurring cyclones, erratic rainfall pattern, elevated storm surges and extended periods of droughts will elevate the vulnerability of the population living in the GBM delta system. Shifting agricultural lands into aquaculture water bodies would create a need for alternate livelihoods and migration (Amoako Johnson et al. 2016). The resulting pressures could destabilize the societal and financial conditions of these people. The continuously exposed environmental threats would lessen the ability of people and communities to withstand these threats and make them extremely vulnerable in the face of environmental challenges (Neil Adger 1999; Adger and Kelly 1999). Since the effects of climate change and other factors are similar for the Ganges, Brahmaputra and Meghna rivers, these have been discussed altogether.

The research of Das et al. (2020) shows that the GBM delta margin on both Indian and Bangladeshi sides is populated with communities that are more vulnerable and marginalized socially. They pointed out the following reasons for such vulnerability:

(a) Nature-based agriculture dependency
(b) Reduced access to clean water and sanitation
(c) Lack of education
(d) Poor living conditions

Some amount of the population is involved in aquaculture and artisanal fishing. Although commercial catch helps them economically, it is still not a viable option for poverty reduction in those regions. The reasons behind this are higher costs associated with labor price, fertilized and seeds reduced agriculture due to salinity intrusion and soil salinization (Das et al. 2020).

The most vulnerable social communities can be observed to be intense in the southeastern part of the GBM delta. Among them, Manpura and Maheshkhali are some of the most vulnerable sub-districts socio-economically. These two sub-districts are continuously hit by recurring cyclones and coastal bank erosion (Ahmed 2009; Tanim and Roy 2013).

23.9 River Management Plan for the Bengal Delta

The GBM delta presents great opportunities but is also overshadowed by a lot of environmental and socio-economic challenges. This delta system and the contributing major rivers bless its population by providing water for domestic and municipal use, irrigation water, hydropower, a number of ecosystem services and navigable channels. Unfortunately, it also suffers from a number of vulnerabilities like river water pollution, natural disaster, land cover change, climate change effects and other challenges. To overcome these above-mentioned challenges, regional cooperation, goodwill and joint research activities must be ensured to deal with transboundary river issues, water pollution and natural and anthropogenic disasters in the region.

23.9.1 Transboundary River Management

India and Bangladesh both have long-standing issues regarding the management of the GBM delta. In this time of Anthropocene, lack of policy formulation and cooperation can bring about a number of conflicts and difficulties for both of the countries. Although Bangladesh shares 54 rivers with neighboring India, only one treaty over the Ganges water use has been signed. It is crucial to understand that boundaries are not defining the best scope of management, basins are. That is why it is so important to manage river basins as a whole.

Table 23.7 adapted from Sadoff and Grey (2002) summarizes the types of benefits transboundary river management can provide.

Table 23.7 Benefits received from transboundary river management (Adapted from Sadoff and Grey (2002))

	The challenge	The opportunities
Providing assistances to the river	Contaminated water, mismanaged watersheds and wetlands, threatened biodiversity	• Mitigating flood and drought challenges
		• Managing sediment and erosion rates
		• Conserving wetlands and species diversity
		• Conserving water to maintain water flow
Yielding profits from the river	Growing water demand, inefficient management and development of water resources	• Improving conditions for hydropower, fisheries and agriculture
		• Optimizing food security to reduce poverty
		• Enhancing navigation to encourage tourism and recreation
		• Sustaining water ecosystem services through carbon tax inclusion
Lessening costs because of the river	Stressed relationships among related nations leading to political and economic degradation	• Achieving political stability through cooperation
		• Moving to a food-secure community from a food-sufficient community
Generating paybacks beyond the river	Transnational fragmentation of the regional countries	• Integrating regional resources
		• Ensuring commercial and industrial developments to achieve regional investments
		• Increasing exports and market access to enhance regional trades
		• Diversifying the economic parameters

The following steps should be taken to further enhance proper and realistic transboundary river management between the above-mentioned countries (Rahman et al. 2020):

- There should be inclusive policy dialogues between the countries
- The dialogues should emphasize on fair and equitable distribution of transboundary waters
- Institutional cooperation should be established between government, non-government and civil society organizations of both countries
- Vulnerability reduction and innovative rehabilitation programs should be jointly organized
- There should be proper sharing of hydrological, socio-economic and regulatory information between the two countries.

Existing treaties can be made flexible by incorporating several mechanisms proposed by Fischhendler (2004), and McCaffrey (2003).

- Making flexible and inclusive allocation strategies
- Provisions for mitigating droughts
- Revising previous clauses and making amendments
- Setting up combined management institutions for better cooperation.

23.9.2 Water Quality Management

The Bangladesh part of the GBM delta suffers from surface water pollution, saline water intrusion, excess sedimentation which causes permanent damage to the ecosystem and surrounding environments. In many cases, some health hazards associated with water quality deterioration can be observed. In the Indian part, the central and lower spreads of the Ganges and the Brahmaputra rivers are more polluted than the rest (FAO 2011). The water quality management for the GBM delta includes (FAO 2011).

1. proper management of solid and liquid wastes,
2. increasing freshwater flow during dry seasons to reduce salinity intrusion
3. proper maintenance of sewage systems
4. increasing land stability in the upstream reaches to reduce landslide hazards in the downstream riparian regions.

23.9.3 Disaster Mitigation and Management

The effects of disasters cannot be completely avoided. However, the damage and the risk can be minimized. Cooperation, transnational efforts can minimize the negative effects of disasters happening in the GBM delta plain. Real-time data sharing on precipitation, discharge, flood forecasting and meteorology between nations can reduce the amount of damage. This type of cooperation also provides enough time for both regions to prepare for flood and drought hazards. Governing bodies get a time frame of 2–14 days to migrate people to safer locations. Basin-wide regional cooperation to harness monsoon water is crucial to transboundary disaster management. The flood forecasting and warning framework should be integrated regionally to ensure the free flow of meteorological and relevant information. Other than the non-structural measures, cooperation in structural intervention in the upstream and downstream regions is also crucial for mitigating and managing disasters in the GBM delta (Biswas et al. 2008).

23.10 Conclusion

The transboundary rivers of the GBM delta require regional cooperation in terms of river management, vulnerability reduction and resource maximization. Many environmental challenges like natural and anthropogenic pollution, land use and land cover variation, natural disasters, hydraulic interventions, climate change stresses and socio-economic vulnerability are associated with the transboundary rivers of the GBM delta. Proper management strategies backed by transnational involvement can reduce the environmental uncertainty of this region. Compliance, enforcement and dispute settlement can resolve long-standing issues in the Ganges, Brahmaputra, and Meghna river management.

23.11 Recommendation

From the findings of the study, the following recommendations can be made to ensure the sustainable management of the Ganges–Brahmaputra–Meghna delta system:

- Effective policy dialogs should be carried out to review transboundary water flow to meet the water needs of downstream riparian regions.
- Vulnerabilities should be minimized through transstate information sharing and cooperation.
- All the parties from all concerned states should agree and act on the protection and conservation of GBM delta and its surrounding ecosystems by sustainable and inclusive management of the Ganges, Brahmaputra and Meghna rivers.
- Upstream regions should acknowledge that proper and equitable flow of river water can play a constructive role in reducing salinity intrusion and bank erosion is the lower downstream regions.
- Regional cooperation should be strengthened by establishing technical and research organizations which will ensure co-learning for the concerned states.
- Governments should account for proper and sustainable waste management to improve the quality of river water throughout the delta system.

- Concerned nations should work determinedly to overcome any sort of stressed situations between and among them.

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Chapter 24
Achieving Sustainability by Retrofitting Circular Economy Models in Food Waste Flow of Bangladesh

Ayushi Khan, Tania Parvin, Fahmida Akther, Niaz Ahmed Khan, Mohammad Mosharraf Hossain, and Mohammad Sujauddin

Abstract Given the dire state of the planet where scarce resources are being exhausted and "waste" is carelessly disposed of, we can find a hero within the concept of the circular economy—a model which aims to achieve a closed loop scenario by recycling the wastes back into the useful economic and ecological flows. Bangladesh, despite her growing population, lacks a dependable institutional waste management system, so the government should apply the concept of circular economy to modify and reconstruct it into a sustainable model. Organic food waste is the major constituent of household waste, containing nutrients and chemicals with too great of an influence on the chemical cycle to simply be disposed of. The current primary waste disposal method followed in Bangladesh is undesirable landfill dumping and such an easily recyclable component like food waste must not follow that path and should be re-circulated back into the loop instead. Currently, there are no comprehensive studies on food waste in Bangladesh to be used for policy guidance. Hence, proper quantification with composition of food wastes is essential to determine the reprocessing potential and provide policy guidance to restructure the existing inefficient waste management system into a sustainable one within the purview of circular economy concept. This chapter attempts to quantify the food waste generation of Bangladesh and explores the various options of available modern technology and methods to recover and reuse food waste. Circularity is the perfect instrument to promote decoupling and achieve sustainability, so its prospect and significance in food waste recycling shall be investigated.

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24.1 An Overview of Circularity and Food Waste of Bangladesh

Over the years, there has been considerable debate and discussion in the academic quarters regarding the connotation and characteristic nature of waste. In an intensive research striving to properly define waste, Pongrácz and Pohjola (2004) collated several definitions considering different scenarios and classes of waste. Here, the rubric of "waste" includes materials that no longer have any purpose, has become useless after completing the said purpose or mandate, has failed to complete its function to an acceptable level, or cannot be entirely utilized by the beholder, thus rendering it useless. However, forcing such a definition onto waste erases its reuse potential and implies that it is simply meant to be discarded (Pongrácz and Pohjola 2004). Instead, we should strive to do the complete opposite and re-utilize our discarded "waste" up to the hilt. It is now unequivocally established that waste generation is greatly detrimental to the environment; we must therefore ensure as little of it is produced as possible; ideally, the volume of waste that reaches the final disposal level should be completely eliminated.

One of the most robust tools we can use in order to achieve this is a concept called the circular economy. It presents a model that takes a circular approach to reuse and recycle as many resources as possible in order to reduce the final waste deposit and the demand for virgin resources, as opposed to the conventional linear model which simply extracts resources from the environment, uses what is required and then discards the remainder (KPMG 2019). The linear method of resource use is extremely undesirable since it depends on the extraction of scarce raw materials and dumps the final waste in landfills; this unsustainable practice will exhaust the natural resources of the planet even further. The circular model, on the other hand, is tremendously sustainable since the "waste" which remains after all process throughputs are salvaged and re-introduced into the process loop to be reused and reutilized afresh. This also promotes resource/impact decoupling, since we are no longer relying on raw virgin resource extraction for manufacture and production but are instead utilizing the resources that are perfectly usable but would have been discarded of otherwise.

In order to properly implement circular economy models into the scheme, we need to understand how the waste management system works. Municipal solid waste (MSW) is the broad spectrum of wastes generated by municipalities and domestic or commercial sites, and its management service is of utmost importance for any country (World Bank 2012). Bangladesh is an emerging developing country where the lack of a proper institutional waste management system is a pressing issue. The current municipal authorities are not efficient enough regarding waste collection considering only 42% of the total MSW generated gets collected and there are little to no policies that would help in the waste management sector (Sujauddin et al. 2008;

Enayetullah et al. 2005). Out of the different categories of waste that is counted as MSW, food waste (organic waste) is the most significant one of them all, comprising of a staggering 50% of the total generated MSW for countries of South Asia (World Bank 2012).This value holds true for Bangladesh as well, which shows that a large amount of food waste (FW) is discharged into the waste stream to end up in unsanitary landfills regardless of its high potential for reuse and recovery. Unattended FW is not only environmentally malignant but also unethical in the context of a country where 21.8% of the population lives below the poverty line and cannot afford proper meals (ADB 2020). The inability to utilize these perfectly good organic resources is a disappointment; hence, if we are able to implement circular economy models and recover the FW to inject it back into the throughput loop, the resource/impact decoupling will prove to be extremely beneficial to both the environment and economy of Bangladesh. Since there is currently no proper waste management system, if we can advocate for circularity to get adapted into the system and create a boundary through which resource use is optimized and the input that is extracted from nature is reduced or potentially eliminated, it will be the most sustainable and desirable model to deal with FW and MSW. One significant example for this is the preservation of phosphorus, an extremely important non-renewable resource whose scarcity is a prevailing problem both environmentally and economically, despite which a heavy amount of phosphorus is lost into the solid waste stream in Bangladesh (Roy et al. 2019). Phosphorus needs to be mined out of the earth and Bangladesh has to import it due to the absence of natural reserves, but recovering it from the solid waste stream for reuse will promote sustainability and resource decoupling which will effectively reduce the pressure for mining, benefitting both the environment and the economy (Rahman et al. 2019).

The purpose of this study was to quantify the nature and magnitude of FW that is discharged into the MSW stream, particularly from households/residential areas, and to address the lacuna through the lens of circular economy as well as to retrofit the system by closing the loop. Unfortunately and surprisingly, there has not yet been any extensive research done solely on FW in Bangladesh, despite it being a significant portion of the total waste generated by the municipal sector. The previous endeavors (Iqbal et al. 2007; Noman et al. 2007; Alam et al. 2008; Sujauddin et al. 2008, 2011; Chowdhury et al. 2010, 2013; Sujauddin and Koide 2011; Sujauddin 2013; Roy et al. 2019; Rahman et al. 2019; Tasmeea 2019; Parvin 2019; Akhter 2019; Baroi et al. 2020) of this research team in the broader spectrum of solid waste management system in Bangladesh addressed a potential sector viz. FW which never got a spotlight despite the magnitude of possibilities surrounding it. Furthermore, the present data at hand are very sparse and subject to scrutiny due to its debatable reliability, and currently, no FW studies with a circular perspective have been carried out in a developing country. In order to successfully integrate FW flow into a circular economy model, we must quantify the amount and composition of food wastes that are being discharged from all levels since waste generation and composition also varies depending on different geographic and socioeconomic factors like location, household income, education level, rapid urbanization, religion, and so forth. This chapter attempts to use the sparse data available to estimate the FW generated on a national scale and illuminate the wide scope available for FW circularity in Bangladesh following the footprints of countries that have made efforts to do the same.

24.2 Methodological Approach

The overall study was fundamentally based on material flow analysis in which all the flows of waste are examined in an attempt to quantify the FW. The system boundary for this study is the geographical border of Bangladesh. The different inflows, throughputs, and outflows of food and FW through different socioeconomic groups and regions of Bangladesh were examined. All information on the FW generation was gleaned from studies that focused on MSW composition, courtesy of this team of researchers that have been working with MSW and circularity in Bangladesh (Sujauddin et al. 2008, 2011; Chowdhury et al. 2010, 2013; Sujauddin and Koide 2011; Sujauddin 2013; Roy et al. 2019; Rahman et al. 2019; Tasmeea 2019; Parvin 2019; Akhter 2019; Baroi et al. 2020) since they have a strong, pre-established comprehensible database which was used to estimate and assume the generation and flow of FW.

A recent published article of this team (Baroi et al. 2020) has an extensive database of the MSW generation, composition, and flow throughout Bangladesh which was intensively utilized to extract the FW branches from each MSW flow. The total MSW generation data containing detailed composition with FW generation percentage were only prevalent from the inputs of 2004–2014, so those were the years we have considered in our study. Among these years, there was a lack of continuous data from the same coverage area; there were a few sporadic studies covering the total MSW generation of mainly Bangladesh, Dhaka, and Chittagong. An estimate of the FW generation value for missing data points of Bangladesh was calculated by determining per capita FW generation in other regions that had available data and finding its product with the total Bangladesh population; any further missing points were determined by using regression. Chittagong city, the industrial hub of Bangladesh, had the highest number of data inputs and also had the longest streak of continuous data from 2005 to 2009, so a separate analysis was carried out for it where a simple regression model was used to extrapolate the data for the four missing years. Furthermore, two more studies of this team (Parvin 2019; Akhter 2019) contain indispensable raw data regarding food waste and consumption, which proved to be crucial for testing our conclusions and speculating trends. Parvin (2019) and Akhter (2019) had carried out field works to collect primary data regarding food consumption patterns and food waste generation, which were extracted and analyzed for this study.

24.3 Research Findings

24.3.1 Overall Food Waste Generation

Data in the World Bank database (2018) indicate that FW constitutes of 50% of the total MSW generation in the South Asian region on an average. However, the data collected via the extensive literature survey show much higher levels of FW generated, with an average of 70.4% of the total SMW generation belonging to the organic waste portion. The areas with the highest levels of FW contribution to the MSW flow were the Southern coastal district Patuakhali and the traditional metropolitan city Rajshahi for 2012, where FW occupied 84% and 82% of their total waste, respectively (World Bank 2018). This is possibly because of the lower income levels and standards of living in those areas, which leads them to spend more of their income on food alone compared to bigger cities where income is more evenly distributed into factors other than foodstuff. In addition, with increased income levels, more money is spent buying packed and processed goods as opposed to fresh organic groceries, which will cause more paper, plastic, and metal wastes to be formed.

The estimated result of the annual waste generation in Bangladesh from 2004 to 2014 taking both the urban and rural populace into consideration is shown in Fig. 24.1a. The annual MSW generation and its FW fraction in tons per day are compared side by side, clearly portraying how FW comprises of a huge portion of the total MSW. Figure 24.1b depicts the FW generation in Chittagong alone. In both the figures, there is a noticeable gradual increase in the total annual generation of food waste with the passing years. This is possibly due to the increase in population along with the urbanization and development Bangladesh has gone through during the last decade. Chittagong, the port city of the country, is already a major commercial hub and there has been significant development of roadways and infrastructure in the last few years. This development would subsequently lead to an overall increase of income and standards of living, causing people to generate more waste since it is proven that the household MS generation level has a positive correlation with income levels (Sujauddin et al. 2008). Furthermore, the amount of MSW generation increases by 1.2% on average every year, so we can expect the total volume of food waste to follow this trend and consequently increase (Yousuf and Rahman 2007). On top of these factors, the ever growing population of Bangladesh will cause a constant rise in FW generation levels as well considering the annual food intake of Bangladesh will get higher, and food consumption is proportionate to the FW generated. To illustrate the interrelationships of all these variables, Fig. 24.2 shows how the rise in population and gross national income ensues in a rise of food income and waste over the years.

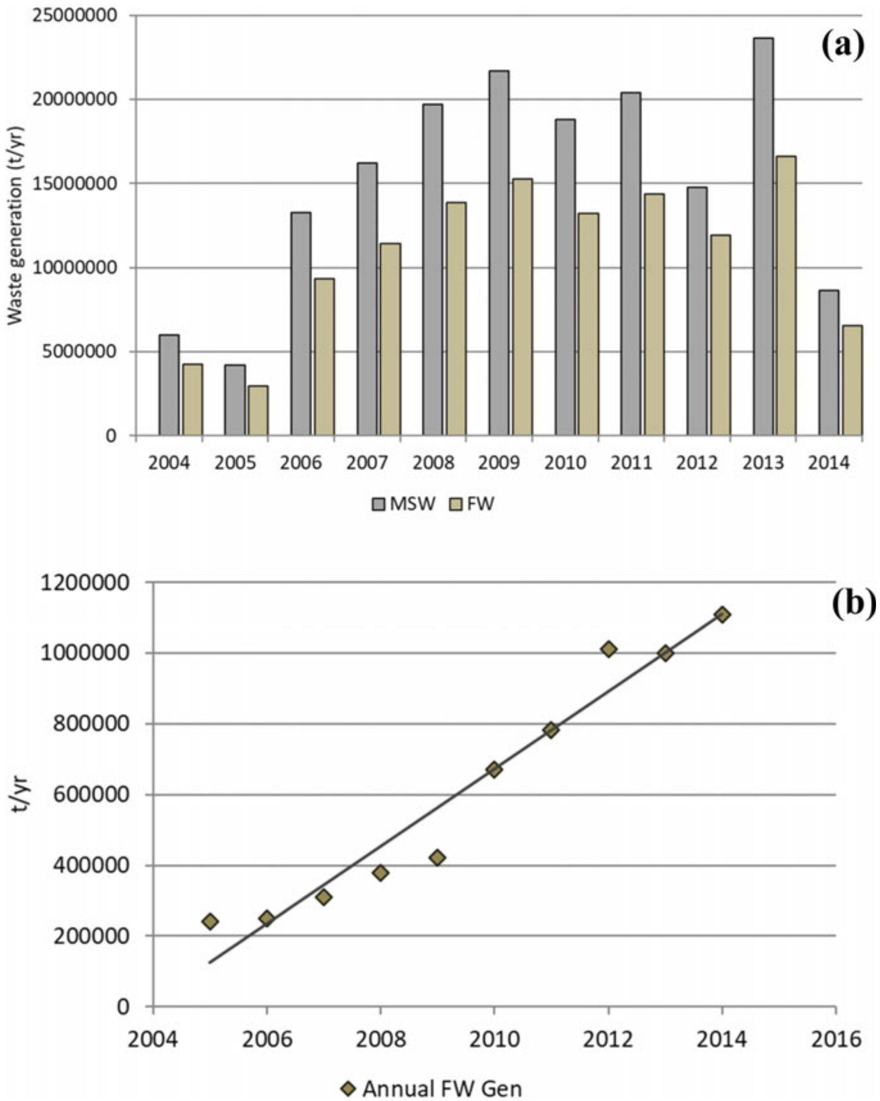

Fig. 24.1 Annual food waste generation in Bangladesh; **a** total MSW and FW portion among yearly generated MSW in Bangladesh; **b** total food waste generation in Chittagong which shows gradual growth over the years. *Source* Chowdhury et al. (2013), Waste Concern (2014)

24.3.2 Food Waste Composition and Socioeconomic Significance

Considering no in-depth research has been carried out yet for FW in Bangladesh, there is no proper way to know the composition of the FW in the country. Doubtlessly,

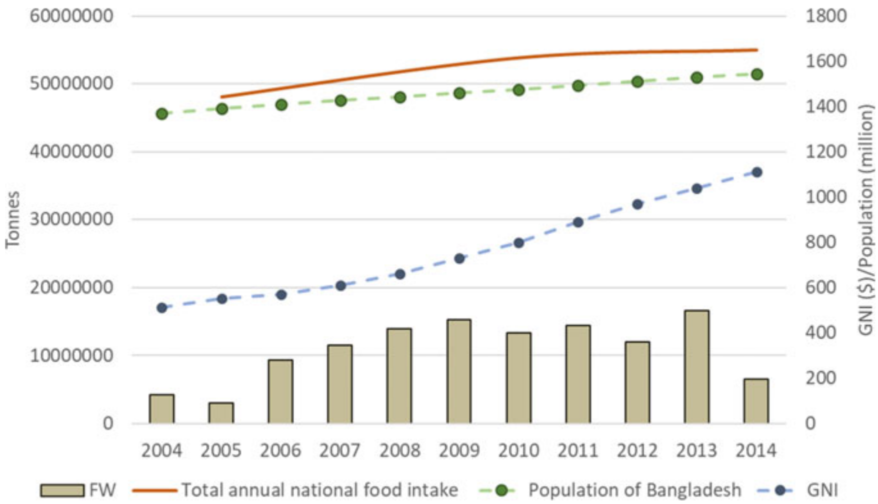

Fig. 24.2 Interrelationships of FW generation with population, gross national income (GNI), and total food consumption in Bangladesh show a gradual increase in FW intake with increased income and population. *Source* World Bank (2018), Waste Concern (2014)

the composition will vary depending on different locations, income levels, education levels, climate, religion, and even on a daily basis in a single household, making it difficult to homogenously quantify the composition of FW for a whole country or even a single area. While Sitakunda is a mere sub-district of Chittagong and cannot seek to be an accurate representation of how the urban and rural portions of Bangladesh actually behave, the household waste generation data can help give us a rough estimate of how the socioeconomic divide affects FW (Parvin 2019). A total of 28.26 million households in Bangladesh are categorized as rural and 11.07 as urban (BBS 2016). Multiplying the urban and rural household FW generation with the total number of rural and urban settlements in the country can give us an approximation of how much FW is formed in at least the lesser developed and

lower/lower-middle income group regions of Bangladesh along with the composition of the FW. Following this, the results show that the rural fraction of the population generates a total of 6,204,184 tons FW per household every year while its urban counterpart produces 2,165,318 tons per household annually. The higher value for the rural sector is perceptibly due to the larger proportion of people on that side. Multiple other factors such as the lack of access to electricity and storage facilities in rural areas also come into play to affect the FW production.

Figure 24.3 illustrates the composition of the food waste of this tentative model. There are no significant variations in the two waste patterns; the rural sector wastes more vegetables and dairy while the urban sector wastes more meat, fish, and cereals. The rural sector tends to have lower levels of income compared to the urban counterpart, which affects the type of food they consume. Vegetables cost less than any other type of foods, and rural dwellers often harvest their own vegetables. Most of

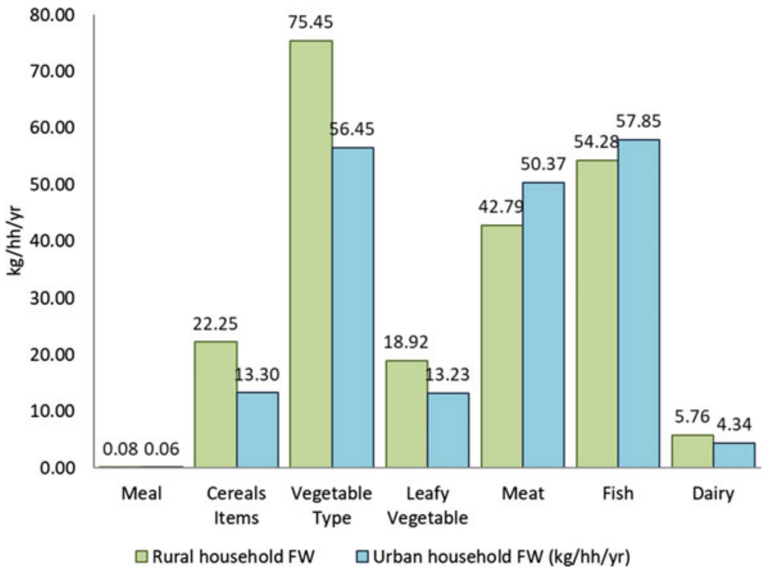

Fig. 24.3 FW composition in urban and rural Bangladesh in 2019 where the urban portion consumes more protein than the rural portion due to the differences in income and purchasing power. *Source* Waste Concern (2014)

them also own cattle such as cows and goats which are their source of milk and dairy. The urban sector is able to spend more money on meat, fish, rice, and other staples; hence, they produce higher levels of waste in these categories. Vegetables, meat, and fish constitute the highest percent in household FW, and knowing an estimate of the FW composition will aid in taking concrete decisions toward what kind of recycling or reusing method can be utilized for specific FW.

24.3.3 Overall Food Waste Flow

The bulk of 42% of the total waste which is collected for disposal by MSW management system ends up in landfills, open areas, or roadsides. Inevitably, most of the FW end up in landfills (Sujauddin et al. 2008; Yousuf and Rahman 2007). In Bangladesh, sites which may require earth filling are used as landfills for MSW. In the face of rapid urban sprawl, finding suitable locations for landfills in municipal areas is also becoming a big challenge. In the absence of source separation of wastes, dumping all wastes together into the landfill leads to the formation of harmful leachate. The leachate created from the landfills is often toxic due to the mix of harmful chemicals, organic, and inorganic compounds that is seeped out by any percolating water. The high percentage of organic components and water makes MSW a perfect candidate for composting, though unfortunately only about 0.27% of the food waste is recycled since composting is not a very prevalent practice in the country (Yousuf and Rahman 2007). The loss of nutrients including phosphorus due to prevailing unsustainable waste management is also a critical issue, in the context that MSW offers a great potential for the recovery of these invaluable elements (Baroi et al. 2020). It puts into perspective the utter wastefulness of the current open loop waste management system and offers a clear indication of the potential offered by circular economy models to improve this current state. Possible methods to use these salvaged resources are explored in the next section.

24.4 Recommendations

24.4.1 Scopes to Retrofit Circularity in the Waste Sector

Ensuring source separation of MSW before, during, and after collection to separate organic wastes from inorganic ones to individually deal with each type and reuse or recycle them to their maximum potential is a prerequisite for the implementation of a circular system. The implementation of circularity to recycle food waste has already been carried out in several countries. We can use these examples as blueprints to design robust policies that would implement circular economy models into the FW flow stream of Bangladesh. Ideally, building a proper MSW system implementing these policies from the very bottom to top level will give the best results in how we handle the waste. A summary of the options and status of recycling food waste is shown in Table 24.1.

Considering Bangladesh already does produce biogas from manure and livestock waste in an attempt to find a source of renewable energy, implementing this technology to produce energy from FW is a viable concept (Chowdhury et al. 2020). In their research, Mirabella et al. (2014) have a goldmine of data collected from a tremendously extensive literature review that explores all the different types of food wastes and the valorization and use of each specific ingredient. This data show all of the available opportunities for recycling or reusing these specific foods (Mirabella et al. 2014). The most popular method of re-utilizing food waste is anaerobic digestion of the organic materials, which has the lowest amounts of emissions and environmental impacts compared to landfilling, incineration, and composting (Slorach et al. 2019). Anaerobic digestion can further convert FW into bio-methanes and fertilizers (Paul et al. 2018; Toop et al. 2017). Food wastes can also be converted into feedstock for animals and aquacultures alike (Maina et al. 2017; Strazza et al. 2015). Another effective recycling method is to form energy with these wastes. Kitakyushu city in Japan has engineered waste treatment plants that convert food waste into ethanol in addition to recovering hundreds of kilograms of oil (Matsumoto and Sano 2011). Wasted animal meat and bones can be burned to produce combustible energy and oil (Chaala and Roy 2003). A special chemical mixture called the “SulphaTrap” formed by Evans et al. (2018) can separate certain organic compounds from food

Table 24.1 Opportunities for food waste recycling

Recycling option	Type of food waste required	FW conversion options	Technology available in the market	Efficacy	Challenges
Anaerobic digestion	Organic wastes	• Biomethane and biofertilizer[a]	Sludge and manure	Very high[b]	High costs[b]
Bio-energy conversion	Household food waste[c]	• Bio-gas[d] • Ethanol production[c] • Methane[b]	Ethanol treatment facilities[c]	High[c]	Requires machines and proper facilities, high capital cost[a]
Animal feed	Fruit, vegetable, and crops[f]	Cattle feed, aquaculture feed[d]	Mills[e]	Moderate[e]	
P and N recovery	Apple pomace, [f] Organic wastes	Nutrient recovery[d]	No current available technology	–	Extraction of nutrients
Composting	Organic wastes	Fertilizers	–	High[d]	–
Biotechnology	Apples, olives, vegetables[f]	• Pectin extraction[f] • Cattle feed[f] • Source of fibers[f] • Biotransformation[f]	Hydrothermal treatment[f]	Moderate[f]	Requires proper lab facilities

Source [a] Paul et al. (2018), [b] Slorach et al. (2019), [c] Matsumoto and Sano (2011), [d] Maina et al. (2017), [e] Strazza et a. (2015), [f]Mirabella et al. (2014)

waste to purify biogas, which shows promise for the recovery of methane. Food waste contains a high stock of important nutrients such as nitrogen and phosphorus, which should be extracted as well to maintain balance of the chemical cycle (Forkes 2007; Rahman et al. 2019). The recovery and recycling of phosphorus in Bangladesh is a topic that has been researched in great detail by this team, considering the country has excessive levels of phosphorus loss (Roy et al. 2019; Baroi et al. 2020). Organic FW in the MSW stream contains high phosphorus levels, and there is tremendous recycling potential if the phosphorus can be extracted from there (Baroi et al. 2020). Moreover, if increased awareness about phosphorus conservation is implemented at a consumptive level and community composting is suggested and practiced in the rural sectors, Bangladesh can very easily work toward phosphorus recycling to preserve the scarce nutrient in a circular fashion (Baroi et al. 2020). Countries like Finland and Denmark very effectively recover phosphorus from the waste sector to reuse it on other subsystems, and China has the highest "decoupling factor," meaning, it has the most efficient rate of phosphorus recovery that compensates for the phosphorus mined; Bangladesh should aim for that too for the sake of both the environment and economy (Rahman et al. 2019).

In Bangladesh, food waste also includes wastes from markets including discards of fresh vegetables, wastes from fish and meat processing, and such other sources. There are many innovations already regarding the management of these wastes including conversion to biogas and compost, production of poultry and fish feed from fish and meat wastes, recovery of materials such a gelatin from fish scales, etc. The informal sector and some exporters have already created a viable export oriented business around these wastes, which needs to be explored, documented and extended to harness the economic potentials of FW. Efforts are visible to initiate MSW to biogas generation and composting at pilot levels in different municipalities in Bangladesh including Jessore and Cox's Bazar. Both Dhaka and Chittagong city corporations tried to adopt waste to energy or waste to compost systems in the past with very limited success mainly due to the lack of strong policy support and long-term commitments.

24.4.2 Policy Potentials

In following the footsteps of these encouraging examples, if the government of Bangladesh inculcates some new waste management policies and strategies for the nation, the country can very easily achieve a circular economy model system. Several steps may be considered with a view to paving the way for introduction of a circular economy model. First, it is imperative to consider and embed the ideas of sustainability through FW circularity in the country's regular and routine development policy and planning exercise, notably, during the formulation of the Annual Development Program (ADP), National Perspective Plans (for example, Five Year Plans), and Sectorial Plans. The General Economics Division of the Government's Planning Commission may coordinate and anchor this exercise toward incorporating and accounting for circularity considerations in the relevant plans and policies. Second, although very limited in number and coverage, there have been experimental efforts on circularity in Bangladesh in the recent years. After necessary assessment and screening, it is important to incentivize some of these efforts for further consolidation and scaling. As part of its green industrialization policy, the central bank of the country (Bangladesh Bank) may consider facilitative support to these experimental initiatives. Third, there has been generally been low level of public awareness on the utility and significance of the circularity ideas and practices. It is imperative to engage and tap in the role of print and electronic media for wider mass conscientization and community outreach regarding the matter. Fourth, proper management of food waste and MSW can be contextualized in relation to SDGs 2 (Zero Hunger), 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), 13 (Climate Action), 15 (Life on Land). Given the nation's special emphasis on the achievement of SDGs, circularity issues may be included in the national reporting of the relevant SDGs. Therefore, renewed efforts in terms of policy and planning to find better financing and implementation mechanisms to promote innovation in technology, infrastructure, and management through enhanced participation of the private sector can help retrofit the current system to mold it into sustainable MSW management system.

24.5 Conclusion

In this age of the Anthropocene, it is extremely important that we ensure our practices are as sustainable as possible in order to guarantee the well-being of this planet. FW in particular should be given more attention due to the high generation rates and high reuse potential. The current waste management system is as dreadful as can be, but that also means it is open for improvement and can easily be modified and developed; by incorporating within it a few circularity models and implementing some effective policies, we can transform it into an efficient system that promotes decoupling and aims to reuse as much of the residual waste as possible. In the distant future, it should come to the state where waste adapts a brand new definition: one that acknowledges the fact that it can, and should, be seen as a resource.

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